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OPTIMAL SITE SELECTION AND TECHNOLOGY DEFINITION FOR FLOATING PHOTOVOLTAIC POWER SYSTEMS AIDED WITH GEOGRAPHIC INFORMATION SYSTEM AND MULTI CRITERIA DECISION ANALYSIS.

PhD Thesis

Supervisor:
Chiar.mo Prof. Giuseppe Marco Tina

YEAR 2022

to My Family

STATEMENT

I hereby certify that this research paper has been composed by myself, and describes my own work, unless otherwise acknowledged in the text. All references and verbatim extracts have been quoted, and all sources of information have been specifically acknowledged. I confirm that this work is submitted for my PhD in the University of Catania and has not been submitted elsewhere in any other form for the fulfilment of any other degree or qualification.

Catania, February 28, 2023

ABSTRACT

The aim of this thesis is to investigate the possibility of using software based on geographic information systems (GIS) and multi-criteria decision analysis methodologies during the design phase of floating photovoltaic systems. As part of this study, studies were conducted to validate the possibility just mentioned both in terms of the choice of the site and in terms of the choice of photovoltaic technology. A bibliographic search was conducted and highlighted the current lack in this regard; there are case studies for the use of these software in the case of ground-mounted photovoltaic systems. For each lake analyzed and selected, after a GIS analysis, criteria were considered that led to well-defined results, validated by sensitivity analyzes. The San Giovanni Dam basin, in Naro (Agrigento), is the best site among those considered for the allocation of floating photovoltaic systems in Sicily.

Three different technologies were used for the choice of photovoltaic systems technology: fixed structures, horizontal axis tracking structures and vertical axis tracking structures; the first technology was considered with the photovoltaic modules in various tilt angles. With the aid of MCDA methodologies, and subsequent sensitivity analyzes, it can be stated that the technology with horizontal axis tracking structures may be more competitive than the others taken into consideration. It allows greater production of electricity, has a lower cost than other tracking technology, the best LCOE, the best performance ratio relative data and the highest value of tonnes of CO_2 avoided emissions.

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1.

INTRODUCTION

1.1 Current scenario

Renewable energy is playing a very important role in energy production by offering an ecological and economical alternative to classic fossil fuels; moreover, it is assuming an increasingly prominent role in the global energy sector for decarbonisation linked to the ecological transition underway. The centuries-old use of fossil fuels seems to be one of the element that is influencing the global warming and climate change that are damaging our planet. The constantly growing demand for energy can no longer be satisfied by burning fossil fuels, which are rapidly decreasing, given the continuous growth of the population and with developing economies. The role of renewable sources in energy production appears to be growing with the hypothesis, in 2050 [1], of the predominance of solar energy as the main source [Fig. 1].

One method to produce clean energy and avoid continuing to use fossil sources is photovoltaics (PV). It has grown significantly in recent years and is destined to establish itself on the world scene over the next twenty years.

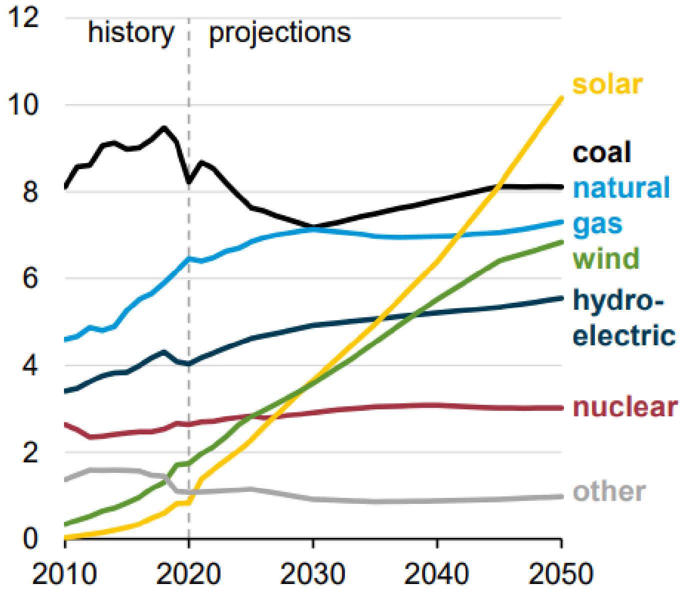

Figure 1 - World electricity production forecast [1]

Due to the invasiveness and environmental impact, as well as the reduced use that can be made of it, a possible solution proposed is that of agricultural plants that combine the production of electricity from solar sources to agriculture, guaranteeing certain requirements [2]. The use of the agricultural sector has also intensified the use of photovoltaic panels above or below the water surface of the basins. This further evolution of terrestrial photovoltaic systems is called floating photovoltaic; since 2015 it has started to spread all over the world [3]. The Global Industry Analysts (GIA) says Floating PhotoVoltaics (FPV) is expected to establish a new global market by 2026. The projected annual production, in 2026, is around 4.8 GW [4]. In August 2020, approximately 2.6 GW of cumulative capacity was produced in more than 60 states where floating photovoltaic plants are built [5]. The floating photovoltaic system is a very competitive technology compared to the conventional land technology; this is also due to the positioning of the panels on the surface of the water and the decrease in water evaporation [6]. The major advantage of the floating system is the natural cooling effect of the water on the panels, with the consequent increase in energy conversion efficiency; in fact, the production of electricity increases by over 10% compared to ground photovoltaic panels [7]. Further advantages are linked to the production of energy and to the greater efficiency of the plant, to the reduction of the flow of water evaporated from the basin, to the inhibition of algae growth, to the lower costs of setting up the site and to the possibility of integration with existing hydroelectric plants [8-14].

The installation of FPV systems requires many construction phases and challenges, so the sites available for the installation of these systems must be carefully selected [8]. Various studies suggest a geospatial approach based on GIS technology, not only to locate the available sites, but also to evaluate the average electrical power generated by the FPV modules by calculating the solar radiation, which can vary significantly in different geographical locations [15]. Furthermore, other studies [16,17] have shown that identifying the areas available for the installation of these technologies can be a very difficult task due to the numerous needs. They therefore proposed a multi-criteria analysis method to determine the sites available for the installation of the FPV system based on the technologies of the Geographic Information System (GIS): the required needs are entered in this software as input matrices and the GIS output tools the geographical coordinates of the areas where the required needs are met. Multi-Criteria Decision Analysis (MCDA) is used to identify the parameters for optimal design; in the case of photovoltaic systems, various thematic areas can be considered: economic, environmental, technical criteria, etc.

1.2 Objectives

To achieve the objectives set at the beginning of the PhD program, it was necessary to carry out an extensive bibliographic search of the existing literature in order to be able to deepen the topics of interest. The state of the art on the subject addressed was at times lacking as, to date, there are few studies that deal with the allocation and/or choice of floating photovoltaic systems using GIS software and MCDA methodology.

Several studies have been carried out for the best allocation of a floating photovoltaic system on the basins in Sicily and, as a subsequent study, on the choice of which can be the best photovoltaic technologies, evaluating more and more disciplinary aspect.

1.3 Methodological process

The introduction and conclusions of this thesis work can be found in Chapter 1 and Chapter 5. Chapter 1 introduces the theme of the research work carried out during the three years of the doctoral path while the final Chapter contains the results and the contribution made to the research of the entire work.

Chapter 2 contains an overview of the existing literature and the discussion of the themes necessary for the comprehension of the following Chapters. The issues relating to floating photovoltaic systems are dealt with both technical, economic and social aspects; in addition, key topics in this research project are involved, such as the Geographic Information System (GIS) and Multi-Criteria Decision Analysis (MCDA).

Chapter 3 describes in detail a case study where GIS and MCDA were tested on how can be useful in choosing the site where to allocate a floating photovoltaic system.

Chapter 4 contains information on a further study conducted for the choice of which are the best photovoltaic systems to be used in plants with a Mediterranean climate.

2.

STATE OF THE ART

It is necessary, in order to allow the total understanding of the work carried out in this thesis, to first clarify the topics that allow to have knowledge on various areas. These topics will be introduced in the following subsections, taking into account the current state of the art of floating photovoltaic technology.

2.1 Floating photovoltaic systems

2.1.1 General introduction

In the common ideology, even as experienced in recent years, photovoltaic solar modules are installed on the roofs of buildings or on the ground using rigid structures. The continuing need for energy combined with the scarce availability of land, the threat of deforestation and population density in some parts of the world, has led to the installation of panels on canals, rivers, lakes and oceans.

Floating photovoltaics is a system that has attracted attention for its many advantages over other renewable energy generation systems [18]; is a new technology in constant growth, the entry into the renewable energy market took place in 2016 [19]. They can be installed in various places, including closed basins, rivers, hydroelectric plants, dams, etc., on floating platforms. A typical photovoltaic module converts between 4% and 18% of the incident solar energy into electricity, depending on the efficiency of the solar cells, climatic conditions and time of year. Irradiation that is not converted into electricity is converted into heat, increasing the temperature of the module [20, 21]. The yield of the solar cells of the panels varies as the temperature changes, so the efficiency of the cells of the photovoltaic modules depends on the temperature. By installing photovoltaic modules on a water surface, it is possible to benefit from a significant reduction into the ambient temperature thanks to the cooling effect exerted by the water [22-26].

Floating PV systems require site-specific planning and careful design to be viable. In fact, the size of the floating module must be versatile enough to adapt to the different internal geometries of the reservoir [27]. The latest developments are stable, modular and scalable and designed to last at least 25 years [28]. In [29] an overview of the design, the technical performance and the feasibility of the structures for the modules of the floating photovoltaic systems was provided. The structural base is firmly anchored to the free surface of the water tank, which is not subject to strong wave forces, and is made up of a combination of a multilayer floating frame in medium or high-density polyethylene (M-HDPE), which guarantees the stability and buoyancy of the network of units [27]. The module is typically designed to host standard solar panels; the access path to the inverters, floating transformer stations and cables, certified for installations in water, is usually located behind the panels [28]. The structure can be anchored with different techniques depending on the characteristics of the basin (ground conditions, basin requirements and deviations from the water level). The anchoring concepts differ between anchoring to the ground around the system, anchoring close to the shore around the system and anchoring to the ground under the system to achieve the best aesthetic integration with the landscape [28]. The modules positioned at the outer limit are fixed to the reservoir by means of rigid anchors along the edge of the reservoir, necessary to support the permanent loads acting on the embankments of the reservoir and the lateral forces caused by wind and waves. The modules, positioned on the floating polyethylene monoliths and connected to each other by tensors and elastic fastening elements (bolt anchoring or metal tie rods), guarantee a good structural performance of the floating platform with the ability to adapt to varying water levels and to tank arrangements, minimizing maintenance and maximizing electricity production. Figure 2 shows the configuration of a floating photovoltaic system.

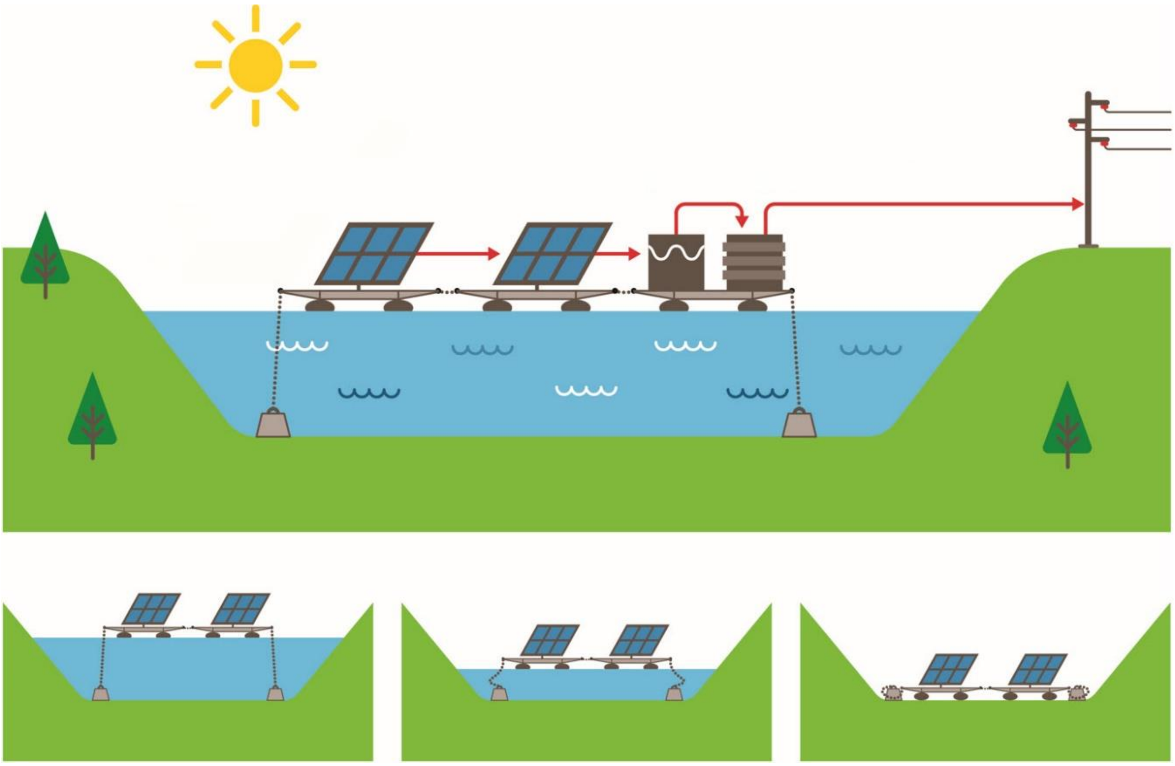

Figure 2 - Schematic representation of an FPV

Floating PhotoVoltaic Systems (FPVs), widely reported in the literature, have several advantages over terrestrial applications:

- reduce the effects of evaporation from basins [12]: they can produce savings of over 20,000m^3/year/ha of water, in hydroelectric plants and in irrigation basins this can be very useful;
- reduce land occupation and the consequent environmental impact that ground photovoltaic systems have, this is very important in agricultural areas by not decreasing the production capacity of the areas and guaranteeing continuous economic revenues [30];
- the floating modules do not produce this effect as the albedo of the water is quite similar to that of the panels which is about 5%, therefore it does not alter the energy balance [31]. Terrestrial albedo varies from 40% for the roofs of buildings, to 50% in desert soils and from 20-30% for areas used for pastoral activities.

- reduce the growth of algae [32] by improving water quality;
- reduce the effects of mutual shading of the panels;
- installation and disposal is much simpler as there are no fixed structures so it is a reversible process;
- the cooling of the panels takes place in a passive way: the favorable microclimate plays a very important role making the panels more efficient in terms of energy production compared to a ground system [33]. On average, the same solar panels when used for both floating PV systems and ground-based PV systems can produce up to 11% more when installed on water bodies [18]; the production capacity of a floating photovoltaic system is therefore greater than that of a traditional photovoltaic system. One of the factors that limit the operation of photovoltaic modules is overheating due to excessive solar radiation and high ambient temperatures; however, several methods have been investigated for lowering the temperature of solar modules [34];
- hybridization with hydroelectric plants: solar energy, if combined with hydroelectric energy, can compensate the losses in terms of energy produced by both technologies. During the summer, a hydroelectric plant suffers losses in terms of production due to the evaporation of water from the reservoirs; the same can happen in winter in a floating photovoltaic system when, since there is less solar radiation, less electricity is generated;coexistence with fishing: in the Eastern states studies have been conducted for fishing activities in basins where FPVs are present; fish or shrimp farming can be coupled to the energy production plant;
- tracking technology: with floating platforms is much easier to have tracking systems as the platform, anchored to the seabed or to the banks of the basin. It rotates very

easily thanks to simpler systems (referred to par. 2.1.2) compared to those used on ground-based photovoltaic systems.

However, floating photovoltaics still have some disadvantages [35]: the environmental impact is currently not fully known, it does not withstand strong waves, the loads and wind fluctuations can lead to cracks, cleaning the panels is not very simple, the aquatic ecosystem could be damaged if sunlight decreases.

2.1.2 Tracking systems

In addition to the conventional panels on a fixed structure inclined by a certain tilt, which depends on the geographical position of the plant, in recent years, tracking structures have been presented on the photovoltaic market. These systems can be single-axis or dual-axis, that is, following in one direction only (E-W or N-S) or in two (with both azimuth and inclination movements) the course of the sun during the day. Single-axis systems can be divided into two categories: vertical when the system follows an azimuth movement (with axis perpendicular to the water), horizontal when the axis is parallel to the water and the system performs an E-W rotation. The axis orientation can be N-S or E-W and is inclined.

In ground-mounted photovoltaic systems, tracking systems are able to increase energy producibility from 22% to 56% compared to the fixed systems [36].

The solutions proposed in the literature over the last few years, to overcome the limitations of the previously adopted solutions, are various and differ in their operation:

1. gable structures with tracking on a horizontal axis;
2. pursuit with partial confinement structures called outer rope;
3. pursuit without a confinement structure through the use of submerged structures or with bow thrusts;

4. tracking inside a confinement structure using floating platforms surrounded by anchored structures equipped with an electric motor that rotates the platform with respect to the structure.

In Korea, the first floating photovoltaic tracking system was installed by K-water inside a confinement structure [fig. 3], there are four 24.8 kW plants, one of which with automatic tracking, two fixed and one with passive tracking [37]. Also Cazzaniga et al. in [11] propose systems with a confinement structure in which there is a fixed part with ballasts anchored to the bottom and a mobile part that rotates on which the photovoltaic panels are installed [fig. 4].

