SELECTION OF THE BEST CONCEPTUAL SOLUTION ALTERNATIVE IN THE PROCESS OF PHOTOVOLTAIC POWER PLANT PRELIMINARY DESIGN PREPARATION

Lappeenranta–Lahti University of Technology LUT

International Master of Science in Engineering, Entrepreneurship and Resources, Master Thesis

2022

Adis Ćato

Examiner(s): Asc. Prof. Arto Pihlajamäki

Doc. Dr. Zedina Lavić

Prof. Dr. -Ing. Martin Sobczyk

Master's thesis

for the Joint Study Programme
"International Master of Science in Engineering, Entrepreneurship and Resources" (MSc. ENTER)

TOPIC: Selection of the best conceptual solution alternative in the process of photovoltaic power plant preliminary design

edited by: Ćato Adis

for the purpose of obtaining one academic degree (triple degree) with three diploma certificates

Supervisor / scientific member (UNSA):	Doc. Dr. Zedina Lavić
Supervisor / scientific member (LUT):	Asc. Prof. Arto Pihlajamäki
Supervisor / scientific member (TU BAF):	Prof. Dr. -Ing. Martin Sobczyk

Handover of the topic:	14.03.2022
Deadline of the master's thesis:	15.09.2022 (exactly 26 weeks later)

Place, date: 05.09.2022.

....	....	....
(Doc. Dr. Zedina Lavić)	(Asc. Prof. Arto Pihlajamäki)	(Prof. Dr. -Ing. Martin Sobczyk)
Supervisor / member UNSA	Supervisor / member LUT	Supervisor / member TU BAF

Supported by

This activity has received funding from the European Institute of Innovation and Technology (EIT), a body of the European Union, under the Horizon 2020, the EU Framework Programme for Research and Innovation

Statement of Originality

I hereby certify that I am the sole author of this thesis and that no part of this thesis has been published or submitted for publication.

I certify that, to the best of my knowledge, my thesis does not infringe upon anyone's copyright nor violate any proprietary rights and that any ideas, techniques, quotations, or any other material from the work of other people included in my thesis, published or otherwise, are fully acknowledged in accordance with standard referencing practices.

Place, date: Sarajevo, 05.09.2022.

………………………………………..

Signature of the student

Supported by

eit RawMaterials ACADEMY

This activity has received funding from the European Institute of Innovation and Technology (EIT), a body of the European Union, under the Horizon 2020, the EU Framework Programme for Research and Innovation

ABSTRACT

Lappeenranta–Lahti University of Technology LUT

LUT School of Engineering Science

International Master of Science in Engineering, Entrepreneurship and Resources (MSc. ENTER)

Adis Ćato

Selection of the best conceptual solution alternative in the process of photovoltaic power plant preliminary design

Master's thesis

2022

62 pages, 15 figures, 30 tables and 8 appendices

Examiner(s): Asc. Prof. Arto Pihlajamäki, Doc. Dr. Zedina Lavić, Prof. Dr. -Ing. Martin Sobczyk

Keywords: Photovoltaic technology, photovoltaic, solar energy, multicriteria decision model, renewable energy source, AHP, Analytical Hierarchy Process

The presence of renewable energy systems in the modern society is increasing every day. Development and implementation of renewable energy sources is an inevitable step towards achieving sustainable, zero-emission energy production and an emission-free society, which has been a long-term goal for many developed countries. Currently photovoltaic energy is regarded as one the renewable energy source with the highest potential and following the increase of solar cell efficiency as well as the decrease in price, it is becoming a competitor to already well-established hydro power. The amount of energy produced by PV modules has risen significantly in the past decade, several countries with solar energy utilization potential are investing and developing solar modules, and many new utility-scale photovoltaic plants are built every year. This new trend has decreased greenhouse gas emissions in energy production in many countries, but it has also created a problem for engineers when designing PV plants. Many new software has been developed for assistance in design, however many of these programs create several layout alternatives of a photovoltaic plant, leaving the engineers with conflicting options and a decision-making problem. A model that can assist engineers in selecting the best layout alternative is developed in this paper. This is done by deconstructing the problem with a multicriteria decision making method, comparing the alternative based on significant criteria and finally scoring and ranking the alternatives. The model is applied to a current multicriteria decision making problem on a project that an energy generating company in Bosnia and Herzegovina is facing. The said project is a utility scale photovoltaic plant, that is going to be built in the near future. Four alternatives have been provided, from which the best alternative is chosen based on economic, technical, and environmental criteria.

ACKNOWLEDGEMENTS

I would like to thank all three of my mentors for their assistance in writing this master thesis. I would also like to thank the coordinators of the ENTER program for giving us an unforgettable experience and an opportunity to study abroad, see new places, meet new people and gain knowledge that I will use in my future career. Lastly, I would like to thank my friends and family for their support in my educational journey both in and out of the university.

SYMBOLS AND ABBREVIATIONS

Roman characters

I	investment cost	[€]
M	maintenance cost	[€]
E	energy	[Wh]
i	discount rate	[%]
R	cash flow	[€]
C	cash inflow	[€]
P	power	[Wp]
Yield	yield	[kWh/kWp]

Greek characters

λ	principal Eigen value

Dimensionless quantities

n	Size of matrix

Subscripts

0	initial
t	time period
tot	total
plant	photovoltaic plant
inst	installed

sp	specific
max	maximal

Abbreviations

ISS	International Space Station
IEA	International Energy Agency
EESI	Environmental and Energy Study Institute
EU	European Union
PV	Photovoltaics
DC	Direct Current
IRENA	International Renewable Energy Agency
NASA	National Aeronautics and Space Administration
USD	United States Dollar
LCOE	Levelized Cost of Energy
USD/W	United States Dollar per Watt
CIGS	Copper Indium Gallium Selenide PVs
CdTe	Cadmium Telluride PVs
PERC	Passivated Emitter and Rear Cell/Contact
PV-T	Photovoltaic-Thermal
APV	Agrophotovoltaic
MCDM	Multi Criteria Decision Making
GST	Grey Systems Theory
AHP	Analytical Hierarchy Process
WASPAS	Weighted Aggregates Sum Product Assessment

GIS	Geographical Information Systems
CBA	Choosing by Advantages
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
ANFIS	Adaptive Neuro Fuzzy Interference System
TODIM	Portuguese Acronym for Iterative Multi-criteria Decision Making
NPV	Net Present Value
IRR	Internal Rate of Return
CR	Consistency Ratio
CI	Consistency Index
RI	Random Consistency Index
FAHP	Fuzzy Analytical Hierarchy Process

Table of contents

Appendices

Figures

Tables

1 Introduction

Energy has been a need for people ever since the dawn of mankind. Even though fossil fuels still hold the title of the most used source of energy in many parts of the world today, renewable energy was the main source of energy throughout most of human history. One of the most used sources being biomass, which was widely used in ancient times for fire. Fire was and still is used as a heat source as well as a source of energy for cooking. Water is another renewable energy source that was used in more recent history, and it was used for mills, which have been powered by water and used for milling and grinding grains for food for a large part of human history. Today renewable energy sources are used differently.