Figure 3 - K-Water Plant

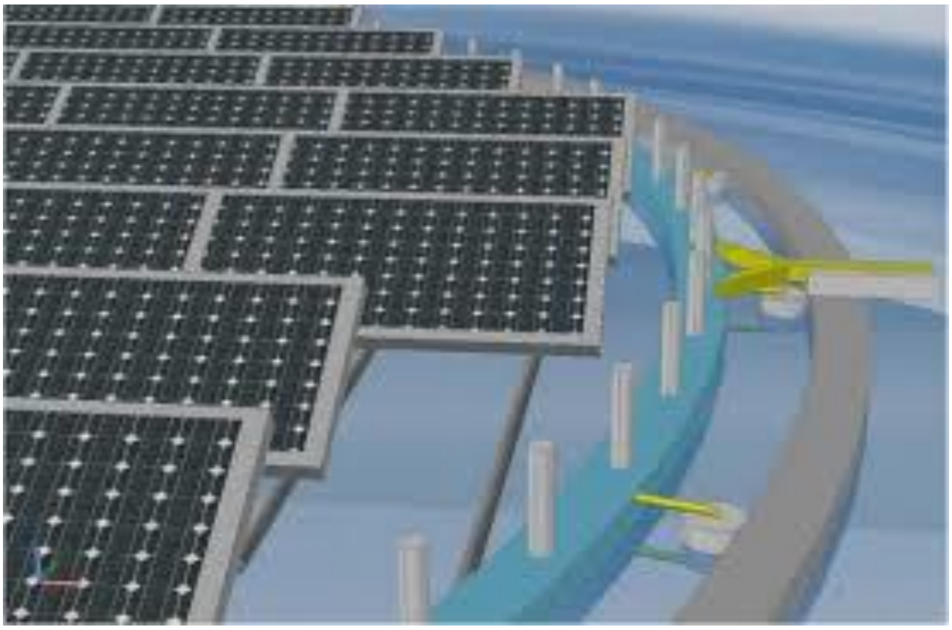

Figure 4 - Confinement structure with ballast and mobile part

The partial confinement system was proposed in [38] and is illustrated in [fig. 5]; Floating Solar has developed its own technique to seal plastic pipes to be used as floats, above a plastic and coated steel structure the photovoltaic modules are positioned. Each building is designed for the water on which that will be positioned, and through a solar tracking system, the floating islands follow the sun. In these structures, winches are used to allow daily solar tracking and ensure that, during the night, the structures return to their original position. It is also a sustainable technology as the materials used meet all the highest requirements to release of substances into the water.

Figure 5 - Partial confinement system

In some pilot plants in Italy, as explained by Tina and Rosa-Clot in [39], a vertical axis tracking structure without confinement was used. This structure, designed to be used in the aforementioned systems, has been adapted to be used even in the absence of shallow waters; the rotating structure is connected to a system of chains to which concrete blocks are connected which are positioned on the bottom forming an equilateral triangle. The system allows to fix the center of rotation and to withstand the wind load forces with a reaction force that increases linearly with the displacement. To turn the platform are bow thrusters that generate the torque for the azimuth rotation; a winch with an anchor allows you to fix the position of the platform when necessary. The example of this system is shown in [fig. 6 and 7].

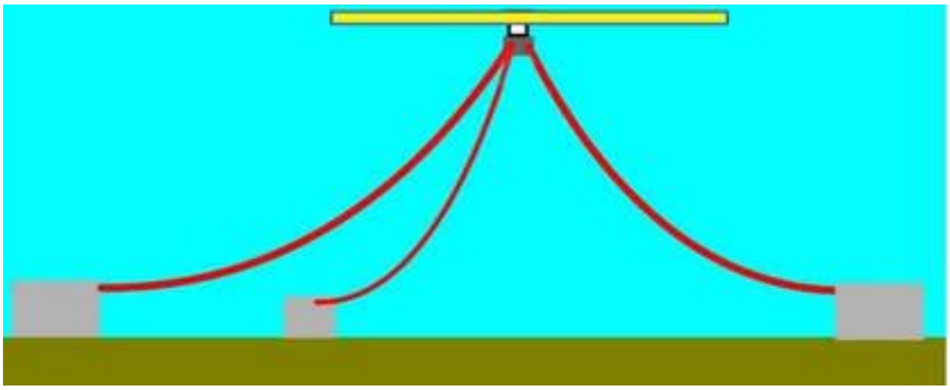

Figure 6 - System without confinement - Detail of chains and concrete blocks on the seabed

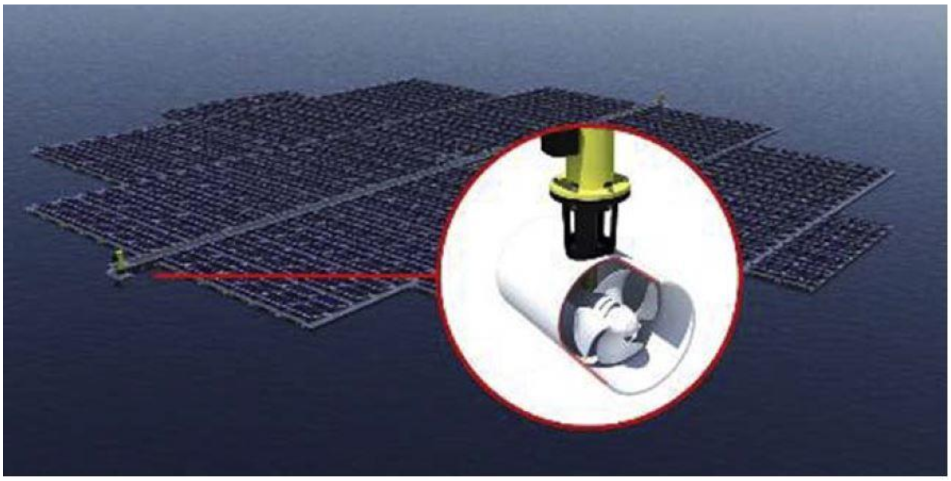

Figure 7 - Non-confining system with bow thruster for vertical tracking

Also Rosa-Clot and Tina in [39] introduce a horizontal axis tracker system that offers considerable advantages if located in places with low latitude; in fact the energy production compared to a fixed system with optimal inclination is greater than 21-32% at low latitudes, in temperate regions these values reach 15-25%. The problem that immediately emerges in tracking systems for floating systems is the shading since in a ground system, by increasing the pitch between the strings and therefore the occupied surface, it is bypassed. The raft in this case was built with a gable structure with an angle of 45 degrees so as to ensure an optimal east-west orientation; each raft, in [fig. 8] can support an axis up to 12 m long. The double sail string can contain 24 photovoltaic modules which, during windy days, could be positioned horizontally to avoid wind load. To overcome the problem of shading, cables of 3-4 m are used, just below the surface of the water, between the rafts as in [fig. 9]; the area occupied is increased but given the large availability of reservoirs and hydroelectric plants this should not be an insurmountable problem. The space left free between the two rafts could be exploited by installing aluminum reflectors, increasing the water albedo to 50%. The system just explained if combined with bifacial photovoltaic modules could further increase the energy efficiency compared to a conventional ground system.

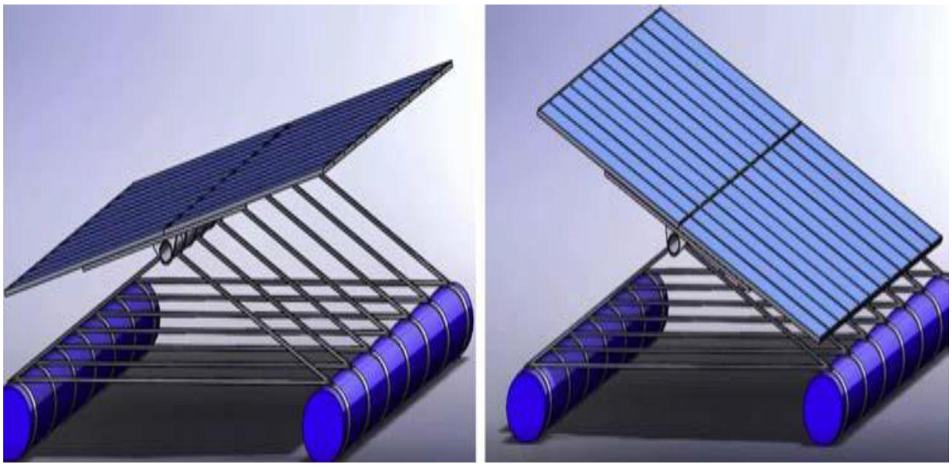

Figure 8 - Horizontal tracking with gable structure

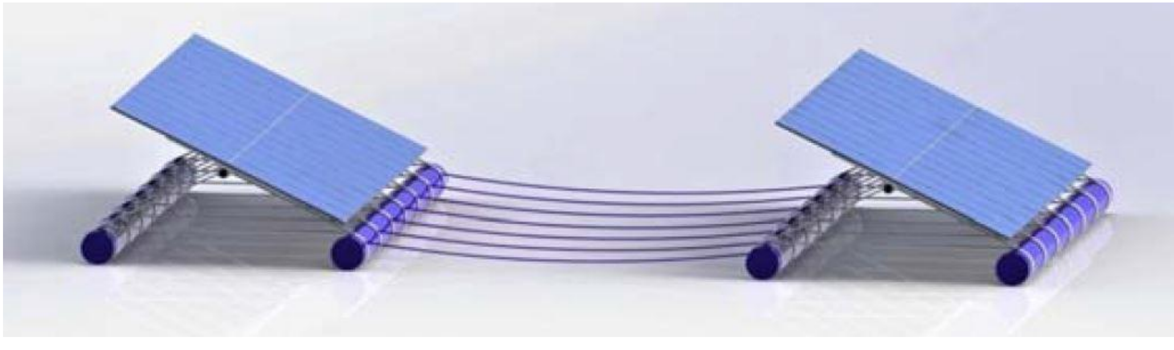

Figure 9 - Horizontal tracking with gable structures - Solution with cables to avoid shading

Over the last few years, with the affirmation of floating photovoltaics, various studies have been carried out on solar tracking systems; Choi et al. in [40], in a study in which various materials for mechanical structures and floats were proposed, have investigated an algorithm for controlling the solar tracker in a confined structure where there is an active and a passive system. This algorithm compensates for the azimuth angle error due to the continuous movement of the floating structure, due to waves and wind, using a geomagnetic sensor and a GPS. Also in [11] are suggested controls based on sensors that adopt two different approaches: one uses shading schemes to find the solar position and the optimal orientation, the other is based on images that are captured by a wide-angle camera that points the sky and directs the system towards the point where there is more light. Even in the event of cloudy skies, with this system, an accuracy of 0.5 ° is guaranteed.

However, it should be emphasized that the systems just exposed absorb energy for the movement of the actuators for solar tracking and being placed in environments with high humidity in the long run they could deteriorate very quickly. In this regard, a study [41] was conducted with a passive tracker system that uses the energy of the wave motion to adjust the position of the system without mechanical drives such as motors. These last, as previously stated, could cause an increase in maintenance costs during the life cycle of the plant.

Floating tracking photovoltaic systems have higher specific investment costs but the higher energy yield compared to fixed systems makes them competitive if we take into account the LCOE (Levelized Cost of Energy) [42].

2.1.3 Hybridization of FPV

Thanks to the complementarity and synergy of the two resources, it is possible to increase the electricity production curve.

Hybrid systems are created by allocating floating photovoltaic modules, often mounted on structures made of polyethylene, in pre-existing hydroelectric plants [27]; floating platforms occupy an area that would not be better exploited, thus also helping to reduce water evaporation [43].

A case study was conducted in a reservoir in southern Brazil, a Hydroelectric Power Plant (HPP) with a relatively large water surface was used to carry out the studies. If the total area of the basin had been covered with photovoltaic modules, the nominal power would have been just over 100 MW. The power of the existing hydroelectric plant was 60 kW, which is why it was decided to install photovoltaic panels capable of producing as much as the hydroelectric plant. Dams, often used for water supply, also represent untapped potential; this can be exploited by combining hydroelectric potential and solar potential with floating PV modules on the water surface, so that both operate in a hybrid hydro-photovoltaic system [44].

Studies have been conducted in [45] to compare the energy density between HPP and FPV; the results obtained showed that photovoltaics have a much higher energy density than hydroelectric plants. The comparison was conducted on 20 hydroelectric plant basins in operation; assuming the installation of a floating photovoltaic system, it has been obtained that the same has an energy density of 135 $GWh/y/km^2$ while the hydroelectric plant has an energy density of 65.7 $GWh/y/km^2$. The results allow us to evaluate how energy production can improve considerably thanks to the FPV coverage of hydroelectric basins; in fact, by covering only 2.4% of the surface of the basins with photovoltaic modules, the energy production of the hydroelectric plant increases by 34% [45].

There are several advantages that lead to the coupling of floating photovoltaic plants and hydroelectric plants:

- the connection to the grid is one of the main advantages: the hydroelectric basins, natural and otherwise, have in fact energy generators and direct connection to the grid, and it is therefore possible to exploit the pre-existing plants with the consequent reduction of the costs of transformers and of the connection to the network for floating photovoltaic systems;
- in temperate regions, photovoltaic panels give maximum efficiency in the warm seasons, a period which coincides with the seasons in which the hydroelectric plants register a reduction in power due to the evaporation of water from the basins; in winter however, when there is less solar radiation, due to lower temperatures, more precipitation and consequently a greater volume of water in the basins, hydroelectric power compensates for the losses of floating photovoltaics. Combining the two energy production technologies, this therefore, results in a reduction of the annual fluctuations in the production of electricity, optimizing the disadvantages of one with the advantages of the other and vice versa;
- the total or partial coverage of the basins involves the reduction of evaporation of surface waters;

Considering the previously analyzed advantages that can be drawn from the coupling between the two systems of electricity production, it is evident that in many areas, from the economic to the environmental one, passing through energy optimization, better results can be obtained.

2.1.4 Costs

Floating photovoltaic systems have recently entered the renewable energy market, and currently, there are not enough installations to be able to make an accurate analysis of the costs required during the life cycle of a plant. Over the next few years, surely, costs will change as soon as a total system technology is implemented.

2.1.4.1 CAPital Expenditure (CAPEX)

Capital costs must be assessed on the basis of the components of the plants and their costs. As already stated, the components of an FPV system are the following:

1. the floats are made of High Density PolyEthylene (HDPE) or glass fiber reinforced plastic. The cost varies according to the type chosen, there is no in-depth knowledge of the costs as they are not used in ground photovoltaic systems;
2. moorings are more expensive if the waters of the basins are deep or if there are significant water level changes. Even in this case, the literature does not offer much since they are not systems used in conventional photovoltaic systems;
3. the photovoltaic modules used are the same as those used for ground systems; they exist with a higher protection index to avoid the penetration of water but have a higher cost;
4. cables and connectors: these are special cables, although they are not in water, IP67 waterproof junction boxes are used;
5. electrical components, inverters and batteries: installed on the ground or on floating cabins, have the same operation as when they are positioned in photovoltaic systems on the ground.

The works for the construction of a floating plant have higher costs as the difficulties, due to the presence of water, are greater. It is estimated in [46], in 2019, that the labor cost of FPV is 60 US$/h while for a traditional ground-based system the labor cost are about 33% lower (40 US$/h).

In the case of a feasibility study of a hybrid plant [47], in the 2015, the cost analysis leads to the assertion that, compared to a ground plant, the costs of the installation of floating structure represents an increase by about 30%.

In 2017, in [12], it was estimated that the costs of an FPV system were 30% higher than a ground-based photovoltaic system. In [48] states that the average total investment cost of a floating photovoltaic plant in 2018, calculated in relation to the size and location of the plant, varied between 0.8 US$/Wp and 1.2 US$/Wp; as the installed power increases, the price decreases. The economy of scale of FPV systems is expressed in [48], in 2019, where it is highlighted that for small systems with capacities of 100 kWp and 500 kWp the costs are 4.4 US$/Wp and 4.35 US$/Wp; the cost of the system with 500 kWp is linked to system optimization. Furthermore, in [48] it is considered that the CAPEX, in large-scale plants, is between 0.7 and 0.8 US$/Wp depending on the location and the panels installed. The study analyzes the costs of the individual components of a photovoltaic system, both floating and ground, in order to obtain a total capital cost of 0.73 US$/Wp and 0.62 US$/Wp respectively for floating and ground PV, so divided:

- assembly of photovoltaic systems: US$ 0.15/Wp and US$ 0.10/Wp for FPV and GPV;
- photovoltaic modules: US$ 0.25/Wp for both plants;
- inverter: 0.06 US$/Wp for both photovoltaic systems;
- system balancing (BOS): US$ 0.13/Wp and US$ 0.08/Wp for floating and ground photovoltaics;
- other costs: US$ 0.14/Wp and US$ 0.13/Wp respectively for floating and traditional photovoltaics.

For Oliveira-Pinto et al. [49], in 2020, the capital costs for a floating system have generally increased by 25% compared to land based systems due to the floats, moorings and anchors. Rosa-Clot and Tina [39], 2020, made a list of the costs considered for the construction of a FPV plant for different technological solutions, reaching the result that, for a 1 MW plant, the construction would cost 0,80 US$/Wp (Singapore), 0,59 US$/Wp (Gable "Slender") and 0,63 US$/Wp (Gable 2) [Fig. 10].

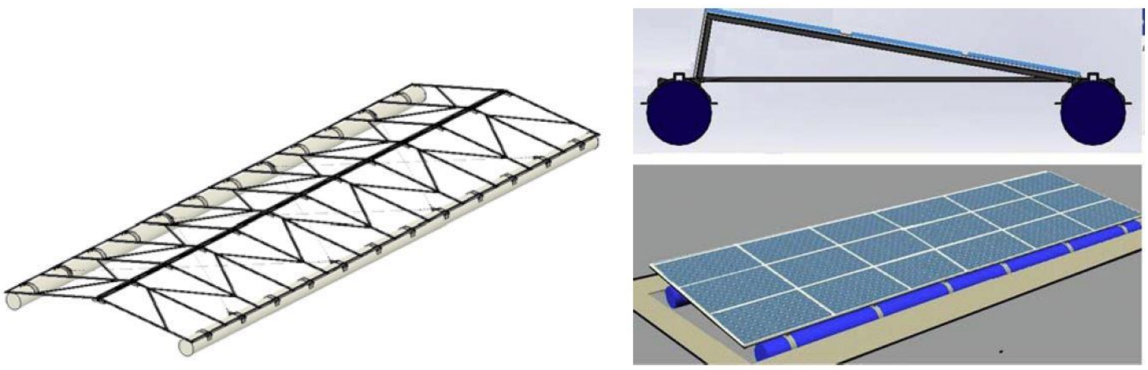

Figure 10 - "Gable Slender" and "Gable 2" structures [35]

Table 1 - CAPEX change

Year	CAPEX	Reference
2018	0,8 – 1,2 US$/Wp	[50]
2019	0,7 – 0,8 US$/Wp	[50]
2019	0,73 US$/Wp	[50]
2020	0,80 US$/Wp	[35]
2020	0,59 US$/Wp	[35]
2020	0,63 US$/Wp	[35]

In a few years, from 2018 to 2020, we went from a maximum price of 1.2 US$/Wp to a maximum price, due to the structure used and the geographical location, of 0.80 US$/Wp. it is therefore possible to state that there was a decrease of about 33%.