Industrial revolutions and the rise of population in the world has created the largest energy demand yet. Fossil fuels have been used in recent history as the most popular energy source, with about 80% of total energy sourced from fossil fuels (EESI, 2021), but environmental risks and new ecological policies have made renewable sources the new norm for most developed countries.

Solar energy accounts for only 3.1% of the global energy production (IEA, 2021). Currently, solar energy stands as the third most used renewable energy source. It stands behind hydropower, which is considered to stay in the first place in the near future as well as wind power, which is already a well-established energy source in many countries.

Technical developments in the solar energy sector have caused in a considerable drop of solar cell prices, with new prices being only a fraction of the prices from the last decade. This has made solar energy a viable option for widespread use and massive investments in construction of photovoltaic power plants in developed countries.

Widespread use has made solar photovoltaic systems an significant topic in the utility scale energy production sector. Many Asian countries, with China being the leading developer, have started upgrading their electrical energy grid with photovoltaic plants. This trend is seen in the EU as well. The upward facing trend has resulted in many companies developing modern software applications for development of solar power plants, which are currently used by engineers around the world.

These modern software applications provide engineers with conceptual design solution for the layout design of the photovoltaic power plant, leaving the engineer with multiple design choices, which are most often conflicting. The provided design alternatives have different layouts of arrays, pitch angles of the solar modules, distance between arrays, which provide the plants which vastly different operation parameters depending on the chosen alternative. Different alternatives have different trade-offs on performance and economic parameters, such as greater energy output at a cost of a significant economic investment or on a more complex example, a greater pitch angle which is more convenient for maintenance, however creates shading for other modules. This poses a classic trade-off problem for the engineers, where the right decision should be made based on specific criteria. The criteria should be weighted, and the alternative with the highest priority should be chosen.

The focus of this work will be development and explanation of a multicriteria selection model in the process of photovoltaic power plant design, as well as implementing this model on a practical project, with a goal of optimizing the criteria selection for the best possible technical solution. Before the model itself, the current position of photovoltaic technology will be explained, along with a brief historical overview and the future trends that are likely going to be seen in use in the near future.

2 Photovoltaic Technology

Photovoltaic technology is used worldwide for one sole purpose and that is generating electrical energy. Photovoltaics (PVs) use solar cells incapsulated in a module to convert sunlight to energy and they can be seen used in many different applications, from small solar cells used for powering calculators, to solar modules on rooftops of buildings, residential houses and also space, where they are used for the same purpose on the International Space Station (ISS).

Use cases for PVs vary vastly and with the rapidly declining manufacturing cost of solar cells and the non-fossil energy environmental initiative, they are becoming one of the first choices for large scale commercial energy production in many developed countries. Reports from IEA claim that solar PVs are becoming the lowest-cost option for large scale electricity generation in most of the world (IEA, 2021). Investments in this field are also expected to propel in the near future, increasing the funding of the field and therefore supporting future developments in PV technology.

2.1 Photovoltaic cells

Photovoltaic cells are nonmechanical devices that produce energy from absorbed sunlight. By itself a PV cell normally generates from 1 to 2 W of power, which is enough to power small handheld devices such as calculators. Multiple PV cells are interconnected to form modules with a goal to increase the power output and these units are called PV panels.

PV cells are composed of six main components:

- Glass top layer – with anti-reflective coating
- Transparent negative terminal
- N layer – negative conductive layer
- P-N layer junction
- P layer – positive conduction layer
- Positive terminal

Components of PV cells as well as the cross-section are shown in figure 1.

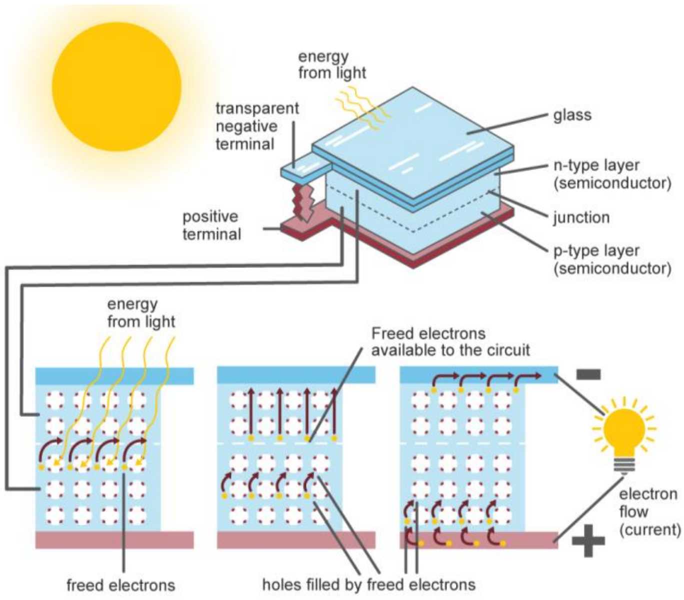

Figure 1. Inside a photovoltaic cell by (EIA, 2022)

Sunlight is composed of photons and these photons contain a varying amount of energy. When sunlight strikes the n-type layer of the PV cell, it penetrates it, and travels to the p-n junction. Energy from photons in the sunlight is sufficient to create electron-hole pairs in the p-n junction. An electric field is created in the junction, which then pushes the electrons and holes out. The concentration difference of electrons in the n-type layer and the holes in the p-type region is very high so a potential difference is developed and as soon as any load is connected electron flow occurs. Electrons move from positive terminal to the holes in the p-type layer, filling the holes and providing direct current (DC), as shown in figure 1.

In a practical example, the n-type layer is much thinner than the p-type layer, this is due to light penetration. More sunlight and therefore photons, reach the p-n junction when the top layer is thinner. Light penetrates more easily, creating more electron flow (current) and therefore making the cell more efficient.

2.2 Historical overview

Sunlight has been used as a source of energy far earlier than photovoltaic cells have been introduced to the public. Some evidence show that magnifying glass has been used for concentrating solar rays for starting fire in the wild and heating bath water even in Greek and Roman times. Modern PV cells however have been invented and developed only in the past century. Some credit Edmond Becquerel, a French scientist, with the discovery on the photovoltaic effect and its potential to produce electricity, however the first practical developed PV cell has been introduced to the public in 1954 by Bell Laboratories (APS News, 2009). Inventors of the first practical PV cell are Calvin Fuller, Gerald Pearson and Daryl Chaplin.

Like any new technology the development of PV cells have been incremental. When the cell from Bell Laboratories has been introduced to the public, it was a very new technology which had limited used and a high manufacturing cost. Due to this, first PV cells were not very accessible to the public and the first public use of these PV cells were by National Aeronautics and Space Administration (NASA). In 1958 first usage cases were proposed and by 1959 these usage cases were accepted, and the first public use of the PV cell was conducted. NASA has launched Explorer 6, an Earth orbiting satellite in space in 1959, which featured four large arrays of PV panels. These panels were the primary energy source for the satellite battery for several months and in the coming years this became a common design feature of most satellites launched in space by NASA. This technology has proved to be one of the best power sources for Earth orbiting satellites and is used even today in modern satellites. (Singh, et al., 2021)

Due to great success in space application by NASA, PV cells have gained public recognition in the energy production industry, and this attracted many investors and new companies to further develop the PV cell. The U.S. Department of Energy introduced the Solar Energy Research Institute in 1977, which was devoted to power generation from the sunlight. In the same year total PV manufacturing production exceeded 500 kW, and PV cells became more accessible to the public, albeit at a very high initial cost (U.S. Department of Energy , 2007).

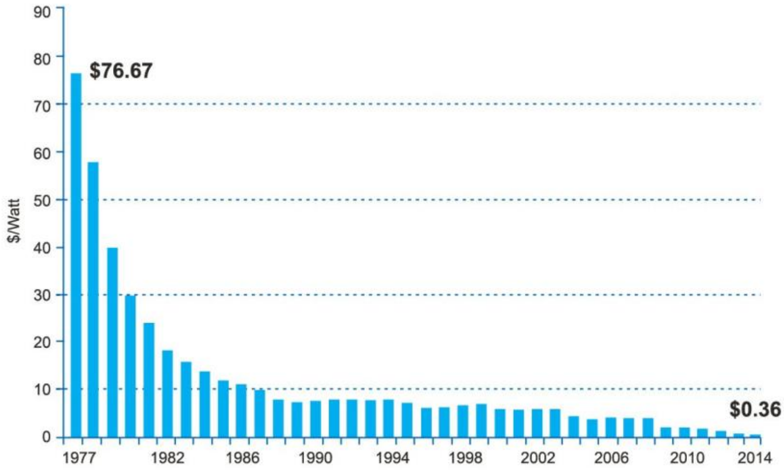

Figure 2. Price of crystalline silicon photovoltaic cells (Bloomberg, 2014)

The price of crystalline silicon (c-Si) PV cells has decreased significantly in the past years. Upon first large-scale manufacturing years the average price of PV cells per Watt (W) was 76.67 USD. The price of production has a downwards facing trend, with the largest fraction of the price being decreased in the first ten years of large-scale production (Figure 2). From that point onwards price drop has maintained its downward facing direction, with current average prices being only a fraction of the original average price from 1977.

Large scale electricity producers have not considered PV modules as a viable choice for energy production due to the high levelized cost of energy (LCOE) of solar energy as well as relatively high cost of crystalline solar PV modules. Other renewable energy sources have shown better performance and a lower LCOE than solar energy, therefore it was never a primary choice for large scale energy producers in the end of the 20th century.

The first PV power plant that produced more than 1 MW of energy was built in 1982 in California, followed by a 5.2 MW power plant in 1984, both constructed by the same company Arco Solar (Arnett, et al., 1984). These plants have been decommissioned since, leaving a mark in the energy production industry as the first PV power plant with meaningful large-scale production in a period where PV power plants were not a primary choice for energy production.

The decreasing price trend of PV modules has played a big role in construction of PV power plants. PV power plant have gained public traction in beggining of the 21. Century, with sunlight becoming a viable energy source for large scale energy production. Many new PV power plants have been constructed in this period and the trend of PV plant construction has increased ever since. Second decade of the 21. Century marks an important period for solar energy. In the period between December 2009 and December 2020, crystalline silicon module prices have declined between 89% and 95% (IRENA, 2021).

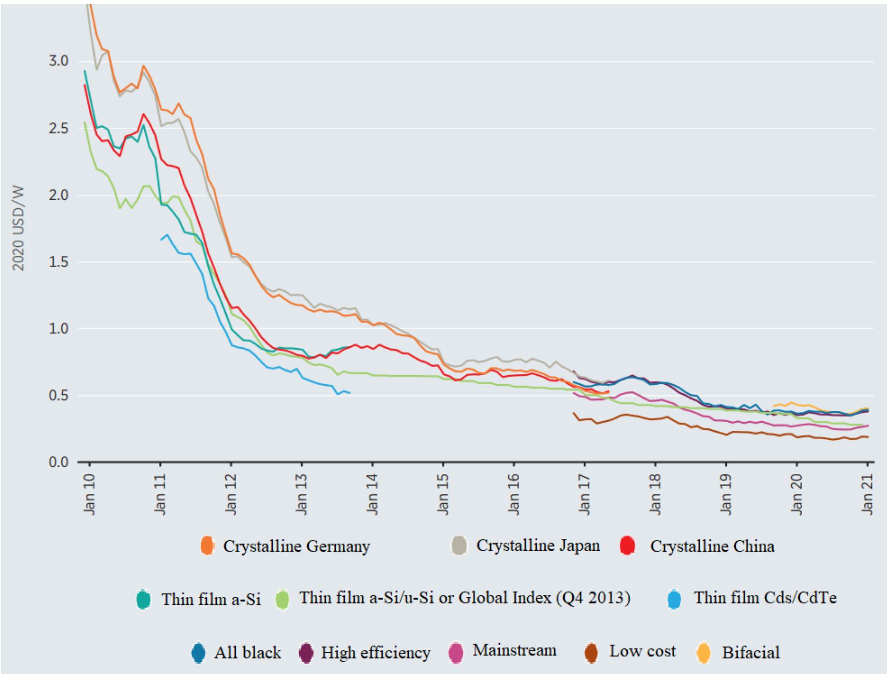

Figure 3. Average yearly PV module price manufacturing, 2010 to 2021 (IRENA, 2021)

Price decline has affected all PV cell production regions as well as different PV cell technologies, as can be seen in figure 3. Modern manufacturing methods as past development has decreased to as low as 0.19 USD/W for lower cost modules and between 0.38 and 0.39 USD/W for all black bifacial modules (IRENA, 2021).