2.1.4.2 Operative Expenditure (OPEX)

OPEX (OPerational EXpenditure) are the costs that must be considered throughout the life cycle of the plants: maintenance, operation, space rental if necessary, insurance for any damage. To determine the costs of a photovoltaic system, as stated in [46], are generally the interventions necessary for the restoration of malfunctioning or defective objects such as inverters, photovoltaic modules, etc., and for cleaning the photovoltaic modules. Cleaning the panels for conventional systems is certainly more expensive due to the presence of dust and earth; furthermore, in the case of floating plants, the cleaning of the ground and the removal of spontaneous vegetation must not be envisaged. Maintenance costs can be higher in a FPV due to moorings, special cables, and floating platforms that require different tools and knowledge. Maintenance in a floating system takes place mainly with boats, which could further affect maintenance costs, to remove any bird droppings, to clean the filters of the water suction pumps in the event that this is too dirty, to check the malfunction, with specialized workers, of the cables immersed in water.

Martin, in 2019, in [46] tackled the issue by stating that the OPEX of a ground-mounted photovoltaic are US$ 13/kWp/year while those of an FPV are US$ 26/kWp/year, that is double. The OPEX costs of a ground-mounted photovoltaic system in Germany, in 2019, were 9,2 US$/kWp/year according to Vartiainen et al. [50], they assume that this cost will remain that until 2050; the previous year, among the reported data of the NREL in the United States were 15,4 US$/kWp/year. By 2030, however, it is expected that they will decrease by 30% and then decrease by 50% by 2050. Taking as reference the OPEX of the study [50] it can be estimated that in 2030 the cost, decreasing by 30%, will settle at around 10,8 US$/kWp/year and that in 2050, with a decrease of 50%, it will be about 7,7 US$/kWp/year. The maintenance costs of a floating photovoltaic system, in 2020, have been assumed by Rodrigues [51] twice as much as the OPEX of a ground-mounted photovoltaic; most of the maintenance costs of a float are for the inverters and this has imposed costs ranging from 6.15 to 9.50 US$/kWp. According to Tina [39], in 2020, maintenance costs are constant throughout the life cycle and are limited for floating systems but still higher than a land-based system. The decommissioning of a floating plant is less expensive since the only fixed structure are the moorings that can be moved easily.

2.1.4.3 Levelized Cost Of Energy (LCOE)

The Levelized Cost Of Energy (LCOE) of a floating photovoltaic system has been treated several times, in various researches, in order to be evaluated. There are many variables that are considered so that it is possible to evaluate how much each of these affects the final result: solar radiation, performance ratio, OPEX, CAPEX, years of operation, energy efficiency, etc.

The LCOE values for the on-shore plants were analyzed by Barbuscia in [52] and range from US$ 48/MWh in Peru to US$ 29.9/MWh in Dubai, passing through US$ 36/MWh in Mexico; what has just been explained leads to affirm that the costs depend on the installation site. In [49] the LCOE was evaluated on the basis of the place of installation and the floats used, in Barrow Gurney it was 96.2 $/MWh while in Almeria it was 50.3 $/MWh, in the case of ground photovoltaics it was 59.3 $/MWh and 33.1 $/MWh. Barbuscia [52] also analyzed the LCOE of floating plants according to their size and the type of float, it was found that the role played by the system's production capacity on the cost of energy is of high impact. The LCOE decreases exponentially as the installed power increases until it reaches the values of conventional technologies. For plants with capacities greater than 2 MW, the LCOE was 120 US$/MWh while for a 52 kW system it was 800 US$/MWh. Rosa-Clot and Tina instead calculated the LCOE relative to the photovoltaic system used; four different cases were conducted in Dubai:

- floating plant with gable structure with 10° inclination and panel cooling: 26.5 US$/MWh;
- floating plant with vertical axis tracking structure and 20° inclination: US$ 26.9/MWh;
- ground-based plant: US$ 36.3/MWh;
- floating plant with fixed structure inclined at 10° and panel cooling: 31.3 US$/MWh.

The current state of floating photovoltaic systems gives hope that there are good prospects for growth and development, also thanks to continuous research on the subject.

2.1.5 Environmental impact

This paragraph presents, based on available literature, the environmental impacts of floating photovoltaic systems throughout the life cycle, that is, from production processes to plant decommissioning.

Already during the design phase of the plant, it is necessary to search for sites where the environmental impact on flora and fauna, on air and water is as low as possible to prevent ecosystems from being altered [53]. For this reason it is advisable not to install floating photovoltaic systems in areas that, even if not protected, have particular plants, protected animal species and environmental restrictions [54]. The manufacturing processes of photovoltaic modules, inverters and each component of the system require significant amounts of energy with the consequent following release of harmful substances into the environment [55]. During the installation of the system, the duration of which is not easily definable in the current state, the processes take place in water; the positioning of the ballast causes the mixing of the water in the basins with the possibility of causing the loss of habitat for water fauna [7]. The impact of noise is negligible during the installation phase, furthermore the production phases take place far from residential areas, thus affecting very few people. In the case of ground-based photovoltaic systems, a tree mitigation band must be placed around the perimeter of the system to reduce the visual impact; in floating systems there are bamboo floats which, in addition to not polluting, have a low visual impact.

The CO_2 emissions linked to the floating photovoltaic system are very low, in fact during the operating phase these are practically null. During the production phase of the photovoltaic modules and all the components, as well as during the transport phase on site, there are CO_2 emissions which will be dealt with in the dedicated chapters of the study. During the construction phase of the plant, the emissions of pollutants are linked to the presence of vehicles on site and to the activities for the installation of the plant components; the same applies to the decommissioning phase of the plant.

The dust emissions relating to a floating photovoltaic system are linked only to the construction phase and to the system maintenance due to the presence of vehicles on site.

As of today, it is not possible, as these are recent systems, to quantify the real environmental impact of the plant during the operation phase. A potential impact during the operating phase could be linked to the use of chemicals for cleaning the panels; these could contaminate the water causing the mortality of animal species and increasing the growth of algae and decreasing the presence of oxygen in the water [56]. During the operational phase of a FPV system, the impacts are absolutely positive [11]: the operation of the system is totally silent and there is also a reduction in the water requirement for cleaning the panels. The quality of the water in the reservoirs improves following the installation of the floating panels [57] and important lands are also saved for agriculture, tourism, etc. [7]. Waste management must also be taken into account, which consists of following the management plan and guidelines for the disposal of batteries, panels or other defective or damaged equipment during the life cycle of the plant [55]. To ensure the penetration of sunlight and the production of oxygen through photosynthesis, it is not recommended to cover the entire surface of the basins [58]; the reduction of oxygen production can lead to an increase in the greenhouse gas emissions of the basin [12]. By installing water status monitoring systems, the problem related to air quality can be solved. Nowadays, to mitigate the reduction of the penetration of sunlight, it is possible to use semi-transparent double-sided photovoltaic modules. During the operation and maintenance (O&M) phase, animals play an important role; these can vandalize structural components or cables, which is why methods are employed to prevent animal assaults. Most of the floating systems are made of HDPE, the galvanized steel of the structures is not in direct contact with water but due to the waves or rain they can get wet, releasing small quantities of materials that can dissolve in water. During the decommissioning phase of the plant, no reclamation is required, thus reducing vehicle noise, pollution and changes in the geomorphology of the site [22]; however, it must be borne in mind that by removing the anchors of the plant and the ballast, the geomorphology undergoes a change, even minimal. The water undergoes a short-term change due to the mixing caused by the movement of water, noise increases due to machinery and vehicles and waste due to the uninstallation of the system must be managed.

2.2 Geographic Information Systems (GIS)

Geographic Information Systems (GIS) technology connects locations and attributes, facilitates spatial investigation, data acquisition, presentation and analysis [59]. They are also designed to store, retrieve, manipulate, analyze and track geographic data [60]. With geographic information systems it is possible to carry out queries to facilitate spatial analysis and the consequent reading of information [61, 62]. The operations that can be carried out with the aforementioned systems allow to obtain maps; the symbols of the maps are different according to the subject of the maps and consider cartographic rules that allow an easy reading. In general, it is possible to state that maps can be a decision-making tool in the field of spatial planning, economic management, environmental monitoring and care studies, as well as a tool for selecting suitable sites for certain types of activities [63]. The representation of GIS occurs with rasters and vectors [64]. Rasters are images represented through a grid of rectangles, pixels, which have the same resolution and size, specific information and a geographical position. Vectors instead have a geometric figure (points, lines and polygons) which is used to define the limits associated with a reference system or a specific position in space [63]. With raster images, the processes for evaluating problems are faster, this also applies to the mathematical combinations used in some MCDM (Multi Criteria Decisions Methods).

In general, as a first step, studies use restrictive criteria to eliminate areas unsuitable for solar energy development. These criteria can be based on topographical and legal constraints. As a second step, several factors can be considered to rank the remaining areas according to their suitability.

The joint use of GIS systems and multi-criterion decision analysis has proved to be a useful tool for estimating regional renewable energy potential [65-67] and for decision-making in energy planning [66, 68-70]. Recently, many researchers used GIS-MCDM methods for the choice of suitable locations for solar power plants [69, 71-73]. Carrion, in [71], presented a support system for the selection of suitable sites for network directly connected photovoltaic plants and the consequent environmental decisions. Beccali, in [69], used the ELECTRE III methodology to evaluate the program for the development of solar energy.

Studies based on GIS, to estimate the availability of solar resources [74-77] and the suitable places for the allocation of plants, both in urban [77-80] and rural areas [72-73, 81-100], are in continuous growth. Studies for rural areas are mostly performed in Asia, Europe, the Middle East and North America; in [72] Uyan assesses the suitability of a site for photovoltaic plants in Turkey, in the Karapinar region. Janke in [90] studies the opportunity of solar power plants in Colorado, in the USA; in the same country Brewer uses GIS, combined with surveys, to determine which sites may be suitable for large-scale plants in the southwestern United States [89]. In China, studies in rural areas were conducted in Fujian province by Sun [81] and in the western part by Byrne [101] for the evaluation of the electric potential from solar sources. The suitability of sites for photovoltaic systems was assessed in Cartagena [73] and Murcia [91], the same was done in Malaysia by Sabo [92]. In the Middle East the studies carried out were different: in Oman by Gastli [82, 86-88, 94], in Afghanistan by Anwarzai [95] and in Vietnam by Polo [96].

2.3 Multi Criteria Decision Analysis (MCDA)

In the past, decision making used a single criterium approach to highlight the most efficient options with the lowest cost. In the 1980s, people became aware of the importance of the environment, and this changed approaches to decision making. When it comes to sustainability, the decision-making process must take into account several factors, which are considered in the concept of triple bottom line (environmental, social and economic aspects). Multi Criteria Decision Analysis (MCDA) is the right approach because it evaluates multiple criteria that otherwise would not be directly comparable. The components of the MCDA are as follows:

- objective or a set of objectives to be achieved;
- decision makers, who can be individuals or groups;

- Criteria (attributes or objectives), which should be understandable and measurable (real values);
- decision alternatives, which consist of action (what to do) and position (where to do it), specified by the decision variables which can be binary, discrete or continuous;
- decision matrix formed by alternatives (rows) and criteria (columns).

The MCDA can be described as a collection of techniques to compare, classify and select alternatives using quantifiable or non-quantifiable criteria [102,103]. This was designed to face four types of problems [104,105]:

1. the choice, in which the MCDA is used to select the best option from a set of alternatives;
2. sorting, in which MCDA is used to assign a set of alternatives to predetermined categories.
3. the classification, in which MCDA is used to sort the alternatives partially or completely.
4. the description, where MCDA is used to define alternatives, construct a set of criteria and determine the performance of all or some alternatives for the criteria, considering additional information.

The choice of MCDA techniques may depend on the objective and complexity of the problem. Decision makers should consider factors such as problem type, decision goal, volume of data, number of criteria, ease of use, consistency, and type of analysis when selecting the MCDA technique. According to Kumar, in [106] the MCDA is a process for evaluating real world situations based on several criteria, which can be qualitative/quantitative in risky/uncertain/determined environments to determine a strategy, a choice or a course of action. The strengths and weaknesses of each MCDA methodology are shown in Table 2.

Table 2 - MCDA methodologies

MCDA methods	Points of strengths	Points of weakness
Analytic Hierarchy Process **(AHP)**	• Allows to verify the presence of inconsistencies in judgments and comparisons between criteria; • The hierarchical structure is easy to understand and communicate.	• The number of pairwise comparisons can be high for medium-large decision analysis; • The 0.1 threshold for the rejection of inconsistency; • The inversion of degree.
Analytic Network Process **(ANP)**	• Unlike AHP, independence between the element is not required.	• The interaction between criteria and alternatives is complex and makes it difficult to understand; • Comparisons between couples are even more compared to AHP; • Uncertainty is not supported.
Data envelopment analysis **(DEA)**	• The relationship between inputs and outputs is not necessary; • The same can have very different units.	• Results can be affected by measurement errors; • Does not process inaccurate data; • Not suitable for large problems due to increased complexity.
Elimination and choice translating reality **(ELECTRE)**	• Takes into account uncertainty; • It supports the idea of the veto, it is the only method to allow it.	• It is difficult to explain the results and the process of the ELECTRE to non-technical people.
Goal programing **(GP)**	• Can handle many variables, constraints and objectives.	• Other MCDA methods should be used to weight the criteria; • The weight setting must be appropriate.
Multi-attribute utility theory **(MAUT)**	• Takes into account uncertainty.	• The order of preferences must be precise.
Preference Ranking Organization Method for Enrichment Evaluation **(PROMETHEE)**	• Supports indifference; • Supports visual aid.	• It does not give a clear method for assigning weights.
Simple multi-attribute rating technique **(SMART)**	• It is considered the simplest method than others; • Requires less effort from decision makers.	• Taking the context into account, this could be an inconvenient procedure.
Simulated uncertainty range evaluations **(SURE)**	• It is a simple method; • Allows you to view the strength and uncertainty of each alternative.	• In the event that there are several uncertainties at the same time, the decision maker may have to choose which alternative to select.
Technique for order preferences by similarity to ideal solutions **(TOPSIS)**	• It takes into account the best and worst possible scenarios; • Supports any distance measurement from best and worst guess (Euclidean, Manhattan, etc.).	• Does not consider the correlation of attributes; • The combination of different distance measurements requires justification.
Weighted product model **(WPM)**	• The relations are used so as not to have any dependence on the unit of measurement.	• It is not possible to give a weight equal to 0 to a criterium, each criterium must have a weight greater than this value.
Weighted sum model **(WSM)**, or simple additive weighting **(SAW)**	• Ability to compensate between the various criteria; • The fairly simple arithmetic operations make it easy to understand.	• All criteria must have the same unit; • It is susceptible to the trap of averages.

As previously stated, MCDA methodologies can be coupled to GIS tools to achieve certain objectives. Carrion in [71], with environmental, geological, climatic, accessibility and proximity criteria, using GIS together with MCDA, selects suitable sites for the allocation of photovoltaic systems. Villacreses in [106] deals with various studies in which GIS and MCDA are used jointly: in a study conducted in Turkey a good position for the design of a photovoltaic system is analyzed, 40.34% of the area was unsuitable while 13.92% was very suitable for a solar source system.

The two MCDA methods used for the preparation of this thesis will be explained below: AHP and TOPSIS.

The reasons why the methods chosen are those previously mentioned are the following:

- the AHP takes into account inconsistency in the final result and when comparing criteria;
- the hierarchical structure of the Analytic Hierarchy Process is easy to understand and use;
- the AHP can be used for a limited number of comparisons between criteria, this can be an advantage for the robustness of the methodology considering a lower error margin;
- it does not appear that there may be consistent errors, unlike other methods, in the final results obtained with the AHP;
- the AHP can be used both to determine the best alternative and to assign a weight to the criteria;
- TOPSIS takes into account the best and worst scenario achievable with the chosen alternatives;

- distance to best or worst solution supports various measures;
- the interaction between alternatives and criteria is simple.

In summary, it is possible to state that the two methods chosen, following bibliographic research and in-depth studies, appear to be the most used for decision-making processes such as those carried out in this thesis work. Their reliability in previously conducted case studies, together with what emerged from the comparison between various criteria, had guided the choice towards these in order to be able to achieve the pre-established objectives in the best possible way.

2.3.1 Analytic Hierarchy Process

The Analytic Hierarchy Process (AHP) belongs to the MAUT (Multi Attribute Utility Theory) models; the main hypothesis in utility theory is that exists a real-valued function, called utility function, which associates a value (real number) that represents its degree of preferability to any admissible action. The preferences of the actions considered can be represented using this utility function: for each pair of actions, the utility of the preferred action is greater than the utility of the other one, while the utility of two actions is equal if and only if they are indifferent.