Apart from the price of modules, the design has changed as well. Most prevalent module design of PV cell has been a square crystalline silicone cell design based on M2 and G1 wafer formats. PV cell have typically been connected in a series and parallel using a copper ribbon with is soldered to busbars of neighbouring cells. As cells have evolved the number of busbars has increased from 2 to 4-8 busbars per cell, with a goal of maximizing power output of a PV module (IRENA, 2021).

These features have positively affected the efficiency and power output of cells with the median power output of a module progressing from 350 W, which was the norm in 2017, to 500 W, which is the norm currently. (IRENA, 2021). Apart from power output efficiency has remained a benchmark for all power modules with modern p-n junction crystalline modules reaching up 25.6% efficiency and slowly approaching the theoretical limit of 33.16% efficiency. (Rühle, 2016)

Finally, the LCOE of solar system has decreased over the past decade by between 71% and 88%, depending on the PV plant location. (IRENA, 2021)

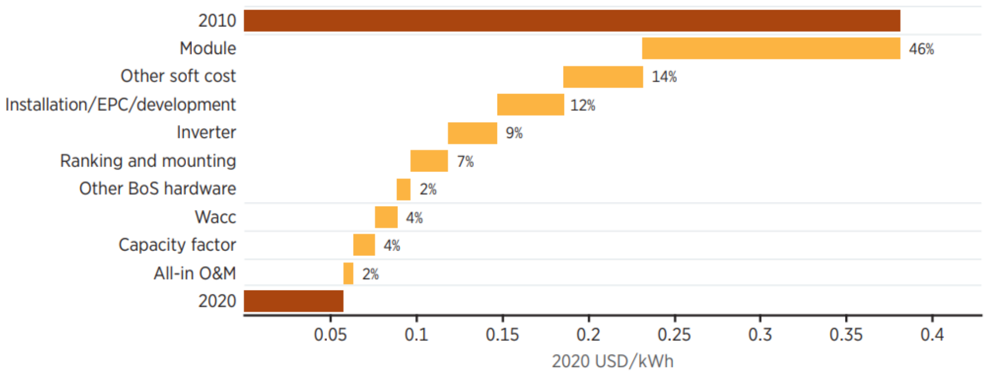

Figure 4. Drivers of solar PV LCOE decline (IRENA, 2021)

Many drivers have had an impact for the LCOE decline, with the most weighted ones being module price (46%), remaining essential hardware (18%), installation and development (12%) and other soft costs (14%), as can be seen on figure 4. These drivers have decreased the LCOE by approximately 84% from the value from 2010 and brought the LCOE down to 0.06 USD/kWh in 2020.

2.3 Future trends of development and use

Solar power will undoubtably become one of the leading renewable power choices in the coming decades in some regions of the world. Its impact will not just be on utility scale electricity generation, but also on local residential home and building sector as well. In the beginning of the second decade of the 21. Century, the prices of consumer grade PV modules have become very attractive for private owned, grid connected and standalone PV systems. This price reduction has attracted many new investors' funding, which help engineers with research and development of new materials that are used in solar cells.

New solar technologies with different materials and efficiency improving features have been emerging on the market recently, some of them being very beneficial for PV power plants. New applications of PV technologies, beyond solar fields and rooftops are emerging as well and some of these innovations have a potential to make PV energy the leading renewable energy source for power generation.

Modern solar plant operation and management solutions are becoming one of the key components of newly build solar plants. Automatization and distant parameter monitoring are newly formed innovations in this field and are considered to become the new industry standard.

2.3.1 New solar module technologies

Modern solar cell technologies have a set goal of manufacturing cost reduction and module efficiency increase. Material selection has been a key factor in manufacturing cost reduction, with new materials and PV cell technologies entering the market in the past years. These new technologies have eliminated silicone dependency of solar cells and some of them have increased the efficiency of cells themselves.

Some PV technologies are still in the research and development phase, while others have penetrated the PV module marketplace and reached their market maturity. These technologies include:

- Crystalline silicone (Conventional solar cell architecture)
    - Monocrystalline silicone (mono-Si)
    - Polycrystalline silicone (poly-Si)
    - Ribbon silicone (ribbon-Si)
- Crystalline silicone (Advanced solar cell architecture)
    - Passivated Emitter and Rear Cell/Contact (PERC)
    - Tandem/Hybrid Systems
- Thin-film technology (silicone based)
    - Amorphous silicone
- Thin-film technology (non-silicone based)
    - Perovskites
    - Cadmium telluride PVs (CdTe)
    - Copper indium gallium selenide PVs (CIGS)

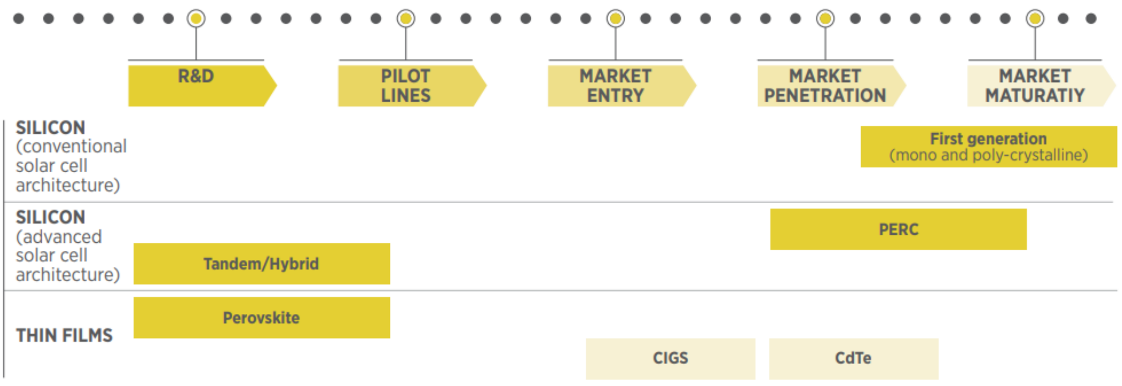

Figure 5. PV technology status (IRENA, 2019)

The conventional crystalline silicone cell structure PV modules are the first-generation solar modules that have been developed, sold and used for energy production. They hold up to 95% of the worldwide PV energy production share and it is safe to say that they reached their market maturity (IRENA, 2019). Average efficiency for these models has reached up to 25%, as previously stated and they are slowly reaching their theoretical maximum, which implies development of new advanced cell technologies.

Advanced silicone solar architecture is considered to be the near future industry standard. PERC technology is a recent entry to the PV module marketplace, and its structure remains very similar to the conventional silicone solar architecture, with an incorporation of a rear passivation layer. This layer provides an increase of overall efficiency of PV cells by increasing light absorption and internal reflectivity, as well as decreasing electron recombination (Marsh, 2018). PV cells benefit from 0.8% up to 1% in efficiency with this technology (Sharavan & Chunduri, 2018).