From a formal point of view, the utility function U aggregates all the criteria g of the set of criteria G i.e. $\forall a \in A$ where a is the alternative and A is the set of alternatives:

$$U(a) = V\,(g_1(a), g_2(a), \ldots, g_m(a)) \qquad (1)$$

where V is a function of m variables, increasing in its marginal utilities (all its arguments); that is, in other words, $\forall a, b \in$ A, where a and b are the alternatives,

$$g\,(a) \geq g\,(b), \forall\, g \in G => U(a) \geq U(b) \qquad (2)$$

The simplest form of utility function U(a) is the additive representation, in which the overall evaluation of a given action is seen as the sum of the products of the weights of the criteria w by the marginal utilities u of each considered criterium, that is:

$$U(a) = \sum_{j=1}^{m} w_j u_j \left(g_j(a)\right) \tag{3}$$

where:

- m is the number of criteria;
- j is the number of the j-th criterium;
- w_j is the weight of the j-th criterium;
- $u_j \left(g_j(a)\right)$ is the marginal utility of the j-th criterium with respect to the analyzed alternatives.

Marginal utilities are defined through direct comparison; this can be seen as the construction of a system of values, which defines the extreme points of the system itself, i.e. the best alternative and the worst alternative. Considering a criterium g_j, the best performance with respect to g_j is assigned the highest score (utility) while the worst performance with respect to g_j is assigned a score of 0. All other performances are placed directly on the system to reflect their usefulness with respect to the two reference points (the one that has the best performance and the one that has the worst performance).

AHP is a method that, on the basis of comparisons between pairs of criteria or alternatives (with respect to the single criterium), can be used to obtain both the weights of the criteria in *G* and the marginal utilities (u) associated with the performance of the alternatives with respect to the evaluation criteria, with the relative weights, taken into consideration. A weighted sum is used to associate each alternative with a real value, representative of the goodness of the alternative itself; very often is considered a special case of the utility function. We thus obtain a utility function expressed in terms of the weighted sum (WS) of the values of the individual criteria:

$$U\ (a) = WS(a) \tag{4}$$

To determine the weights of the criteria is necessary to provide the preference information, with respect to all the pairs of criteria taken into consideration, by filling in a matrix A in which the elements a_{ij} (where $i, j = 1, 2, \ldots, m$ represent the number of criteria) represent the preference entity of the criterium g_i over the criterium g_j.

$$A = \begin{pmatrix} 1 & a_{ij} & \ldots & a_{im} \\ 1/a_{ij} & 1 & \ldots & a_{jm} \\ \vdots & \vdots & \ddots & \vdots \\ 1/a_{im} & 1/a_{jm} & \ldots & 1 \end{pmatrix} \tag{5}$$

where:

- a_{ij} is the preference of the criterium g_i over g_j ;
- a_{im} is the preference of the criterium g_i over g_m ;
- a_{jm} is the preference of the criterium g_j over g_m ;

The evaluations of the criteria weights are expressed on a scale from 1 to 9, with the following interpretation:

a_{ij} = 1 ⇔ g_i has equal importance of the criterium g_j ;

a_{ij}= 3 ⇔ g_i has a moderately higher importance than the criterium g_j ;

a_{ij} = 5 ⇔ g_i has much greater importance than the criterium g_j ;

a_{ij} = 7 ⇔ g_i has a much greater importance than the criterium g_j ;

a_{ij} = 9 ⇔ g_i has importance absolutely higher than that of the criterium g_j ;

The values 2, 4, 6, 8 are intermediate values used in case of indecision between the judgments just expressed. It follows that, for each $i, j = 1, 2, \dots, m$, $a_{ij} = \frac{1}{a_{ji}}$ (i.e. the matrix is reciprocal) and $a_{ij} = 1$ for each $i, j = 1, 2, \dots, m$ (since each criterium is indifferent to itself).

Each value of matrix A can therefore be interpreted as the ratio between the weight of two criteria (g_i, g_j) or $a_{ij} = \frac{w_i}{w_j}$. If the information provided is consistent need to be verified that:

$$a_{ij} = a_{im} \times a_{mj} \ \forall\, i, j, m$$

Matrix A is perfectly coherent if and only if $\lambda_{max} = m$, with λ_{max} denoting the maximum eigenvalue of A and m being the order of matrix A.

Finally, the overall S_a score of each alternative is calculated with respect to the goal for which the multi-criteria decision analysis was supported. The calculation is obtained through the equation:

$$S_a = \sum_{j=1}^{m} p_a(j) \times wg\,(j) \tag{6}$$

where:

- wg is the derived priority vector for each criterium, i.e. the principal eigenvector of the matrix of pairwise comparisons for the targets, with respect to the target;
- p_a is the derived priority vector for an alternative to the higher level criteria, that is, the principal eigenvector of the pairwise comparison matrix for each of the criteria.

What has been explained is taken from the existing literature [107-109].

2.3.2 TOPSIS

Hwang and Yoon developed the TOPSIS method in 1981; considered as a significant method among multi-criteria decision analysis methods, it has been used by many researchers, academics, and stakeholders in various fields of study. It has various fields of application: chemical engineering, logistics, water management, energy management [110]. The method makes full use of the information provided during the analysis (objective, alternatives and criteria) and these do not need to be independent of each other; in addition, it works with a fundamental ranking. However, it has points that should be improved, for example it works on the basis of the Euclidean distance and makes no difference between negative and positive values; at the same time, the values of the criteria should decrease or increase in a diminutive way between them [111-115]. Using the TOPSIS method, an attempt is made to choose the alternative that should have, at the same time, the shortest distance from the solution that maximizes all the benefit criteria and the longest distance from the solution that minimizes the benefit criteria.

Given a set of alternatives $A = (a_{ij} = 1, 2, \dots, m)$, a set of criteria $G = (g_{ij} = 1, 2, \dots, m)$ and a set of weights $W = (w_{ij} = 1, 2, \dots, m)$ denote the decision matrix. To be inserted into the matrix, the values must first be normalized, this is done through the use of a formula.

$$\bar{a}_{ij} = \frac{a_{ij}}{\sqrt{\sum_{i=1}^{n} a_{ij}^2}} \tag{7}$$

where:

- $\bar{a}_{ij}$ is the normalized coefficient of a specific alternative linked to a specific criterium;
- a_{ij} is the alternative that must be normalized, also linked to a specific criterium;

- $\sum_{i=1}^{n} a_{ij}^2$ is the sum of the alternatives, linked to all the criteria, which must be inserted in the same column.

After having normalized the coefficients to be inserted in the matrix, they must be related to the weight of the criteria:

$$v_{ij} = \bar{a}_{ij} \times w_j \tag{8}$$

where:

- v_{ij} is the weighted normalized coefficient of an alternative linked to the analyzed criterium;
- w_j is the weight of the criterium.

The Euclidean distance must be calculated from the ideal solution and the worst solution; to do this, we must first identify the worst and ideal values of each criterium. The ideal weighted normalized coefficient is (v_j^+), the worst weighted normalized coefficient is (v_j^-). The Euclidean distance is calculated with the following formulas

$$S_i^+ = \sqrt{\left[\sum_{j=1}^{m}\left(v_{ij} - v_j^+\right)^2\right]} \tag{9}$$

$$S_i^- = \sqrt{\left[\sum_{j=1}^{m}\left(v_{ij} - v_j^-\right)^2\right]} \tag{10}$$

The score of each alternative is obtained with a specific formula that implements the previously calculated Euclidean distances. The best alternative will be the one that will have the P_i value closest to 1 since they are normalized values.

$$P_i = \frac{S_i^-}{S_i^+ + S_i^-} \tag{11}$$

3.

Optimal site selection for floating photovoltaic systems based on Geographic Information Systems (GIS) and Multi-Criteria Decision Analysis (MCDA)

This chapter is based on the paper:

S. Di Grazia, G. M. Tina, *Optimal site selection for floating photovoltaic systems based on Geographic Information Systems (GIS) and Multi-Criteria Decision Analysis (MCDA). A case study,* International Journal of Sustainable Energy. DOI: 10.1080/14786451.2023.2167999.

Solar energy is growing rapidly thanks to reduced implementation costs; European development plans foresee a significant increase in installed capacity in the coming years. In this scenario, new identifiable areas on water surfaces are needed. This would lead to the development of floating photovoltaic (FPV) systems, which would mitigate the environmental impacts of terrestrial installations. Therefore, it is necessary to develop and propose a methodology to identify suitable sites for the installation of such plants. This chapter is useful to demonstrate the potential benefits that can be achieved using the methods of GIS for the optimal siting of FPVs in combination with the use of MCDA in areas such as Sicily, which are characterized by high summer temperatures. Seven watersheds were studied and the best site for FPV allocation selected using MCDA is presented at the end of the Chapter.

3.1 Introduction

The world continues to energize, driven by the developing economy, at the same time there is an increasing need to produce new clean energy. Therefore, renewables play a crucial role in this continuous-changing scenario. Prospects for the coming decades explain that by 2040 renewable energies will overcome coal as the first global energy source [116].

According to italian energy policies, the electricity produced from renewable sources should reach approximately 132 TWh by 2030, thus covering 38.7% of the total electrical energy produced, against 34.1 % of 2017. Focusing on the single sources, the significant residual potential technically and economically exploitable and the reduction in the costs of photovoltaic and wind power plants, for these technologies, also envisage growth in current policies. Still in the same time horizon, a limited growth in additional geothermal and hydroelectric power and a slight decline in bioenergy are considered. Looking ahead to 2040, the electricity from renewable sources will grow to 40.6% [117] [Table 3].

Table 3 - Present and future European renewable production [117]

	2020	2025	2030	2040
Renewable production (TWh)	**118.50**	**120.50**	**132.00**	**142.90**
Hydro (normalised[1]) (TWh)	49.40	49.10	51.00	51.60
Wind (normalised[1]) (TWh)	20.10	21.80	25.10	33.20
Geothermal (TWh)	6.70	6.90	7.00	8.30
Bioenergies (TWh)	16.30	14.70	14.20	12.30
Solar (TWh)	26.00	28.00	34.60	37.40
Denominator – Gross inland electricity consumption (TWh)	**327.10**	**333.10**	**340.60**	**351.70**
RES-E share (%)	**36.30%**	**36.20%**	**38.70%**	**40.60%**

The recent COVID-19 pandemic, and the war in Ukraina, had a serious impact on global economy [118]. The overall electric power and gas prices raised. This is a reminder that modern life needs abundant energy: without it, bill become unaffordable, as a consequence many communities that are still dependent on these technologies can suffer from these in creases and businesses stall [118].

In [119], an analysis was conducted during the first four months of the pandemic COVID - 19, focusing on the impact of the pandemic on mobility and thus on carbon dioxide emissions. Two airports in Croatia were considered as study cases and the results showed a decrease in flights, reaching a low point in April 2020 with 89% fewer flights in Europe. The pandemic had a major impact on the national energy system and laid the foundation for the energy transition towards renewable and clean energy [120].

Renewable energy systems such as photovoltaics (PV) can be used to achieve an energy transition: They allow urban and rural areas not to depend on traditional technologies, to

[1] For production from hydro and wind sources, for the period 010-2017 both the actual figure (continuous line) and the normalised figure are given, according to the rules established by Directive 2009/28/EC [118]

achieve primary energy savings or even to sell electricity to the grid. Years ago, some studies [121] already examined the potential benefits of integrating photovoltaics, or PV, in urban areas and concluded that PV systems can be a powerful tool to achieve energy savings and reduce dependence on fossil fuels. Moreover, PV is competitive with other renewable energy sources. It is estimated [122] that by 2050 it will be comparable to both other renewable energy sources and nuclear energy.

Floating photovoltaic panels are an interesting alternative to traditional ground-based photovoltaic panels, as water-cooling achieves higher efficiency [26], which leads to a reduction in electricity costs.

Another study [7] analyzed a new type of PV technology that can be installed in rural areas, floating photovoltaic (FPV) systems, and concluded that these systems can generate much more electricity compared to traditional ground-based PV and are a useful tool for coupling with agriculture.

However, the installation of FPV systems requires many construction steps and challenges, as outlined in [7], so available sites for the installation of these systems need to be carefully selected. Various studies such as [14] suggest a geospatial approach based on GIS technology, not only to locate the available sites, but also to assess the average electrical power generated by the FPV modules by calculating the solar radiation, which can vary significantly in different geographical locations.

However, other studies [16, 17] pointed out that locating the available areas for the installation of these technologies can be a very difficult task due to the many requirements. Based on technologies that use *GIS*, they have proposed an analysis method to establish the sites available for the installation of floating photovoltaic systems: the required needs are

entered into this software as input matrices and the tools of GIS output the geographical coordinates of the areas where the required needs are met.
It is necessary to find usable areas where there are no competing uses, the basins must in any case be suitable for providing floating power plants with solar capture. This is only possible if, thanks to the multi-criteria analysis, ZPS (special protection areas, *Zone di Protezione Speciale* in italian) and SIC (Siti di Interesse Comunitario in italian, sites of Community interest) areas, basins where anthropic activities are carried out, areas where controlled recolonization of flora and fauna takes place and unproductive areas that are not suitable for agricultural use are excluded from the outset.

This type of approach, based on GIS, has been applied in many studies [26, 123-125], not only to locate suitable areas for the installation of FPV systems, but also to evaluate the energetic performance of these systems in different developing zones of the world, such as Cameroon, Indonesia, Pakistan or Turkey: they concluded that FPVS can be a very powerful tool for rural economies and community energy supply, no longer dependent on traditional oil and gas power plants.

Today, the global economy is creating new challenges for many local communities and has led to the introduction of a new circular economy. Renewable energy sources can be a very powerful tool to achieve this goal. The integration of such systems on Sicilian territory could be a great improvement for the economic development of the region.
For a local economy like the one in Sicily, the introduction of photovoltaic technology is a great improvement thanks to the high annual solar radiation. For example, electricity consumption for irrigation can be covered with electricity generated from this system, and the surplus electricity can be sold to the national grid: Residents are then no longer dependent

on electricity from petroleum-based gas and steam turbine power plants, resulting in higher incomes and lower global environmental impacts.

This chapter follows a GIS methodological approach reinforced with the MCDA plugin on the Sicilian territory in order to locate the best performing sites where FPV equipment can be installed. The use of the software GIS makes it possible to quickly filter out basins that cannot be used for normative or environmental reasons. The MCDA, carried out using two methods, makes it possible to study the same issue and evaluate the results. Particular attention is paid on Levelized Cost of Electricity (LCOE): the criteria take into account the annual energetic profit, the capital and operating costs and the life cycle of the installation. These criteria cover some of the most important topics of current scientific research, LCOE is a fundamental issue when dealing with the issue of renewable sources and their continuous evolution in recent years. Geographic information systems have become a fundamental design tool on a global scale thanks to the ease of retrieval of data; MCDA, in fields other than floating photovoltaics, is used as a decision-making method in order to make objective and convenient design choices. A sensitive analysis must be carried out to evaluate the soundness of the results by the two different MCDA methods.

3.2 Methodology

The methodological approach that has been adopted for the optimal allocation of floating photovoltaic systems in Sicily is organized according to the following steps:

- Identification of lakes in Sicily;
- Definition of criteria;
- Research for the optimal allocation of floating photovoltaic systems.

The next few paragraphs will consider these different aspects mentioned.

3.2.1 Identification of lakes in Sicily

To obtain the data of the geographical coordinates of 47 basins in Sicily [Table 4], a database compiled by ISPRA [52] (Higher Institute for Environmental Protection and Research) was considered during the analysis phase. The surfaces areas were obtained jointly using satellite maps and QGIS.

Table 4 - Water basins in Sicily

Basin Identification	Coordinates (° ′ ″)	Surface Area [km^2]
Biviere	37°19′29"N, 14°57′03"E	9.312
Pozzillo	37°39′34"N, 14°35′32"E	6.275
Garcia	37°47′49"N, 13°07′17"E	3.496
Rosamarina	37°56′32"N, 13°38′21"E	3.206
Arancio	37°37′48"N, 13°3′36"E	2.687
Ogliastro	37°26′38"N, 14°33′57"E	2.535
Piana degli Albanesi	37°58′27"N, 13°17′49"E	2.264
Poma	37°59′24"N, 13°6′0"E	1.630
Trinità	37°42′02″N, 12°45′10″E	1.581
San Giovanni	37°18′40"N, 13°46′10"E	1.548
Castello	37°34′56"N, 13°25′05"E	1.488
Fanaco	37°39′33"N, 13°32′59"E	1.330
Rubino	37°53′34″N, 12°43′16″E	1.267
Longarini	36°42′41"N, 15°00′47"E	1.240
Santa Rosalia	36°58′33"N, 14°46′46"E	1.222
Pergusa	37°30′50"N, 14°18′20"E	1.126
Ancipa	37°50′12"N, 14°33′28"E	1.100
Baiata	37°58′26″N, 12°35′04″E	1.065
Roveto	36°47′24"N, 15°05′31"E	0.941
Nicoletti	37°36′36"N, 14°20′24"E	0.864
Prizzi	37°43′48"N, 13°24′25"E	0.816
Scanzano	37°55′11"N, 13°22′12"E	0.745
Dirillo	37°7′40"N, 14°41′52"E	0.730
Biviere	37°01′14"N, 14°20′27"E	0.690
Morello	37°35′04"N, 14°12′28"E	0.610
Disueri	37°12′0"N, 14°17′24"E	0.559
Olivo	37°24′18"N, 14°17′18"E	0.463
Pian del Leone	37°40′16"N, 13°28′30"E	0.431
Gorgo	37°24′31"N, 13°19′30"E	0.328
Ganzirri	38°15′40"N, 15°37′3"E	0.320
Comunelli	37°9′27"N, 14°9′19"E	0.277
Prèola	37°37′16″N, 12°38′20″E	0.263
Furore	37°15′42"N, 13°43′43"E	0.247

Biviere	37°57′6"N, 14°42′60"E	0.170
Trearie	37°57′8"N, 14°50′23"E	0.128
Gammàuta	37°41′08"N, 13°21′14"E	0.093
Gorghi tondi	37°36′40″N, 12°39′05″E	0.069
Soprano	37°27′36"N, 13°52′38"E	0.063
Cartolari	37°57′24"N, 14°49′9"E	0.052
Maulazzo	37°56′28"N, 14°40′18"E	0.050
Gurrida	37°51′24"N, 14°54′0"E	0.047
Gariffi	36°44′00"N, 14°56′19"E	0.020
Favara	37°35′52"N, 13°14′55"E	0.010
Pisciotto	37°58′45"N, 14°50′52"E	0.009
Marinello	38°08′12"N, 15°03′15"E	0.006
Urio Quattrocchi	37°54′5"N, 14°23′45"E	0.006
Spartà	38°01′50"N, 14°38′53"E	0.004

As shown in Table 4, the basin with the largest surface area is Lake Biviere in Lentini, in the province of Syracuse, and the basin with the smallest surface area is Lake Spartà in Sant'Agata di Militello, in the province of Messina. From the values listed in Table 4 it can be deduced that the average value of surface areas of the Sicilian basins is 1.17 km^2. The total area of the basins analysed is about 55 km^2, which is about 0.2% of the total area of the Sicily region (25832.39 km^2). The two basins of Biviere and Pozzillo can be defined as large; with an area between 3.50 km^2 and 1.07 km^2, they next 16 medium-sized basins, while the rest 29 are small, considering that they are basins with an area of less than 1.00 km^2. Thus, the identified basins are mostly small and located mainly in the eastern part of Sicily, in the province of Messina, Catania, Syracuse and Ragusa.