Tandem or otherwise known as hybrid cells are a new emerging PV technology that is still mostly in the research and development phase (figure 5). Stacked individual cells form a tandem cell, where every stack converts a specific light band into energy. This technology has been used to create the most efficient cell thus far. The most efficient tandem solar cell has an efficiency of 46%, unfortunately this technology is still new and undeveloped and therefore is very expensive to manufacture. (Cherradi, 2019)

Thin film technology is considered a second-generation technology of PV technology. This technology is recently introduced in the market, with only 5% of total shares of worldwide PV energy production (IRENA, 2019). Thin film technology has been developed with rising prices of silicone and these cells are mainly non-silicone based, however recently amorphous silicon based thin film cells have been developed which are a far less common option. Perovskites are a non-silicon based thin film technology, which proved to be very good at light absorption and creating high-efficiency cells. Recent technologies have accomplished models with up to 26.7% efficiency. However, this technology faces durability problems, which must be addressed before market saturation. Perovskites crystals are easily soluble, which makes them not appropriate for humid conditions and high moisture conditions. If these problems can be solved by tight encapsulation with a low manufacturing cost, these cells have a potential to change the market dynamic. (Extance, 2019)

CIGS and CdTe cells are very similar in performance with both achieving comparable efficiency of 21% (Fraunhofer ISE, 2019). CdTe currently half the most market shares out of all thin film technologies, and this is due to a very simple and affordable manufacturing process (Cherradi, 2019). CIGS cells only hold 1-2% of the market due to indium supply dependence in the manufacturing process (Green, 2019).

One of the most important new innovations in PV technology for large scale utility electrical energy development are bifacial cells. Bifacial cells are capable of utilizing reflected light to create electricity, as seen of figure 6. Unlike their monofacial counterparts, these cells are capable of using both sides of the unit (figure 6), therefore vastly improving their efficiency. This technology has changed solar plants tremendously.

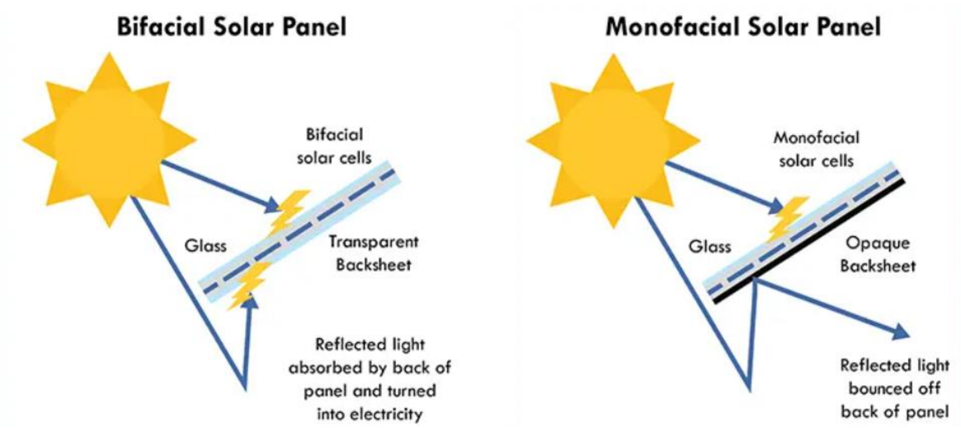

Figure 6. Bifacial and monofacial solar panel comparison (Coulee Energy, 2021)

These units use a heavy duty fully glass design, which incapsulates the solar cell from both sides. This not only enables the light to pass from all angles, but also provides a heavy-duty design that can withstand harsh weather conditions. Manufacturers of bifacial solar modules are using PERC technology to upgrade the efficiency of bifacial modules, providing them with a 5% to 20% efficiency increase (Fraunhofer ISE, 2019). Even though these cells have many upsides, they come with some downsides as well. Their high manufacturing cost and heavy weight due to a full glass encapsulation are their biggest downsides, these factors bring the installed cost a to very high level.

Solar technologies have made their advancements on the residential level as well. Some companies are currently offering solar shingles, which are constructed to replicate the style of conventional roofing tiles with solar energy generating capabilities. These modules are an attractive option because of their aesthetics, and they may become a viable option for residential buildings in the coming future.

2.3.2 Evolving solar module applications

The rapidly growing solar technology trend has led to a development of usage of solar technology beyond residential building rooftops and solar fields. Currently, many of these applications are in their development phase and they have never been used in practice, however some innovating solar applications are in their use phase currently, most notably floating PV plants.

Floating PV plants are a relatively new innovation, with real use cases emerging only about half a decade in the past. Floating PV plants have shown rapid growth since then, with many floating plants being installed in Asian countries, mainly China, Thailand and South Korea, where these plants have shown a potential for massive growth in the industry. The working concept is simple, PV modules are mounted on a floating platform, which is secured in place with concrete anchors. The generated electricity from these floating modules travels through an underwater power cable to a power cumulating system and from there to the electrical grid (figure 7).

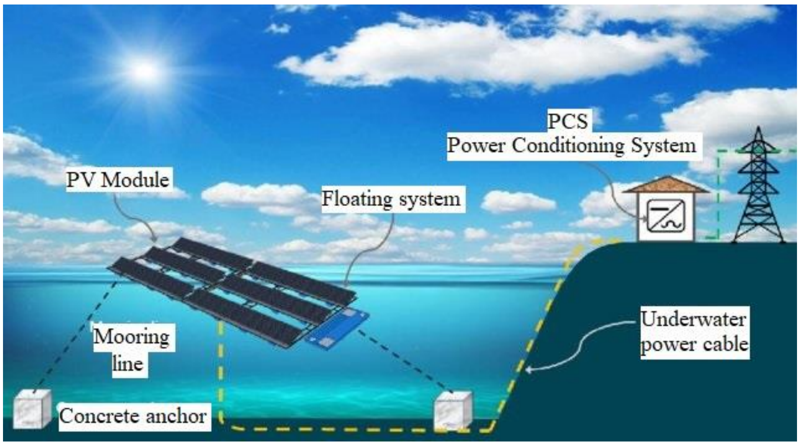

Figure 7. Floating PV systems concept scheme (Jeong, et al., 2020)