3.2.2 Criteria definition

It is conceivable that in Sicily solar irradiation is optimal for the production of solar energy. The choice of criteria and their weights can be defined as subjective; the chosen criteria in order to evaluate the optimal siting on Sicilian lakes are:

1. costs of the plant: costs related to installation and maintenance greatly affect the construction of new systems, the minimization of this criterium is a huge advantage;

2. the distance of the plants from nearby medium voltage connection grid: proximity to connection grid is very important, thus the costs of capital expenditure will be reduced [126,127];
3. the annual energy yield by the plant: the more a plant is able to produce the greater its revenues, this is a criterium that acts to significantly reduce the payback time;
4. LCOE (levelized cost of energy): it is a measure that quantifies the average cost at which to sell the electricity generated during the plant life. It is a criterium that depends on the investment costs, maintenance costs, interest, how long the life cycle of the plant lasts and the electricity it produces;
5. CO_2 emissions: measure the amount of carbon dioxide that can be avoided by generating electricity from renewable sources. This criterium depends on the energy produced, needed to calculate the kg of CO_2 saved during the plant's operating phase, and the area occupied by the plant, useful to the measurement of emissions generated during the production cycle of the plant components, their transport and installation. This criterium was chosen to demonstrate the real environmental convenience of floating photovoltaics for the production of electricity compared to definable conventional techniques, which use fossil fuels. The implementation of renewable sources would allow nations to reduce CO_2 emissions.

In [128], different hypotheses for the weighting of criteria are put forward; in most of the proposed scenarios, technical and financial criteria are given greater importance than ecological and social criteria. In [106], the group of climatic criteria has a weight of 40%, that of socio-economic criteria 35% (social 14% and economic 21%) and that of environmental criteria 25%. In [127], the economic criteria are maximized in relation to the technical and social criteria; environmental criteria are not considered. In [127], two scenarios are considered, with the technical criteria having a weight between 38.1% and 50.6%, the economic criteria between 43.9% and 56.3% and the social criteria between 5.4% and 9.5%; as the weights of the criteria vary, the result may vary, the subjectivity of the weights of the criteria allows for different design approaches. In [129], various criteria are considered, classified as social, technical, economic, environmental and political; these are assigned 9.9%, 18.4%, 24.2%, 15.6% and 31.9% respectively. We can thus conclude that in the literature, the criteria of the technical domain are assigned between 18.4% and 50.6%, those of the economic domain between 21.0% and 56.3%, and those of the environmental domain between 15.6% and 25%. In [127], in Table B.1 of appendix B, the weights assigned to various criteria from different studies are reported. As a demonstration of what was previously stated, the objective thinking of each designer generates different scenarios, case by case. For example, the distance from power lines is assigned 2,15% weight by Ziuku [83], 32,5% by Sanchez-Lozano [73], 20% by Janke [90], 25,9% by Watson [98], there is therefore a fairly wide range for the same criterium in different studies.

Table B.1 Appendix B [127]

Factor	*Ziuku [83]*	*Charabi et Gastli [88]*	*Uyan [72]*	*Sanchez-Lozano et al. [73]*	*Janke [90]*	*Watson [98]*	*Brewer et al. [89]*	*Carrion et al. [71]*
Solar irradiance	26.83	0.545		23.802	3	0.489	1.1	30
Equivalent sun hour								25
Distance to power lines	2.15		0.748	32.539	2	0.259	0.8	
Distance to substation				8.946				2
Distance to major roads		0.168	0.071	4.291	1	0.069	1	2
Distance from settlements (maximization)			0.250		1	0.049		
Distance from settlements (minimization)				2.849				2
Distance to water bodies	10.73						0.8	

Distance from historically important areas						0.065		
Distance from wildlife designations						0.06955*		
Visual impact								4
Land slope	10.73		0.180	11.203			1	9
Land orientation				4.815				7
Plot areas				1.241				
Land cover	3.22		0.750		1			5
Agrological capacity				5.553				
Population Density					1			
Average temperature				4.7604				14
Restrictive criteria		0.287			1			

In this chapter, the capital and operating costs and the electricity production costs are the economic criteria, the environmental criterium is the CO_2 emission, and the technical criteria are the annual energy yield and the distance to the power line.

Therefore, it is considered that the focus should be on minimizing LCOE, costs, both installation and maintenance, and maximizing annual energy yield and CO_2 avoided emissions. A relatively high and equal weight was given to costs and energy efficiency, the two criteria can be considered connected to each other; a relatively high weight has been given since these are two fundamental factors for the realization of a project and equal to each other since the business plan of a project works if the capital and operating costs can be covered by the earnings, determined in a floating photovoltaic system from energy efficiency. The distance of the plants from the medium voltage grid must be reduced to the minimum, but this criterium has been given less weight than the previous ones since the costs of connection to the 20 kV national electricity grid affect the project in a smaller percentage. A relatively high and important weight has been assigned to CO_2 emissions as it is a criterium of fundamental importance in the national, European and global panorama due to climate change. The leveling of energy costs has been given the greatest weight among the five criteria, as this is the parameter that clarifies what the economic performance of the plants should be to balance the costs. The weights, like the criteria, were determined based on what was said before, with a relative weight assigned to each criterium. Minimizing costs (installation and maintenance) and maximizing the criterium of CO_2 emissions and energy yield are given much greater importance in this analysis than minimizing distance to the connection grid. As mentioned above, each criterium must be assigned a weight between 1 and 9, depending on how important it is for the case study. The interaction between weighting and criteria has to be done according to the ideas of the experts dealing with the case, the local regulations and the rules for awarding floating photovoltaic plants. Greater weight was given to the electricity production costs and CO_2 emissions, and somewhat less weight to the costs and energy yield, as these are criteria of fundamental importance. Minimizing electricity production costs and costs and maximizing CO_2 emissions and annual energy yield is a requirement that must be taken into account in the planning and construction of new floating photovoltaic systems. Keeping the distance to the connection grid as small as possible is important for capital expenditure and reducing grid losses. This criterium also depends on the size of the plant, as it determines the connection to a specific voltage line (low, medium, high and extra-high voltage). In addition, the cost of connection to the grid, to be borne by the owner who builds the plant, varies according to the voltage level and distance from the connection line; however, less weight is given to this criterium, as it has a lesser impact on the study carried out. The energy generated, which is relevant for the annual energy yield, and the associated grid losses, together with the capital costs and the distance from the power line, influence the LCOE criterium. Taking into account the ranges that can be derived in the literature and after the elaboration, linked to the specific case study and to the design ideas of the authors, the criteria listed in Table 6 were weighted.

Table 5 - MCDA's criteria

Criterium	Criterium category	Weight
Capital and operating costs	Economic 46%	16%
LCOE		30%
Distance from the grid	Technical 29%	13%
Annual energy yield		16%
CO_2 emissions	Environmental 25%	25%

The construction of floating photovoltaic systems involves various costs. In [39] the capital costs (CAPEX) for floating plants of 1 MW, with different technologies, are divided for photovoltaic panels, electrical parts, inverters and cables, assembly costs, for the structure and for the rafts. In [49] CAPEX are assumed to be 1.09 US$/Wp and include photovoltaic modules, inverters, system balancing costs, engineering, procurement and construction costs (EPC) and other costs. In [130] a review was carried out on the capital costs of FPVs and it is stated that the costs, in 2018, varied in a range between 0.8 and 1.2 US$/Wp.

The maintenance costs are assumed to be constant during the plant life cycle, considered, in this case study, to be 25 years. For floating photovoltaic systems maintenance costs are limited as no maintenance is required at the site where the panels are located unlike the ground systems where soil cleaning is required. For the tracking systems, maintenance of the movement systems and panels is necessary, while in the case of panels with built-in cooling it is not necessary to clean the modules [39]. For the evaluation of the costs, in this case study, the basins investigated were divided into 4 categories based on the installed capacity, due to the limited data available in the literature, the costs were assumed constant as the power varied; for the CAPEX the model used in [49] was applied which takes into account the cost of the panels, inverters, balancing, construction costs, etc.. For plants with size between 0-1 MWp, a capital expenditure of 1.24 US$/Wp was considered, for plants between 1-2 MWp capital expenditure have been set at 1.09 US$/Wp ; CAPEX for the plants with size between 2-3 MWp are fixed at 0.98 US$/Wp , for larger plants, 3-4 MWp, capital costs at 0.87 US$/Wp has been processed. It should be noted that connection costs to the power line were not taken into account during this analysis since the connection costs to the national transmission grid vary according to the voltage level, the environmental or plant interferences that the cable duct may encounter, etc. These are aspects not considered in this research.

$$\text{Costs [US\$/Wp]} = \frac{CAPEX+OPEX}{Power\ unit\ installed} \quad (12)$$

$$\text{Power unit installed} = \text{panels number} \times \text{maximum panel power} \quad (13)$$

where:

- the number of panels depends on the available surface of the basin (1% of the total surface) and the surface of the panel;
- maximum panel power depends of the characteristics of the panel itself; in this case the power of the panel is 410 Wp [131].

The distances from the connection grid have been derived from QGIS using polyline layers and the annual energy yield has been calculated as:

$$\text{Annual energy yield} \left[\frac{MWh/y}{MWp}\right] = \frac{Energy\ generated}{Power\ unit\ installed} \quad (14)$$

$$\text{Energy generated} = (solar\ radiation\ \times\ hypothesized\ coverage\ \times\ \eta\ \times\ TREr) - grid\ losses \quad (15)$$

where:

- GHI is evaluated in each month of the year 2016;
- hypothesized coverage is the 1% of the extension expressed in Table 4;
- η denotes the real efficiency of one module. According to [131] the chosen efficiency has been stated to the yield of monocrystalline technologies, corresponding to a value of 20.38%;
- TREr is the Theoretical-Real Efficiency ratio (average ratio between the manufacturers' declared efficiency and the one site's real one for mono-polycrystalline cells) whose value, evaluated in [81], is equal to 78%;
- grid losses are established by the national authority of electricity and gas [132], on grids with third party connection obligations. These are conventional values set in percentages that depend on the system voltage levels, the installed power of the plant and on the grid energy injection point taken into consideration. The grid losses are 2.3% of the energy generated;
- the power unit installed is calculated with the equation (13).

The LCOE formula was used in a previous study [133]. In this case, the parameter relating to fuel consumption is not used as it concerns production plants from renewable sources

$$\text{LCOE [US\$/MWh]} = \frac{(CAPEX \times CRF) + OPEX}{Energy\ Generated} \qquad (16)$$

where:

- CAPEX are the investment costs;
- OPEX are the maintenance costs;
- energy generated is the energy efficiency of the (15);

- CRF is the Capital Recovery Factor equivalent to $\frac{(((1-p)^n)\,p)}{(1-p)^n-1}$, p is the interest rate (2%), and n is the plant life cycle (25 years).

$$CO_2 \text{ emissions } [tCO_2] = CO_2\ emissions\ for\ the\ installation\ of\ the\ FPVs - CO_2\ avoided\ emissions \quad (17)$$

where:

- The CO_2 emissions for the installation of the FPV were calculated taking into account the square meters of surface occupied by the floating photovoltaic system and the emissions entered into the atmosphere for each square meter of system (137.73 $kgCO_2/m^2$) [134], making the relationship between the two factors are obtained the CO_2 emissions produced during the production, transport and installation phase of the system;
- for the avoided emissions, on the other hand, we took into account the emissions quantity a thermoelectric production plant from fossil sources would produce, considering the same power as those from renewable sources covered by this study. This value was calculated with the product of the energy produced by the plant and the CO_2 emissions for each kWh, (536.4 gCO_2/kWh for energy produced from petroleum products, in 2019, in Italy) [135]. In the last 30 years, this value has undergone a significant decrease [135] also due to the introduction of other sources of energy production into the past scenario, creating a new energy mix. In the historical period the globe is going through, due to the war and the energy independence that every State must achieve, these values could increase again due to the need to use coal-fired plants. The result was multiplied by 25 years, that is the life cycle of the floating photovoltaic system.

3.2.3 Topological determination of the best reservoir for allocation of floating photovoltaic systems

GIS software has been widely used to determine the performance of ground-mounted photovoltaic systems, taking into account variations in tilt and latitude, and to evaluate the integration of these systems in urban areas. The software has been used to analyze FPV systems to determine the optimal geographical position. The area of interest of this case study concerns the region of Sicily in the southern part of Italy. The geographical coordinates of the natural lakes in the region described in Table 4 were imported into QGIS as a geodatabase downloaded from the official website of the Italian Institute for Environmental Protection, the ISPRA Institute (Istituto Superiore per la Protezione e la Ricerca Ambientale). With the QuickMapService plug-in it was possible to identify the basins via a satellite view and with OpenCoordinator, another plug-in, the coordinates were derived from the ISPRA database. The official data on the geographical coordinates of the protected areas were downloaded from the government portal [136] and the resulting geographical points were loaded into QGIS. This chapter evaluates lakes that are at least two kilometers as the crow flies from SIC or ZPS areas, archaeological areas, rivers, etc., since an environmental impact assessment should be carried out close to these areas. Next, solar irradiance values such as global horizontal irradiance was obtained.

The global horizontal irradiance was evaluated for the lakes analysed, for the geographical coordinates of each lake and for each month. The GHI values for each month of the year were derived by a spatial and temporal evolution of the GHI through the PVGIS-SARAH database.

3.2.4 AHP

Using the SuperDecisions software, developed by the Creative Decisions Foundation, a model was created to carry out multi criteria analysis according to the AHP method. Having set the goal, that is, the identification of the optimal allocation site, the criteria were loaded into the software. The usable alternatives, i.e. the basins obtained from the analysis carried out with the QGIS software, were then attributed. The software used then requests, comparing the criteria two at a time, to assign the weights. The priorities of the criteria, as mentioned, have been assigned subjectively.

The matrix (5) was built by the software, the terms within it represent the coefficients of relative importance of each criterium with respect to the objective, the eigenvalues instead represent the relative priorities of each criterium with respect to the alternatives. The weights of each alternative are determined as the eigenvalues of the matrices, the terms are the normalized quantities of each alternative with respect to each criterium. It is therefore the terms of the matrix that quantify the relative importance of the various alternatives with respect to the others for each of the four chosen criteria. In order to overcome the consistency check of the hierarchical analytical process, the software requires that, for each criterium, a comparison must be made between two alternatives at a time. After carrying out the entire process relating to multi-criteria decision analysis, the software is able to deliver to the designer the result relating to the initially entered objective by assigning a score to each alternative. Thus it is possible to determine which is the best site for the allocation of a floating photovoltaic system.

3.2.5 TOPSIS

To obtain the best site for the allocation of a floating photovoltaic system, through the TOPSIS method, a spreadsheet was used where the formulas useful for achieving the desired result were set. It is necessary to calculate the weighted normalized matrix in order to obtain which is the ideal solution and which is the worst solution. All the coefficients of the matrix are first normalized:

$$\bar{a}_{ij} = \frac{a_{ij}}{\sqrt{\sum_{i=1}^{n} a_{ij}^2}} \quad (18)$$

where:

- $\bar{a}_{ij}$ is the normalized coefficient, of a specific criterium linked to a specific alternative, which must then be related to the weight of the criterium;
- a_{ij} is the criterium, linked to a specific alternative, to be normalized;
- $\sum_{i=1}^{n} a_{ij}^2$ is the sum of the criteria, of all the alternatives, to be inserted in the same column.

The coefficients, after having been normalized, must be related to the weight of the criterium so that they can be inserted in the weighted normalized matrix:

$$v_{ij} = \bar{a}_{ij} \times w_j \quad (19)$$

where:

- v_{ij} is the weighted normalized coefficient, of a specific criterium linked to a specific alternative, to be inserted into the matrix;

- $\bar{a}_{ij}$ is the normalized coefficient of a specific criterium linked to a specific alternative, which must be related to the weight of the criterium;
- w_j is the weight of the criterium.

To calculate the value of the ideal solution and the worst solution, the corresponding value must be chosen, depending on the criterium being analyzed. For costs, distance and LCOE the ideal solution will be the lower coefficient between the row of values obtained for the two criteria, for the installable potential the ideal solution will be the higher coefficient of the column of the examined criterium. The worst solution for the first three criteria will be the higher coefficient, for the technical criterium it will be the lower coefficient. Having calculated which are the ideal solutions and the worst solutions, we can proceed to the calculation of the Euclidean distances, respectively from the ideal solution (S_i^+) and from the worst solution (S_i^-) [137].

$$S_i^+ = \sqrt{\left[\sum_{j=1}^{m}\left(v_{ij} - v_j^+\right)^2\right]} \tag{20}$$

$$S_i^- = \sqrt{\left[\sum_{j=1}^{m}\left(v_{ij} - v_j^-\right)^2\right]} \tag{21}$$

After having calculated the Euclidean distance from the ideal solution and the Euclidean distance from the worst solution, we can proceed to deduce the score obtained from each alternative (P_i).

$$P_i = \frac{S_i^-}{S_i^+ + S_i^-} \tag{22}$$

Since the values used during the final phase are normalized, the result will be analyzed considering the maximum value of 1. The optimal allocation will therefore be the one with the score closest to 1, while the worst will be the one with the score furthest from 1.