These plants benefit from not occupying land, potential of producing hybrid systems with wind and hydro energy and also energy storage opportunity. Apart from natural bodies of water, hydropower tanks as well as other artificial bodies of water have very good potential for floating PV plant utilization. Main downside of this system is the instalment cost, which is 20-25% high in comparison to land mounted systems, as well as maintenance complexity and long-term reliability due to natural causes (waves and fast winds) (Martin, 2019). Further research and development will lead to a solution of these technological downsides and common implementation in the electricity grid. Currently only a small number of floating PV plants are in use, and they only make up a small amount of energy generated by PV systems. The largest floating PV plant is currently in China in the Shandong province, this is a hybrid plant which combines wind and solar power, reaching an energy output of 320 MW. (Lee, 2022)

Integration of panels in building structure is another future concept that may be implemented with further development. Solar shingles, which have previously been introduced, are a technology that can be integrated in the roofing of buildings. Solar shingles provide active and passive benefits to the user. Active benefits are energy production, while passive benefits are acoustic and thermal isolation to the building, like many other building materials. Solar shingles have a potential to reduce the final construction cost as well, this is achieved through savings in separate cost for roofing materials and conventional solar modules, their transport and installation. Solar shingles offer an all-in-one solution, with only one transport and instalment bill, that can later produce zero emission energy. Furthermore, a newly developed project “PVSITES”, that is funded by the European Union, is developing solar modules that can be integrated in residential houses in places like walls, windows and roofs. Apart from modules, this project is developing software design tools to help architects implement these modules into the house layout. (IRENA, 2019)

Modern PV technologies are finding their way into seawater desalination. Currently, desalination plants are mainly operation on energy from fossil fuels, however recently the demand for water desalination has risen, making fossil fuels an unfitting long term energy source. This has sparked interest in renewable energy sources being used for this purpose. Membrane based desalination techniques (ex. reverse osmosis and electrodialysis), require no heat, therefore they can be used well with solar and wind power generation, however thermal techniques (ex. Multistage flash desalination) does require thermal energy and it can only be paired with photovoltaic-thermal (PV-T) technology. One of the first project using PV-T technology used in desalination has been built in United Arab Emirates. It is designed in a way where PV-T solar farms generate sufficient electrical and thermal energy to run the desalination plant 24/7, independent of the main electrical grid. (Cen, 2019)

The current trend of replacing internal combustion engine vehicles with hybrid and electrical vehicles has had an impact on the solar industry as well. Solar carports have appeared in recent years as a response to conventional fuelling stations. Solar carports are built with roof mounted solar modules which produce electrical energy for vehicle battery charging, as well as protecting the car from the sun. Solar carports are a new trend in the EU, which closely follows the trend of electric vehicle implementation.

Agrophotovoltaic (APV) is a term that is used to explain a symbiose between agriculture and PV technology. In this concept crops are grown on the same land where PV modules are placed, utilizing the land as much as possible. (Figure 8)

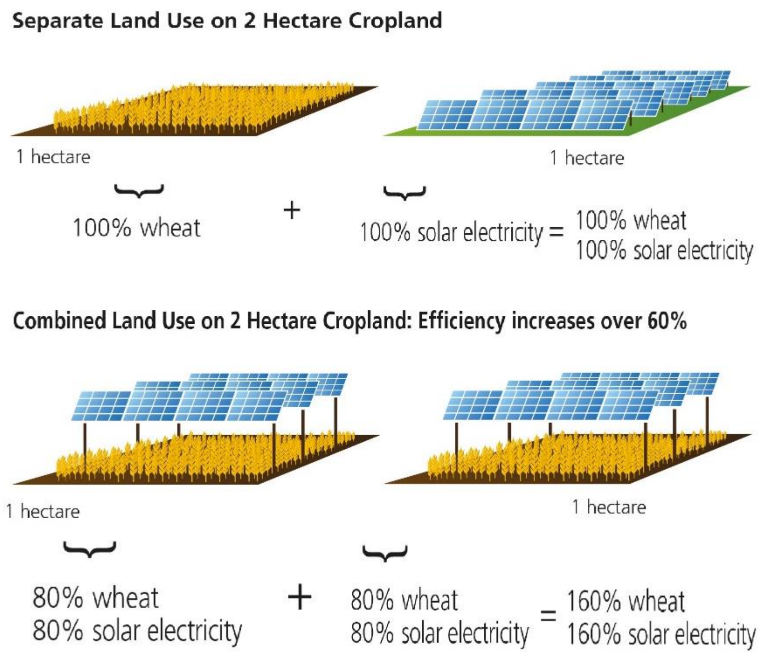

Figure 8. Agrophotovoltaic concept (Schindele & Hogy, 2017)

Concept of APV was introduced earlier, but its use cases have only appeared in the past couple of years. It is considered by several researchers that growing some crops beneath the shade can benefit the crop production and yield, while at the same time producing energy from the top mounted PV modules (Beck, et al., 2019). This technology proposes a successful solution for energy and crop production simultaneously. The crops benefits from growing in shade created by the modules, and the modules are cooled naturally through plant transpiration. This benefits very hot climates the most, where crops are kept out of the hot intense sunlight.

One APV concept located in Germany has shown 186% land use efficiency (Tsanova, 2019). Its structure consists of 194 kW of solar modules lifter 5 meters from the ground, with crops like celery, potatoes and wheat underneath. It showed very good performance results in hot and dry summer climate, due to the fact that the air temperature remained constant, while soil temperature was lower than without the APV concept. This results in the moisture content of the soil higher and a need of less often watering of crops. (Tsanova, 2019).

2.3.3 Future trends in operation and maintenance

PV plants are expected to maintain a high level of performance during its long life cycle. A typical life cycle for PV plants is about 20-35 years (IRENA, 2019).

Production of large-scale high power producing PV plants has developed a need for better maintenance and inspection tools. Monitoring of a system is one of the most basic actions that is essential for maintaining optimal operation parameters and monitoring of these large-scale PV plants requires development of new intelligent monitoring methods. One of the methods that has started its development process is intelligent drone monitoring. Drones are a staple in the video production industry and the already well-developed cameras on drones can be used for remote surveillance and monitoring of a large area covered by a PV plant. One of the things drones are used for are surveillance of PV module cleanliness and damage on modules. This monitoring can be done quickly and effectively with one drone pilot, which operates the drone through the PV plant, recording surroundings and later reviewing the recording. (IRENA, 2019)

Smart monitoring systems of plant performance parameters are a new innovation that helps engineers identify causes of performance decrease. These smart monitoring innovations are:

- Automated maintenance (preventative and emergency)
- Intervention management algorithms
- Algorithms for equipment and plant behavior predictions

These smart innovations are based on plant performance data, operation parameters and historical data of failure rate and various simulation models. (KIC InnoEnergy, 2015)

Excluding new smart maintenance innovations, some efforts have been made to reduce the maintenance interval. One of the main ways this is achieved is by cooling the PV modules. In his article “The importance of staying cool” (Filatof, 2019), the author has stated that “degradation of solar modules doubles for every 10ºC above ambient temperature (25ºC)”. Degradation is cause by chemical reactions in the solar module, reducing their lifetime and energy output.

One future approach to solve degradation due to temperature is applying a transparent silica coating to surfaces of cells. This coating captures heat from infrared ray and then radiates it back to the atmosphere and the benefits include an increase of 1% in absolute cell efficiency (IRENA, 2019). Studies from (Filatof, 2019) have found that the process of “Infrared Reflation and Radiative Transfers” can lower the module temperature by 3ºC. The concept behind this process is reflection of infrared wavelengths of light that the module cannot use before it even enters the module, after which the captured light is radiated to the atmosphere and cooler areas around the module. This process not only prolongs the lifetime of the solar module, but also has a potential to boost PV module efficiency with further development. (Filatof, 2019)

Significant part of solar module maintenance is keeping the solar module free of any surface contaminants. This problem varies dependent on the geographical location of the solar plant and the climate it is located in. Soiling of the glass surface of solar module can heavily influence the amount of light that passes through, therefore influencing the overall power output of solar modules. PV plants in North Africa and the Middle Eastern Asia region, where sandstorms can be common, are currently battling with this problem the most. Most PV plants in the region cannot use sprinkler cleaning systems due to water scarcity and easily clogged spraying nozzles due to sand particles. A current solution for this is robotic cleaning, where a robotic cleaning device in set on rows of PV modules and simply passes on the surface of the module and cleans the module. However, this is not considered a long-term solution, therefore anti-soiling coatings are being developed. Most developed coatings are TiO_2/SiO_2 based hydrophilic gel films, TiO_2 hydrophilic evaporation films and functionalized- SiO_2 hydrophobic films. These coatings perform differently in different climates and locations. (Moraes Lopes de Jesus, et al., 2019)

3 Literature review

Multi-criteria decision-making (MCDM) models are used and studied since the 1960s. These models have been thoroughly researched in many different fields, developing many different MCDM models with different decision-making methods that are unique to the field that they are developed for. MCDM models are used by engineers in the renewable energy sector and with the extensive use and development in the renewable energy sector, these models can be commonly found used in plant development decision making scenarios. Commonly used MCDM models that are used in the renewable energy sector are suited for supplier selection problems, plant design problems, plant location problems, etc.

MCDM models have been used in an article published by (Wang, et al., 2021), where a model has been used for an appropriate selection of a suitable renewable energy source that is going to be used for energy production in a specific area. A combination of Grey Systems Theory (GST) and Analytic Hierarchy Process (AHP) was used to calculate criteria weight and Weighted Aggregates Sum Product Assessment (WASPAS) method to rank the different renewable energy options. This study has been done with an end goal of assessment of the best renewable energy source for different locations in Vietnam, a country which showed a very good potential for all renewables. A similar AHP model which was developed by (Haddad, et al., 2017) applied to assess and rank renewable energy options for Algeria. In this report the model has shown solar energy as the most favourable source for energy generation in Algeria, which has a goal to be 40% renewable by 2030.

Optimal selection of PV plant location is a common modern research topic and many MCDM models are being developed for this topic. Many different criteria come in question for solar plant development, some of them being geography, climate, economical question, ecological risks in the area, and many of these are conflicting. AHP method based models have been developed by (Ibrahim, et al., 2021), which have been used in a study paper regarding PV plant location selection in the Duhok province in Iran. Geographical Information Systems (GIS) method is a commonly used method for MCDM model for this topic as well, one of them being researched by (Zambrano-Asanza, et al., 2021). A combination of GIS method and AHP method was used by (Al Garni & Awasthi, 2018) in their report which focuses on utility-scale PV plant location. This detailed model takes into consideration many restrictions and considers irradiation of modules the most important criteria for utility-scale PV plant location selection, closely followed by ease of connection to the grid, gradient of land, proximity to protected lands etc.

Choosing By Advantages (CBA) method model was utilized in a research paper by (Goh, et al., 2021) for site selection and development of large-scale PV plants in California. These methods for PV plant site location selection models, as well the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) and fuzzy MCDM approaches, have been review and compared by means of performance results is a study paper by (Ghasempour, et al., 2019). A MCDM model by (Rediske, et al., 2020) is a model for evaluation and classification of best location for solar farm implementation in Brazil. This model uses GIS, a combination between AHP and TOPSIS as well as sensitivity analysis to evaluate the locations. This methodology is very modifiable and can be used by researchers on different areas apart from Brazil. A location planning report by (Tavana, et al., 2017) has used a three-stage fuzzy evaluation framework which has a goal to locate solar farms. First step uses Adaptive Neuro Fuzzy Interference System (ANFIS) in order to provide coherent approximations for every location, followed by fuzzy AHP method which is utilized to weight decision criteria. Finally, a fuzzy inference system is applied for site selection.

An original MCDM model for PV module selection in Buildings has been developed by (El-Bayeh, et al., 2020), which uses the TOPSIS method for ideal alternative selection. This study is aimed more towards module selection for residential buildings, and not large-scale PV plants. Optimal design of a standalone PV system has been studied by (Ridha, et al., 2021). In this paper the authors have used a large array of methods for the final system design selection and these methods are aimed more for standalone systems and not for ones that are grid connected. In fact, only one recent study was found regarding layouts of utility-scale grid connected plants. A research paper by (Zidane, et al., 2020) has used a method for utility-scale PV plant layout design in Algeria. This method used is not directly a MCDM method itself, but a hybrid method which is executed by taking advantage of available data of the location for optimal plant design.

Apart from location selection some MCDM models for optimal sizing have been developed as well. One of them has been developed by (Alsayed, et al., 2014), with no recent inquires on this topic. This model is used for optimization of size of a hybrid PV and wind turbine system, which is considered to be a very efficient hybrid system for energy production.

Solar carports, as one of the future uses of PV technology have started being built in some developed countries. A similar location decision problem is relevant with building solar carports. A MCDM model has been developed by (Zhou, et al., 2020), which uses TODIM (Portuguese acronym for Iterative Multi-criteria Decision Making) and GIS to choose an optimal construction site. The specific model in the report is focused on the Beijing area.

4 Multicriteria decision making model design

Many types of multicriteria decision making (MCDM) models have been developed for the renewable energy industry, many of which are presented in the Literature Review chapter. Most of the MCDM models that have been developed focus on selection of the best location for the PV plant and others focus on the ideal renewable energy source selection for large scale energy production in a specific area. An insignificant number of models have been developed for alternative selection itself, therefore a tool for assistance in alternative selection is needed.