3.2.6 Sensitivity analysis

Evaluating how much a criterium influences the final result is the main objective of the sensitivity analysis, this can be done by manipulating the variables [138]. Carrying out this analysis helps in evaluating the minimal changes in the weights of the criteria, primarily hypothesized, and the alteration of the positions obtained after an initial multi criteria decision analysis [139]. This approach can be done using EXCEL or, as in this case study, Super Decisions for the AHP method.

3.2.6.1 Sensitivity AHP

The sensitivity analysis for the MCDA AHP method was conducted with the aid of the Super Decisions software. Using the same model previously developed for the decision analysis, it is possible to carry out the sensitivity analysis. With this software it is possible to conduct the sensitivity analysis in two different ways:

1. The AHP sensitivity shows how the best alternative changes when the weight of a criterium changes;
2. Dynamic sensitivity shows how the priority of all alternatives changes as the priority of a criterium changes.

The first modality can be done using the “Sensitivity” command: by selecting the criterium whose weight you want to change, the best alternative is displayed as the weight varies.

The second modality is used with the "Node Sensitivity" command; there are four different views of the variation that the alternatives prioritize. With the "Barchart" option it is possible to observe through a three-dimensional histogram how the ranking of the alternatives varies.

The method chosen to carry out the sensitivity analysis, during this process, is the second. It is possible to have a result, by being able to manage the weight of the criterium analyzed, by a command placed above the display of the results.

3.2.6.2 Sensitivity TOPSIS

The sensitivity analysis for the TOPSIS method was carried out by varying, all five at the same time, the weights of the criteria chosen to carry out the multi criteria approach. This procedure was carried out using an Excel sheet and structuring four different scenarios; initially it was assumed that the four criteria have the same weight, i.e. that each of them accounts for 25% in the final decision. Then one criterium was maximized at a time: first the energy potential, then the costs, the distance from the connection grid, the LCOE and finally the CO_2 emissions.

3.3 Results

The data on the geographical coordinates of the 47 identified catchments in Table 4 on the territory of the Sicily region were loaded into the QGIS software. They were identified on the map using the QuickMapService plug-in; the coordinates were obtained using the OpenCoordinator plug-in.

Data on the geographical coordinates of the protected areas (SIC, ZPS, archaeological areas, etc.) were downloaded from the Sicily Region website and uploaded into QGIS. At this stage, the 7 available lakes in Table 7 could be selected for the subsequent step of multi-criteria analysis in order to evaluate which is an optimal location for the placement of floating photovoltaic plants. Data useful for evaluating the best location were also sought, such as annual rainfall, average and maximum summer temperatures, and average annual temperatures. The data were extrapolated from the annual ISPRA database and refer to 2016, the latest year available [140]. These data are useful for a possible assessment of water evaporation in the catchments and for calculating the decline in water volume. Annual global horizontal irradiance data (GHI) for the seven lakes studied were also extrapolated from the PVGIS-Sarah database. The contribution of global horizontal irradiance is fundamental to the assessment of the energy generated in the basins. Specifically, the 2016 data were used for the analysis phase. The values of GHI, available in Table 8, do not differ much because the evaluation is based on geographical coordinates of a relatively small area such as Sicily; if the values were different, they would not be justifiable. The calculation for the evaluation of the annual energy yield was carried out considering the values in the database PVGIS-SARAH, as explained below.

The coverage hypothesis of the study is 1%, the surfaces are specified in Table 7. Of the 47 river basins, listed in Table 4, the study was conducted on 7 basins, following the analysis of regulatory and environmental constraints imputed, which characteristics are given in Table 7.

Table 6 - Basins surface area

Basin Identification	Surface Area [km^2]	Available Surface [m^2]
Trinità	1.581	15.810
San Giovanni	1.548	15.480
Baiata	1.065	10.650
Nicoletti	0.864	8.640
Dirillo	0.730	7.300
Morello	0.610	6.100
Comunelli	0.277	2.770

Table 7 - Available basins for FPV's allocation

Basin Identification	Use	Annual rainfall [mm]	$T_{sum, avg}$ [°C]	$T_{sum, max}$ [°C]	$T_{ann, avg}$ [°C]	Annual GHI [kWh/m^2]
Trinità	Irriguous	508.0	26.0	39.7	19.1	1780.93
San Giovanni	Irriguous, sport	548.2	24.5	35.7	17.5	1794.99
Baiata	Irriguous	331.8	25.0	36.5	19.9	1777.71
Nicoletti	Irriguous, industrial	439.4	25.3	39.1	17.4	1771.32
Dirillo	Irriguous, sport, industrial	605.3	25.3	37.7	17.6	1810.96
Morello	Irriguous, sport	471.9	25.3	39.1	17.4	1767.90
Comunelli	Irriguous	391.6	24.9	37.8	18.2	1812.09

3.3.1 Criteria

The criteria addressed to paragraph 3.2.1 have been calculated with the formulas previously mentioned:

$$\text{Costs [US\$/Wp]} = \frac{CAPEX+OPEX}{Power\ unit\ installed} \tag{23}$$

The distances from connection grid have been derived from QGIS using polyline layers and the annual energy yield has been calculated as:

$$\text{Annual energy yield } \left[\frac{MWh/y}{MWp}\right] = \frac{Energy\ generated}{Power\ unit\ installed} \tag{24}$$

$$\text{LCOE [US\$/MWh]} = \frac{(CAPEX \times CRF)+OPEX}{Energy\ Generated} \tag{25}$$

$$\text{CO}_2 \text{ emissions [tCO}_2\text{]} = CO_2\ emissions\ for\ the\ installation\ of\ the\ FPVs - CO_2\ avoided\ emissions \tag{26}$$

Table 8 - Cost and power installed values

Lakes	Costs (CAPEX+OPEX) [USD]	Power unit installed [MWp]
Trinità	3280018	3.68
San Giovanni	3211723	3.61
Baiata	2488329	2.48
Nicoletti	2028670	2.01
Dirillo	1882709	1.69
Morello	1587502	1.42
Comunelli	819315	0.65

The results obtained for each criterium, for each lake, are shown in Table 10:

Table 9 - Criteria's values

Lakes	Costs [USD/Wp]	Distance from connection grid [m]	Annual energy yield [MWh/y/MWp]	LCOE [USD/MWh]	Avoided emissions in 25 years [tCO_2]
Trinità	0.89	3433	1188.59	54.68	56477.55
San Giovanni	0.89	1716	1195.18	54.62	55727.14
Baiata	1.00	2060	1186.00	61.48	37975.16
Nicoletti	1.01	4882	1182.49	66.17	30682.93
Dirillo	1.11	2939	1209.38	64.59	26407.30
Morello	1.12	2428	1180.31	69.74	21634.95
Comunelli	1.27	4124	1199.95	76.61	10077.69

3.3.2 AHP

With the use of the SuperDecisions software [141], the multi criteria decision analysis was conducted following the AHP method and its related application methodology (par. 3.2); the five criteria, with their weights, related to the seven alternatives have given very important indications regarding the optimal allocation of a floating photovoltaic system in Sicily.

The following scores, in Table 11, have been obtained:

Table 10 - AHP's score of Sicilian water basins

Lake	Score
San Giovanni	1.00
Trinità	0.69
Baiata	0.59
Dirillo	0.58
Comunelli	0.37
Nicoletti	0.33
Villarosa	0.32

The obtained results suggest San Giovanni dam as the best alternative to be chosen.

3.3.3 Topsis

The TOPSIS method pursues the idea of establishing ideal solutions and worst solutions to carry out the study; the alternative that comes closest to the ideal solution turns out to be the best of those analyzed and consequently is the one to be taken into consideration. An Excel sheet was used to perform multi criteria decision analysis which, assuming ideal solutions and worst solutions for each criterium, made it possible to calculate the performance score of each solution. These are normalized values also in this case, having first normalized the weighted matrix.

The resulting, normalized, is reported in Table 12.

Table 11 - TOPSIS' score of Sicilian water basins

Lake	Score
San Giovanni	0.985
Trinità	0.830
Baiata	0.643
Dirillo	0.407
Nicoletti	0.406
Morello	0.347
Comunelli	0.081

According to the results, the minimum value of the distance from the ideal solution is found for San Giovanni dam.

3.3.4 Sensitivity analysis

For both MCDA methods, a sensitivity analysis was carried out to evaluate how the results vary as the weight of the criteria, inputed during the analysis, varies. The results obtained how much the subjective choice of the decision maker affects the final result and the choices that this could entail.

3.3.4.1 Sensitivity AHP

The sensitivity analysis was carried out with the SuperDecisions software, setting it dynamically, changing the weight of the criteria from time to time and displaying how the results vary.

The variation of the result, with the variation of the weight of each criterium, and therefore the variation of the best alternative, gave a result for each situation. For costs, the best alternative, when the weight varies from 0% to 100%, remains the San Giovanni Dam; the best alternative, also for the criterium relating to the distance from the national transmission grid, is the Dam. Up to 68% of the weight attributed to the energy efficiency criterium, the best alternative is the San Giovanni Dam, for a heavier weight it is Lake Dirillo. For the last two criteria, LCOE and CO_2 emissions, the best alternative is always the San Giovanni Dam. These results show that, except in the case in which the annual energy yield is attributed a weight higher than 69%, the San Giovanni dam represents the best alternative among those proposed.

3.3.4.2 Sensitivity TOPSIS

The scenarios assumed in the sensitivity analysis of the TOPSIS method are six. The first scenario assessed is the one considered during the study phase explained earlier. In the second scenario, the five criteria were equally weighted, i.e. 20% of the total weight. The third scenario maximises the criterium of annual energy yield by weighting it with 30% of the total weight; 25% was attributed to the distance of the connection to the transmission line, 11% to the electricity production costs and 17% to the costs and CO_2 emissions. In the fourth scenario, 30% of the weight was attributed to costs, 25% to energy efficiency, 11% to distance and 17% to electricity generation costs and CO_2 emissions. In the fifth scenario, the distance-from-connection criterium was maximized at 30% of the weight; in the last scenario, the CO_2 criterium was maximized at 30%, and 17% of the weight was attributed to LCOE, 25% to costs and 11% to annual energy performance.

The analysis was carried out by varying the weighting of the criteria from time to time. Again, in all scenarios, the San Giovanni Dam basin was shown, in fig. 11, to be the best choice for the hypothetical deployment of a floating photovoltaic system.

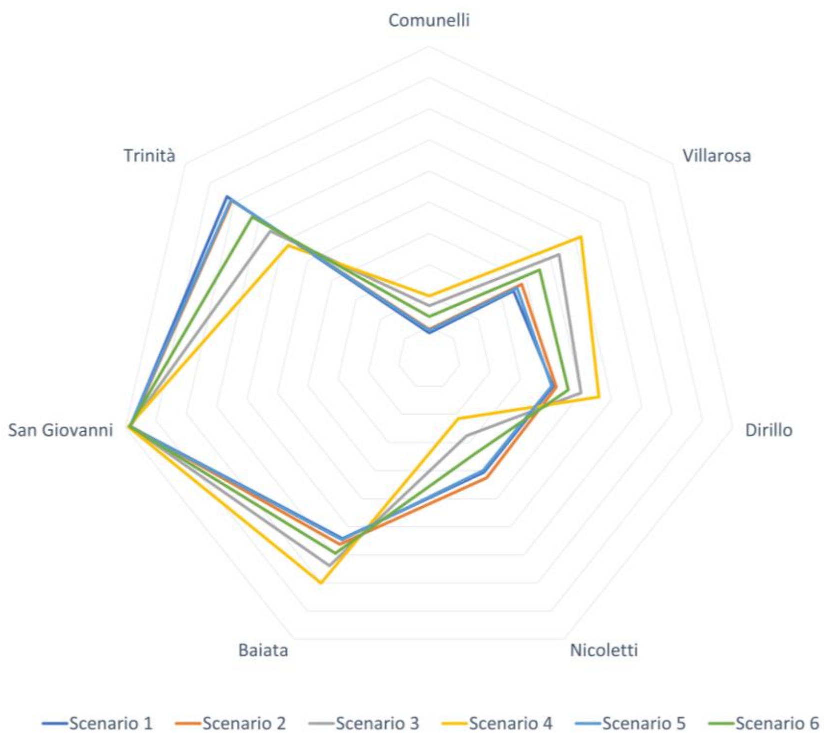

Figure 11 - Radar chart: TOPSIS' sensitivity results

3.4 Conclusions

The technology of floating photovoltaic systems is constantly spreading around the world and has created new opportunities for the renewable energy sector, leading to great advantages over non-renewable energy. Floating photovoltaic systems can play an important role in meeting the energy needs in Italy and around the world, as estimated by the Global Industry Analysts in the 2021 Report, the technology will reach 4.8 GW by 2026. This study aims to improve the potential of the joint use of MCDA and GIS software for the optimal allocation of floating photovoltaic plants. The case study, applied to the region of Sicily (in Italy), was carried out by first selecting the usable basins. Two different multi-criteria decision-making approaches (AHP and TOPSIS) were used; using five environmental, technical and economic criteria with predefined parameters, the LCOE analysis was carried out, the results of which were used as criteria for the decision analysis. The five alternatives analysed are in fact geographically far from protected areas, archaeological areas or from sites where it is not possible to allocate plants. The multi- criteria decision analysis gave the same result for both methods. The San Giovanni dam was indeed the best location for the allocation of floating photovoltaic plants. The above results illustrate how floating photovoltaic systems can bring about a positive development in renewable energy production, focusing on environmental friendliness, costs comparable to conventional photovoltaic systems and high energy performance. It should be noted that the study was conducted at a regional level and that a detailed analysis should be carried out, perhaps based on sites with different implementations of the method, to be sure of the robustness of the method. One of the limitations of this method may be the regional level analysis used to conduct the study: for example, the solar radiation data does not differ between the different methods. Another limitation of the study is the sparse literature on maintenance costs during the life cycle of the plants. This has limited the data collection and its comparison in the analysis. This approach could be used by those interested in identifying areas for power generation. In addition, the current state of the literature for this type of study is constantly evolving, especially for ground-based photovoltaic systems. Finally, a sensitivity analysis was carried out after obtaining the results of the multi-criteria decision making approach. For the AHP the sensitivity analysis was conducted using the SuperDecisions software which allows to observe how the result changes as the weight of each individual criterium varies, as set out in paragraph 3.3.4.1. The analysis was conducted, for TOPSIS methods, assuming six different scenarios in which the weights of the criteria vary, as duly detailed in paragraph 3.3.4.2, and it was observed how the results change as the weight of the criteria themselves. This shows the soundness of the methods used, as when the criteria selected and weighted by the decision maker were varied, the result did not change in either case, as visible in the Figure 11. Considering what has been obtained in this study, it is possible to state, also following the sensitivity analysis, that the use of multi-criteria decision-making methodologies could be appropriate in the design of floating photovoltaic plants. A multi-criteria scenario should be carried out in the design phase as part of measures to consider several aspects simultaneously, but it should be emphasized that different results are obtained depending on the criterium to be maximized. In [142] the MCDA is used to establish which is the best site for the installation, at sea, of a floating photovoltaic system. Assigning criteria weights, it is argued, has no predefined procedure and is a subjective process that depends on the decisions of researchers or experts.

The methodology used in this case study can be further developed and applied, and the results obtained can serve as a starting point for a more in-depth study of the topic.

4.

Floating photovoltaic technology definition aided with Multi-criteria Decision Analysis

This chapter is based on the paper:

S. Di Grazia, G. M. Tina, *Floating photovoltaic technology definition aided with Multi-Criteria Decision Analysis: a case study,* International Journal of Sustainable Energy. DOI: 10.1080/14786451.2022.2124412.

The demand for electrical energy is constantly growing. Power generation from renewable sources, especially solar energy, will play a role in meeting the demand for electricity. Floating photovoltaics is an increasingly cost-effective solution that still needs to be explored in the design and construction phases. The floating system has important characteristics: it reduces evaporation of water and algae growth in the basins where it is placed, it does not occupy land and has a high efficiency due to the evaporative cooling effect. Floating systems can be realised by using fixed or tracked floating structures and mono/bifacial photovoltaic modules. Multi-criteria decision analysis is used to determine the best technology and an analysis is carried out on a system in Sicily. The aim of the study is to determine the best photovoltaic system for the installation of floating photovoltaic systems in Sicily. After selecting the San Giovanni dam site from a previous case study, the first evaluation was to determine the alternatives for the multi-criteria analysis. It was decided to use bifacial photovoltaic modules on a fixed structure and on a trackable structure with horizontal and vertical axes. Before starting the decision analysis, the five criteria and their weighting were determined, taking into account the literature on the state of the art and the knowledge of the researchers. The multi-criteria decision analysis provided results regarding the superiority of horizontal axis tracking systems; the Levelized Cost Of Electricity is 64.37 US$/MWh and the avoided CO_2 emissions are 23491.60 tonnes.

4.1 Introduction

The Global Industry Analysts (GIA) projects that floating photovoltaics (FPV) will create a new global market by 2026. The projection of FPV deployment in 2026 is approximately 4.80 GW [15]. As of August 2020, there was approximately 2.60 GW of cumulative capacity installed in the more than 60 states where floating systems are being implemented [2]. Despite the existence of specific commercial models, floating systems are made with conventional solar modules mounted on floating rafts anchored to the bottom of the reservoir [49]; the modules used in floating systems can be fixed or tracking, tilted or not [134]. The floating system is a very competitive technology compared to the traditional technology, as a result of the positioning of the modules on the water surface and their nature [35]. These advantages are related to the energy production and higher efficiency of the system, the reduction of the evaporation rate of the water from the water basin and the inhibition of algae growth, the lower cost of site preparation and the possibility of integration with existing hydropower plants [8-13, 35]. The biggest advantage of the floating system is the natural cooling effect of the water on the panels and the resulting higher efficiency of energy conversion; in fact, power generation increases by more than 10% compared to panels on the ground [6, 143]. In [143] a comparison is made between the efficiency of ground-mounted photovoltaic systems and floating photovoltaic systems; the difference is given by the temperature of the panel which, by cooling down thanks to the water, is able to convert more solar energy into electricity. In fact, about 80% of the solar radiation captured by a panel on the ground is lost [6]. The production costs of photovoltaic panels have decreased over the last decade, leading to a significant increase in energy from solar power [144]. This increase could lead to a reduction in the energy costs of floating photovoltaic systems [19]; currently, the Levelised Cost of Energy (LCOE) is still higher than that of ground-based solar systems [49].

FPV plants have been tested in Jordan. They have shown positive results in the water quality of reservoir, minimizing treatment costs thanks to the mitigation of algae proliferation and the generation of harmful chemicals [145]. The collapsed coal mines in the Chinese province of Anhui have been used as a place to install the largest plant in the world capable of producing 70 MWh per year [9]. In Japan and South Korea, where land scarcity and population density predominate, the allocation of floating plants could be ideal [145, 146]. In Chile, as in the United States, Australia, Spain, Iran or other nations considered arid or semi-arid, the use of floating panels on water bodies can reduce the evaporation of water, thus avoiding periods of scarcity of water [13, 24, 147]. The main reason for investing in floating photovoltaic systems, for countries that are planning to install or have implemented FPV, could therefore be linked to land use, the redevelopment of degraded or abandoned areas and the minimization of the evaporation of water basins.

The choice of places to install floating photovoltaic systems can be made with the use of multi-criteria decision analysis (MCDA). Considering various environmental, technical and economic factors, such as electrical producibility and distance from the connection line, the best allocation of solar plants can be obtained [106]. The selection can be made with alternatives, corresponding to the locations, on the basis of a set of criteria; analysis is an analytical tool used to judge which is the best alternative among various possibilities. Some studies [148, 149] use the Methodology of Multi-Criteria Decision making (MCDM) or the MCDA, comparing various elements, to select the best alternative for the allocation of a photovoltaic system on the ground.

In this chapter, which follows on from the previously chapter, a MCDA is used to determine the best technology for floating photovoltaic modules to be installed in a closed basin on Sicilian territory.

The novelty of this study is the use of MCDA for the siting of a floating photovoltaic system. Specifically, the aim is to select the best photovoltaic system among those currently on the market in order to determine which might be the most suitable choice in a habitat such as that of Sicily. This topic is not currently covered in great depth in the literature. It is a new innovation for renewable source installations that has never been studied specifically for floating photovoltaic systems.

4.2 Methodology

The approach used for the optimal choice of the best photovoltaic system, in a reservoir in Sicily, was organized in various phases:

- Choice of the reservoir where to allocate a floating photovoltaic system: through the use of GIS software, using Wep Map Service (WMS) available from national and regional institutional web sites, different levels of restrictions are applied to obtain suitable basins for the allocation of a floating photovoltaic system. After the first phase, in which 47 basins were analyzed, there were seven usable sites; to these, using different criteria, two different MCDA methods were applied in order to obtain the optimal site. Finally, for both results, the sensitivity analysis was conducted in order to verify the solidity of the results;
- Choice of photovoltaic systems to be used as alternatives: an extensive literature research was conducted in order to evaluate the state of the art of photovoltaic systems. The choice focused on the best technologies to be used in the Mediterranean climate with an average latitude of 41°, these were chosen as the alternatives of this study;
- Definition of criteria: the criteria were chosen with a view to having to evaluate various thematic areas and having to use the discriminants inherent to the choices of the designers. Various studies, related to terrestrial photovoltaics, were examined to evaluate which criteria were used and with what weights. The choice fell on environmental, technical and economic criteria, giving greater importance to the

technical domain, with two criteria, followed by the economic one, also with two criteria, and finally to the environmental domain with only one criterium;

- Search for the best choice of photovoltaic system in a floating photovoltaic system: the research was conducted using two MCDA methods. AHP and TOPSIS are two useful methods for obtaining a ranking, the result of a multi-criteria analysis, of the various alternatives. The two analyzes are conducted in a different way, as explained below, as they involve a different approach;
- Sensitivity analysis: subsequently, for both methods, the sensitivity analysis was carried out in order to assess the solidity of the results derived from the multi-criteria analysis.

The phases previously mentioned are dealt with next paragraphs.

4.2.1 Choice of the reservoir where to allocate a floating photovoltaic system

The reservoir that will later be used to study the choice of the best photovoltaic system in this article was selected in a previous study, explicated in the previously chapter. This began with the selection of 47 basins located in Sicily from the ISPRA database (Higher Institute for Environmental Protection and Research) [150], subsequently with the use of the Geographic Information System (GIS) software the lakes in proximity of Special Protection Areas (ZPS), Special Conservation Areas (ZSC), Sites of Community Interest (SIC), archaeological areas, natural and/or oriented reserves, etc. were excluded. The basins that could be used for the allocation of a floating plant were 7; the choice of the best one was made with the use of the MCDA and, in fact, criteria were chosen to be used during the multi-criteria analysis phase. Specifically, the criteria chosen to which weights were subjectively assigned were five; a real value has been attributed to each criterium in order to carry out, with two different methods, the multi-criteria decision analysis. Both AHP and

TOPSIS, assuming 1% coverage of the surface of the reservoir, gave a unique result: the San Giovanni Dam located in the municipality of Naro, in the province of Agrigento, was found to be the optimal site to locate a floating photovoltaic system. For both methods, a sensitivity analysis was conducted on the results obtained, which confirmed the validity of the results processed with the MCDA.

4.2.2 Choice of photovoltaic systems to be used as alternatives

Photovoltaic systems, as stated, can be made with different technologies; in this chapter the photovoltaic modules used are bifacial in monocrystalline silicon with peak power of 550 W. The multicriteria decision analysis has one goal, in this case the choice of the best photovoltaic system, which is achieved by entering alternatives among which will be derived later the best.

In this case study, the alternatives considered are seven:

1. Photovoltaic modules with fixed structure inclined at 5°;
2. Photovoltaic modules with fixed structure inclined at 10°;
3. Photovoltaic modules with fixed structure inclined at 15°;
4. Photovoltaic modules with fixed structure inclined at 20°;
5. Photovoltaic modules with fixed structure inclined at 25°;
6. Photovoltaic modules with horizontal axis tracking structure, azimuth 20°, rotation angle ± 50°;
7. Photovoltaic modules with vertical axis tracking structure, inclination 30°, azimuth ± 120°.

4.2.3 Definition of criteria

The choice of criteria and their weights, in MCDA methods, is a subjective choice dictated by the preferences of the designers, the knowledge of the subject and what imprint to give to the study. In the literature there are other studies in which the MCDA is used for the allocation of photovoltaic systems on the ground and wind power plants or for the choice of which is the best panel to install; the criteria are usually gathered into several categories. The definition of the criteria weights was dealt with in the previous chapter in paragraph 3.2.2.The researchers of [151] divide the criteria into economic, technical and environmental, giving greater importance to the technical component to which 45% of the weight is attributed. To the economic criterium 30% and to the environmental criterium 25%. Also in [152] the criteria are divided into economic, technical and environmental ambits giving greater weight, also in this case, to the technical aspect with 56%. Environmental and economic criteria are given more or less equal importance, 20% to the first and 24% to the latter. The findings in the literature combined with the priorities of the designers led to the subsequent choice of the criteria weights.

The criteria, in Table 10, chosen for this case study are:

- Plant cost: capital and operating costs, that is, the costs necessary for the installation and maintenance of the plant during its life cycle;
- LCOE (Levelized Cost Of Energy): quantifies how much the energy produced by the plant should be sold during its life cycle;
- Annual Energy Yield: explicit the annual energy yield of the plant, it depends on the horizontal solar irradiance and on the photovoltaic modules used;

- Performance Ratio (PR): it is necessary to evaluate the efficiency of the system, it is calculated taking into account the theoretical and real energy performance of the system;
- CO_2 emissions: evaluates the impact that a renewable source plant has on the environment, highlighting how much difference there is compared to a classic fossil source production plant.

The criteria relating to plant costs and LCOE must be minimized, unlike the annual energy yield, the CO_2 emissions and the performance ratio must be maximized. The weights assigned to these criteria, give greater importance to the LCOE and annual energy yield. These are parameters that express the amount at which energy must be sold in order to balance the investments and maintenance costs of the plant during its life cycle and the production of electricity by each technology. The LCOE is a criterium that takes into account, in addition to costs, the interest rate and performance in terms of energy produced. CO_2 emissions and the performance ratio were assigned a slightly lower weight than the two criteria already set out. The total costs of the plant, capital and maintenance, have received less importance as they already affect the calculation of the LCOE and because the topic of this research is more oriented in the technical field. A percentage weight has been assigned to each criterium, the sum of weights of the five criteria is equal to 100%. The annual energy yield must be maximized since a plant that produces more is cheaper than a plant that produces less; increasing energy production also increases economic revenues. Economic costs, in terms of capital costs and operating costs, are an important factor in the installation of a system. Costs generally decrease as installed power increases due to the economy of scale but, in this case, the system assumed with the various photovoltaic systems will have the same power; the costs will vary as the systems vary due to the different technologies.

The performance ratio is an important parameter for evaluating the efficiency of the system, the higher the value of the PR the greater the efficiency; in fact, the relationship between the theoretical energy and real energy must be maximized as it is an important criterium for comparison. The value of CO_2 emissions must be maximized since these are the emissions that are avoided, in 25 years, if a floating photovoltaic system is installed for the production of electricity.

Table 12 - MCDA's criteria

Parameter	Criterium category	Weight
Costs	Economic 35%	10%
LCOE		25%
Performance Ratio (PR)	Technical 45%	20%
Annual energy yield		25%
CO_2 emissions	Environmental 20%	20%

Floating photovoltaic systems have different costs related to construction. In one study [39] the costs are split into photovoltaic panels, inverters and cables, electrical parts and the assembly costs for the structure and floating rafts. In another case [49] the capital expenditure (CAPEX) includes the cost of photovoltaic modules, inverters, EPC (engineering, procurement and construction costs), system balancing and other costs. Maintenance costs for floating photovoltaic systems are limited as cleaning of the installation site is not required, for tracking systems maintenance is required for panels and handling systems [39]. In this case study the costs were calculated as in [39] and divided according to the fixed or tracking structure. For systems with fixed panels, and with different inclinations, the CAPEX were assumed 1.01 $US/Wp and OPEX 0.052 $US/Wp, for systems with panels equipped with horizontal axis tracking structure, the CAPEX were considered 1.27 $US/Wp and OPEX 0.057 $US/Wp. For systems with panels with a tracking structure with vertical axis, the CAPEX were considered 1.43 $US/Wp and the OPEX 0.066 $US/Wp.

$$\text{Costs [US\$/Wp]} = \frac{CAPEX+OPEX}{Peak\ installed\ power} \quad (26)$$

where:

- the peak installed power was assumed to be equal to 1 MWp;

The annual energy yield and the performance ratio were deduced, for each alternative, through the simulations conducted with the PVSyst software. Seven different simulations were carried out considering the same panel for each case, the meteorological data of the site, and consequently, the data relating to the solar irradiance of the place.

The LCOE was calculated using a formula previously used in another study [133] with some settings since, compared to the original case, fuel consumption is excluded since energy production is from renewable sources.

$$\text{LCOE [US\$/MWh]} = \frac{(CAPEX \times CRF)+OPEX}{Energy\ Generated} \quad (27)$$

where:

- CAPEX and OPEX are the investment and maintenance costs,
- Energy Generated is derived from the PVSyst report;
- CRF is the capital recovery factor calculated with a formula $\frac{(((1-p)^n)\,p)}{(1-p)^n-1}$ that takes into account the interest rate (p) and the life cycle of the power plant (n).

$$CO_2 \text{ emissions } [tCO_2] = CO_2\ avoided\ emissions + (-CO_2\ emissions\ for\ the\ installation\ of\ the\ FPVs) \quad (17)$$

where:

- CO_2 avoided emissions are those not produced since it is a green source plant; they are derived by simulating the production of the same energy from a thermoelectric plant powered by oil refining process. This amount is obtained combining the energy produced by the system and the CO_2 emissions (517.4 gCO_2/kWh) from the fossil fuel thermoelectric plant [153] in Italy in 2020 and multiplying it by 25, the life cycle of the floating photovoltaic system;
- CO_2 emissions for the implementation of the FPVs are derived with the combination between the square meters surface occupied by the plant (4704 m^2) and the $kgCO_2$ emitted for each plant square meter unit (137.73 $kgCO_2/m^2$) [134].

4.2.4 Search for the best choice of photovoltaic modules in a floating photovoltaic system

With the multi-criteria decision analysis, in the following paragraphs, the best solution between various photovoltaic systems will be established. This paragraph illustrates the methodology applied to achieve this goal.

4.2.4.1 AHP

The MCDA according to the AHP method was conducted using the Super Decisions software. The decision-making process starts by setting the goal of the analysis and input which are the criteria to be taken into consideration to the software; subsequently the alternatives, i.e. the various implemented photovoltaic systems, are inserted. The comparison between criteria is requested by the software and must be carried out by comparing them two at a time, thus assigning the relative weights. The matrix is built by the software and a comparison is made between two alternatives at a time for each criterium to pass the consistency check of the hierarchical analytical process. Finally, the software is able to provide the result on which is the best solution to achieve the goal.

4.2.4.2 TOPSIS

The TOPSIS method was runned with the EXCEL spreadsheet. The ideal and worst solution are deducted after the calculation of the weighted normalized matrix which is necessary to reach the final solution, the same formulas are also used in [154, 155]. In order to be inserted into the matrix, the values must first be normalized, this is done through the use of the formula (7).

After having been normalized the coefficients to be inserted in the matrix, they must be related to the weight of the criteria, with the formula (8).

The Euclidean distance must be calculated from the ideal solution and the worst solution; in order to do this, the worst and ideal values of each criterium must first be identified. The ideal weighted normalized coefficient (v_j^+) for LCOE and costs will be the lowest coefficient while, for energy efficiency and performance ratio, the ideal coefficient will be the highest. Then the worst weighted normalized coefficient (v_j^-) will be, for the LCOE and costs, the highest and for the other two criteria the lowest. The Euclidean distance is calculated with the following formulas:

$$S_i^+ = \sqrt{\left[\sum_{j=1}^{m}\left(v_{ij} - v_j^+\right)^2\right]} \quad (28)$$

$$S_i^- = \sqrt{\left[\sum_{j=1}^{m}\left(v_{ij} - v_j^-\right)^2\right]} \quad (30)$$

The score of each alternative is obtained with a specific formula that implements the previously calculated Euclidean distances at (9) and (10). The best alternative will be the one that will have the P_i value closest to 1 since they are normalized values.

$$P_i = \frac{S_i^-}{S_i^+ + S_i^-} \quad (31)$$

4.2.5 Sensitivity analysis

Through manipulating the variables, as shown by the study [138], it is possible to evaluate how much a criterium influences the final result. This evaluation is the goal of the sensitivity analysis that helps to evaluate how the ranking obtained after an MCDA varies when the weights of the criteria are varied [156]. In this case, the analysis was conducted for the AHP with the Super Decisions software and for the TOPSIS with the use of the Excel software.

4.2.5.1AHP Sensitivity analysis

As previously stated, the sensitivity analysis of the AHP method was conducted with the Super Decisions software. The sensitivity analysis can be conducted in two different ways, in this case the dynamic mode was used.

This mode is performed with the "Node Sensitivity" command, where it is evaluated how the priority of an alternative changes when the priority of a criterium varies. Variation can be viewed with four different options; specifically, the Barchart option allows to evaluate the variations with three-dimensional histograms. An immediate and easy to interpret result is obtained by being able to manage the weight of the criterium under consideration.

4.2.5.2 TOPSIS Sensitivity analysis

The sensitivity analysis of the TOPSIS method was conducted with a spreadsheet by varying the weights of all the five criteria at the same time. Six different scenarios were hypothesized by maximizing one criterium at a time: first the energy efficiency, then the costs, the performance ratio, the LCOE and the CO_2 emissions; a sixth scenario was also hypothesized where the five criteria were given the same weight.

4.3 Results and discussion

The basin on which the case study was conducted is the San Giovanni Dam. The San Giovanni dam, localized in Figure 12, on the Naro river is an artificial basin. The basin is intended for the collection of water from the Naro river. The dam blocks the course of the river about 20 km from its mouth. Its waters are mainly used for irrigation of the neighboring countryside. It is located in the municipality of Naro belonging to the Free Municipal Consortium of Agrigento. Table 14 reports some climate data of the site of the basin, derived from the 2016 ISPRA annual database [140]. The average summer temperature ($T_{sum,avg}$) was calculated considering the temperatures recorded in the period from the 1st June to the 30th September; period in which the maximum summer temperature ($T_{sum,max}$) was also measured. From the same database [140] the annual rainfall and the average annual temperature ($T_{ann,avg}$) were recorded. The annual horizontal solar irradiance (annual GHI) is a fundamental datum for the calculation of the energy that can be generated from a solar source; was extrapolated from the PVGIS-Sarah database.

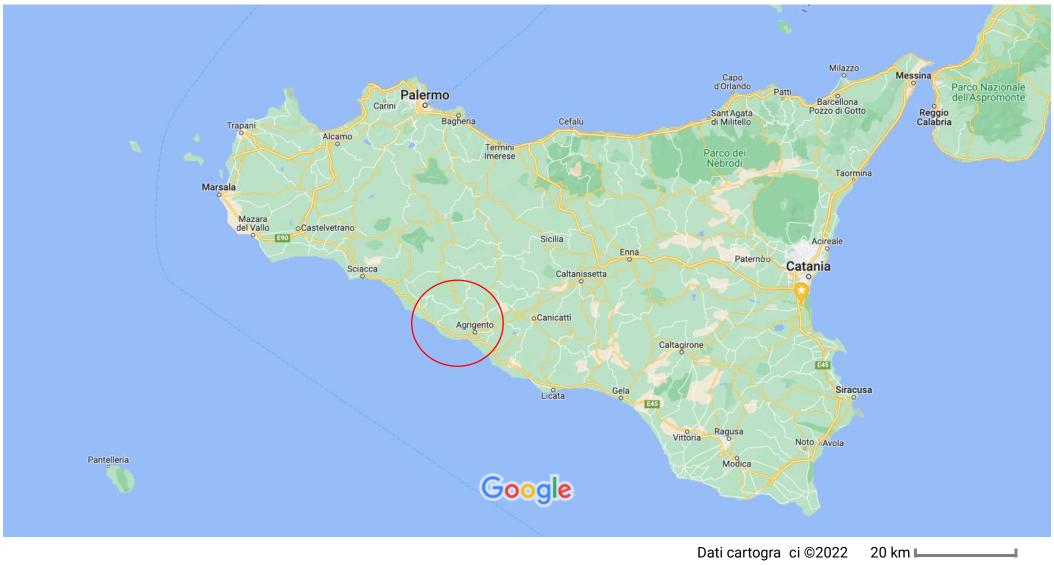

Figure 12 - Location of the San Giovanni Lake

Table 13 - Meteorological and physical data of San Giovanni Dam

Coordinates (° ′ ″)	Surface area [km²]	Height [m]	Annual rainfall [mm]	$T_{sum, avg}$ [°C]	$T_{sum, max}$ [°C]	$T_{ann, avg}$ [°C]	Annual GHI [kWh/m²]
37°18′40"N, 13°46′10"E	1.548	<15	548.2	24.5	35.7	17.5	1794.99

The results obtained during all phases of the study, from the multi-criteria decision analysis and sensitivity analysis will be presented in the next paragraphs.

4.3.1 Criteria

The criteria have been attributed a real value, using the formulas expressed in paragraph 3.3, in order to be able to carry out the multi-criteria decision analysis. The costs of the systems with a fixed structure are the same for each tilt angle considered; the performance ratio increases as plant performance increases and is maximum for systems with a tracking structure on a horizontal axis. The maximum production of energy and the maximum saving of CO_2 emissions is obtained with the modules with vertical axis tracking; the best datum relating to the LCOE is instead recorded by the tracking system with horizontal axis. As the tilt angle increased, the change in pitch between the rows of panels was also taken into account to avoid shading effects. The results are reported in Table 15.

Table 14 - MCDA's criteria values considering different photovoltaic systems

Photovoltaic Systems	Costs [USD/Wp]	Performance Ratio [%]	Annual energy yield [MWh/y/MWp]	LCOE [USD/MWh]	CO_2 Emissions [tCO_2]
Fixed 5°	1.06	85.84	1473	70.52	-18405.4
Fixed 10°	1.06	85.92	1518	68.43	-18987.4
Fixed 15°	1.06	85.96	1553	66.89	-19440.2
Fixed 20°	1.06	86.03	1579	65.79	-19776.5
Fixed 25°	1.06	86.06	1595	65.13	-19983.4
Horizontal tracking	1.33	86.60	1901	64.37	-23941.6
Vertical tracking	1.50	86.43	1968	70.87	-24808.2

4.3.2 AHP

The best alternative turned out to be the tracking system with horizontal axis, as the second best alternative the software has decreed that these are panels with a tracking structure with vertical axis. The fixed system with inclination at 25° is in third position followed, in descending order with respect to degrees, by all the fixed systems. In figure 13 the order obtained with the scores of each alternative.

The multi-criteria analysis, following the AHP method, was conducted with the Super Decisions software; the methodology applied by the software has been explained in paragraph 4.4.1. The 5 criteria, and their relative weights, placed in relation with the alternatives relating to photovoltaic systems are able to give indications on which could be the best choice for a floating photovoltaic system with the Mediterranean climate and at the latitude in which Sicily is located.

The best alternative turned out to be the tracking system with horizontal axis, as the second best alternative the software has decreed that these are panels with a tracking structure with vertical axis. The fixed system with inclination at 25° is in third position followed, in descending order with respect to degrees, by all the fixed systems. In Figure 13 the order obtained with the scores of each alternative.

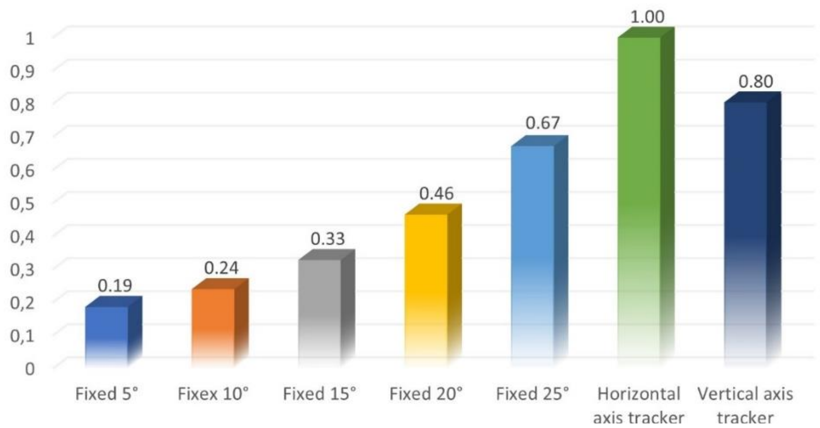

Figure 13 - AHP's results

4.3.3 TOPSIS

The multi-criteria analysis was conducted with a spreadsheet following the TOPSIS method, that is, assuming an ideal solution, and taking into account the methodology already explained.

After using the formula (7) the result, in Table 16, is obtained:

Table 15 - TOPSIS' Normalised Matrix

	Costs	**Annual Energy Yield**	**Performance Ratio**	**LCOE**	**CO_2**
Fixed 5°	0.341457919	0.334341668	0.376733856	0.395	0.33293
Fixex 10°	0.341457919	0.344555772	0.377084959	0.3833	0.34345
Fixed 15°	0.341457919	0.352500075	0.377260511	0.3747	0.35164
Fixed 20°	0.341457919	0.358401557	0.377567727	0.3685	0.35773
Fixed 25°	0.341457919	0.362033239	0.37769939	0.3649	0.36147
Horizontal axis tracker	0.428433049	0.431489145	0.380069338	0.3606	0.43307
Vertical axis tracker	0.483195168	0.446696811	0.379323243	0.397	0.44874

After having normalised the matrix it is necessary to take into account the weights of the criteria, reported in [Table 1], so as to obtain a normalised matrix, weighted using the formula (8). The results are reported in Table 17.

Table 16 - TOPSIS' Weighted Normalised Matrix

	Costs	**Annual Energy Yield**	**Performance Ratio**	**LCOE**	**CO_2**
Fixed 5°	0.034145792	0.083585417	0.075346771	0.0988	0.06659
Fixex 10°	0.034145792	0.086138943	0.075416992	0.0958	0.06869
Fixed 15°	0.034145792	0.088125019	0.075452102	0.0937	0.07033
Fixed 20°	0.034145792	0.089600389	0.075513545	0.0921	0.07155
Fixed 25°	0.034145792	0.09050831	0.075539878	0.0912	0.07229
Horizontal axis tracker	0.042843305	0.107872286	0.076013868	0.0901	0.08661
Vertical axis tracker	0.048319517	0.111674203	0.075864649	0.0993	0.08975

In order to calculate the ideal solution and the worst solution, the best and worst values, in Table 18, must first be defined (v_j^+ and v_j^-).

Table 17 - Best and worst values

	Costs	**Annual Energy Yield**	**Performance Ratio**	**LCOE**	**CO_2**
v_j^+	0.034145792	0.111674203	0.076013868	0.0901	0.08975
v_j^-	0.048319517	0.083585417	0.075346771	0.0993	0.06659

Euclidean distances, reported in Table 19, were then calculated in order to determine the best and worst solutions (S_i^+ and S_i^-).

Table 18 - Euclidean distances

	S_i^+	S_i^-
Fixed 5°	0.0374	0.01418
Fixex 10°	0.0336	0.01495
Fixed 15°	0.0307	0.01633
Fixed 20°	0.0287	0.01767
Fixed 25°	0.0275	0.0186
Horizontal axis tracker	0.01	0.03323
Vertical axis tracker	0.0168	0.03641

The results obtained, normalised, show that the best alternative for the AHP is the system with a tracking structure with a horizontal axis. The alternatives ranked from the third position onwards are all systems with a fixed structure, starting with the one with an inclination of 25° and ending with the one with 5°; even in this case, as the inclination decreases, the convenience in applying that system decreases. The second system, according to TOPSIS, is the system with vertical axis tracking, as shown in Figure 14.

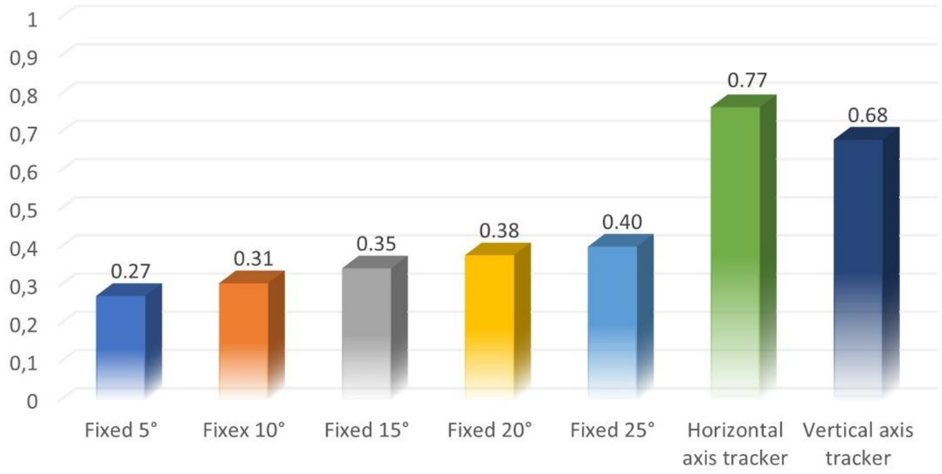

Figure 14 - TOPSIS' results

4.3.4 Sensitivity analysis

In the following paragraphs, the results relating to the sensitivity analysis conducted for both MCDA methods will be presented to evaluate the validity of the results obtained.

4.3.4.1 Sensitivity analysis AHP

The sensitivity analysis was carried out for the AHP method using the "Node sensitivity" command of the Super Decisions software. The weighting of each criterion was changed to evaluate how the result changes when the weighting is changed. For all criteria except the cost of LCOE, the best alternative is the horizontal axis tracker. As long as a weight of about 66% is applied to the criteria cost, annual energy efficiency and CO_2, the horizontal tracker is the best alternative, which is then surpassed by the vertical axis tracker. For the cost of electricity, the LCOE, the best alternative if 20% of the total load is attributed to it, and is therefore surpassed by the Horizontal Tracker. However, the performance ratio in each situation does not change the result, as the Horizontal Tracker is always the best alternative. The results obtained lead us to conclude that the horizontal tracker remains the best alternative, which gives the study a technical character, as well as an economic and environmental character. The sensitivity analysis has thus confirmed what was determined with the multi-criteria decision analysis.

4.3.4.2 Sensitivity analysis TOPSIS

For the sensitivity analysis carried out for the TOPSIS method, six different scenarios were assumed in which the weighting of all criteria is varied simultaneously. In each of the first five scenarios, one criterion is maximised, while in the sixth scenario all five criteria are equally weighted, i.e. at 20%. In the first scenario, annual energy efficiency is maximised, accounting for 30% of the total weight, while 25% is allocated to PR, 17% to costs and avoided CO_2 emissions, and 11% to electricity production costs; in this case, the horizontal axis tracking system was identified as the best alternative. In the second scenario, where the cost criterion is maximised at 30% and the electricity production cost at 25%, the best alternative is the system with fixed panels tilted at 25°, which has lower costs and higher energy production compared to the tracked systems, and thus a lower electricity production cost value than other fixed systems. Also for the third scenario, the best alternative is the one with a fixed structure and 25° inclined panels; in this case, the performance ratio criterion is maximised. For the other three scenarios, the best alternative is always the system with a horizontal axis tracking, both in the case where the LCOE criterium is maximised and when the avoided CO_2 emissions are the most important and when all five criteria are equally weighted. This sensitivity analysis shows how maximising the economic criteria combines the best result with fixed structure systems due to their lower costs; in the case of the third scenario, the environmental component also leads to the same result due to the 25% weighting of the cost criterion. All other scenarios thus confirm the results obtained with TOPSIS in the previous phase of the decision analysis and show that when the technical component is maximised, the tracking systems provide the best results.

4.4 Conclusions

In this study, to determine which is the best photovoltaic technology, was used MCDA; it was decided to maximise the technical aspect by giving more weight to the criteria related to energy yield and power ratio, followed by LCOE and cost (economic criteria) and finally the criterion related to avoided CO_2 emissions, as it is a renewable energy plant. The MCDA was then carried out using the AHP and TOPSIS methods. From the analysis, it emerged that the best photovoltaic installation is the one that uses a tracked structure with a horizontal axis, while the least suitable installation is the photovoltaic installation with a fixed structure with an inclination of 5°.

The sensitivity analysis performed for the five criteria has shown, in the case of the AHP, that the best alternative for most criteria is the horizontal tracker, as long as they are weighted with a total of about 65%. The only criterion where the result differs up to a weighting of 20% is LCOE; however, above this percentage the result is the same as for the previous criteria. However, in the case of TOPSIS, the six hypothetical scenarios produced different results: When all criteria have the same weight or when the annual energy yield, costs and CO_2 emissions are maximised, the best system is the horizontal tracker. In the case where the PR and the LCOE are maximised, the best system is the one with a fixed structure with an inclination of 25°.

So, based on the results obtained, we can confirm that the systems with horizontal trackers are more expensive but offer better technical performance, lower long-term environmental impact and advantages compared to fixed systems. The systems with tracking structure are the best alternative among the inputs according to both MCDA methods. Specifically, the system with horizontal tracking costs 1330 $US/kWp, while the system with vertical axis costs 1500 $US/kWp. Both systems are the most productive (1901 and 1968 MWh/year/MWp, respectively) and have high CO_2 avoided emission over the life cycle of the system, as expressed in Table 15. The horizontal tracking system, which turned out to be the best, has the best performance ratio value and the lowest LCOE among the calculated.

5.

CONCLUSION

The results of the analyzes carried out show that taking into account all the basins that insist in a region with a Mediterranean climate, such as Sicily, it is possible to make a first selection using GIS software based on current regulations, on the morphological characteristics of the basins and on the environmental constraints of the area under exam. The basins considered usable, compared to the 47 initially examined, were seven; for all seven basins, five criteria were taken into consideration. On the basis of the choice of criteria, for which the weights were established, the multi-criteria decision analysis was conducted, followed by the sensitivity analysis, obtaining as the best site for the installation of a floating photovoltaic system the San Giovanni dam in Naro, in the province of Agrigento. The second site for the allocation is Lake Trinità while the third is Lake Baiata, through the sensitivity analysis it has been shown that the final result is neither influenced nor changed except when the weight is maximized, approximately 69 %, of the energy efficiency criterium. The weights attributed to the criteria substantially affect the final result; as treated, weights contained in the ranges used by experts in other studies present in the literature were used despite the fact that it is a purely subjective decision-making process.

Having obtained the result on which is the best site in Sicily for the allocation of an FPV, using the same method, it was found which is the best photovoltaic technology for a floating photovoltaic system. Slightly different weights were attributed to the criteria, which partly coincide, since the objective in this phase of the study is no longer the choice of the site linked to the feasibility of the intervention, especially at an economic level, but the analysis of the various technologies present on the market. The alternatives taken into consideration during this phase of the study are based on the tilt of the panel, in fact, the tilt angle maximizes the yield; it should also be taken into account that the maximum yield occurs with the minimum shading between panels. The best technology for a floating photovoltaic system in a Mediterranean climate turned out to be the tracking structure with a horizontal axis. It has an excellent energy efficiency, the best performance ratio and LCOE, and given the high energy efficiency, a high value of CO_2 avoided emissions. Also in this, a sensitivity analysis was conducted, for both MCDA methods, to validate the results previously obtained confirming what was obtained with the decision analysis methods.

At the end of the study, having finalized the methodology, it was deduced which is the best basin and which is the best photovoltaic technology for a floating photovoltaic system. For the choice of the ideal basin, the environmental and regulatory constraints, both national, regional and local, were taken into account; this allows us to have results that are truly applicable in reality.

Studies focused on this topic are rapidly increasing, in the same way, the costs of floating photovoltaics are reducing thanks to the expansion that photovoltaic systems are having. The increase in electricity costs and the optimization of the performance of photovoltaic systems, especially as regards floating photovoltaics which have greater energy efficiency thanks to the cooling that the water carries out on the panels, will make it necessary to re-evaluate the economics of this study.

It should be emphasized that this study was conducted on a regional scale and that the methodology, if used on a large scale, should be expanded. The study conducted, however, leads to some considerations: the importance of a multi-criteria design approach can be demonstrated, by conducting this type of study various aspects can be assessed, giving greater importance to what the designer deems most important; the economy of scale plays a fundamental role in these studies, the environmental impact of plants from renewable sources is practically null and can only bring improvements.

To increase this research, and the current state of the art in this regard, the methodology should be expanded taking into account a larger area so as to diversify some values related to the criteria that are closely linked to the geographical location of the plant area. The research could also be implemented using other criteria related to the morphology of the surrounding areas, the shading that these can cause on the surface of the basins; a study could also be carried out for the choice of panels by analyzing those available on the market, studying their characteristics and the potential they could have in a floating photovoltaic system in a Mediterranean climate.

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