In the development and design process of a PV plant, modern software tools provide engineers with multiple conceptual solutions to the design problem, with all solutions having different design parameters. In this section, a MCDM model with a focus on the selection of the ideal conceptual solution alternative in the process of PV plant design will be developed. However, before the model itself is developed it is crucial to list components that make up a large-scale PV plant, which are going to be one of the differences of said alternatives, as well as the criteria on which the final ranking will be conducted.

4.1 System description

Large scale PV plants are complex units that are made up from many different components that work simultaneously to produce electrical energy and deliver it to the electricity grid (figure 9). All solar plants contain the following major components:

- PV modules
- Inverters, transformers and other major equipment
- Energy storage units
- Transmission towers and power lines
- Other components (such as monitoring stations)

All of these components have a specific purpose, and it can be arranged in many different ways, hence different alternatives created by software solutions.

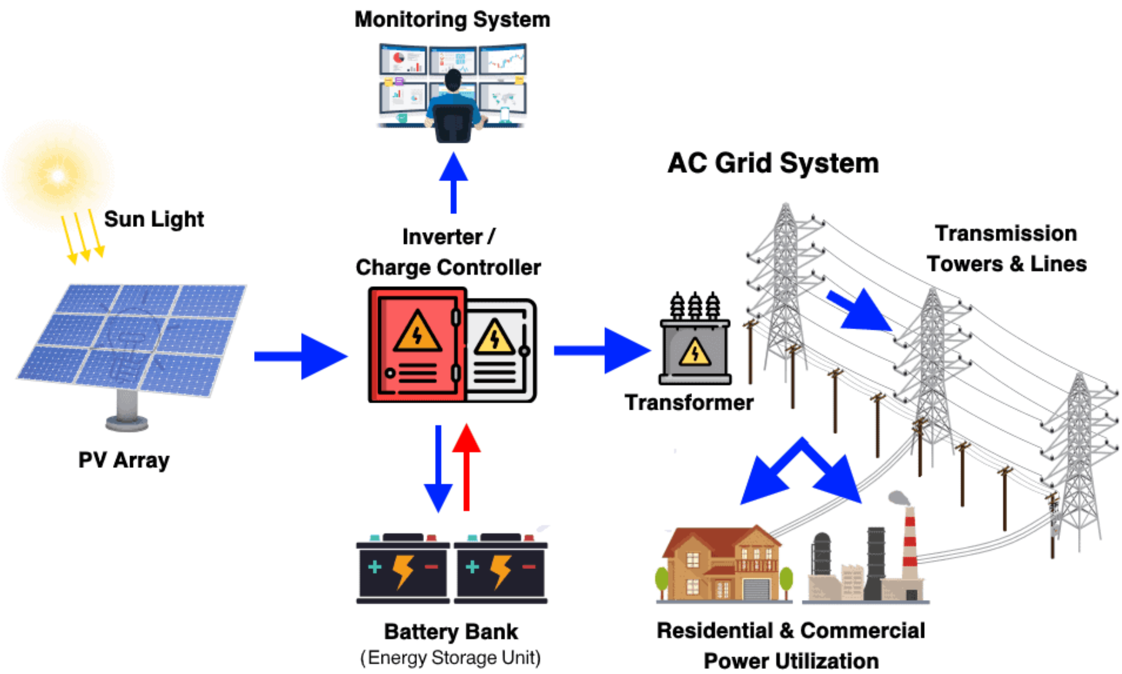

Figure 9. Components of a photovoltaic plant (Electrical Technology, 2018)

Modern large scale PV plants are designed using modern software tools which provide engineers with conceptual design solutions and detailed analysis capabilities of solar PV plants. These software tools are capable of analysing many location parameters (irradiance, sun position, detailed terrain models etc.) to provide engineers with design assistance, problem solutions as well as final alternatives of the design task. Apart from design, these tools are capable of simulations as well, which can assess parameters such as the energy output of PV plants.

Alternatives that are provided from software tools can differ in many areas, some of which are:

- Type and amount of PV plant hardware components
- Layout of plant components
- Pitch of modules and distance between arrays
- Performance and operation parameters
- Technical parameters (such as total installed power)

The model which is developed in this paper is focused on finding the best conceptual solution alternative provided by a software tool for an already pre-existing fixed location, therefore all alternatives will have PV plant components divided upon the same property which is strictly dedicated to the plant itself. Alternatives are different in other areas that are listed and are reviewed and ranked based on key criteria.

4.2 Criteria definition

Criteria for model development have been divided into three main criteria groups, all addressing criteria from a different aspect for the best alternative selection. The criteria groups are:

- Economic criteria – equipment and operation cost alongside economic indicators
- Technical criteria - technical parameters along with performance indicators
- Environmental criteria – impact of the PV plant on the environment during its entire life cycle

All of these criteria groups contain several criteria within them. (Figure 12)

4.2.1 Economic criteria

Economic investments in the project are a significant criterion for alternative selection. Most projects have a fixed budget that needs to be followed and investment fund planning is one of the first problems most project engineering teams face. Economic criteria are often the most important criteria for investors.

Economic criteria selected for this model are:

- Initial investment cost
- Cost of operation
- Levelized cost of electricity (LCOE)
- Net present value (NPV)
- Internal rate of return (IRR)

All of these criteria are quantitative and are therefore simple to weigh and comparison between alternatives is straight-forward.

Initial investment cost criterion covers the cost of major PV plant equipment, mounting, connection to the electrical grid and preparation of the land for the project itself. Alternatives can have a vastly different initial investment cost depending on the amount of equipment being installed, price of the equipment, ease of terrain access, ease of land preparation, ease of connection to grid and many more factors. Initial investment cost is an important criterion because often there is a limited budget intended for the project. When designing the PV plant, the engineers must take into consideration the budget and work with it to get the best results possible. A higher initial investment cost will result in a higher LCOE, which can make PV plants an undesirable option for investors.

The other cost that needs to be considered is the cost of operation during the life cycle of the PV plant. This criterion covers the maintenance and repair cost, as well as the cost for replacement equipment in case of equipment failure. Not all components of PV plants have the same life expectancy. PV modules have the longest expected lifetime of about 30 years while inverters have an average expected lifetime of about 10-15 years (Sangwongwanich, et al., 2017). This means that the inverter will likely need to be replaced at least once during the PV plant lifetime, further adding to the economic expenses that are accumulated during the life cycle of a PV plant. This cost influences LCOE as well, a higher operation cost will result in a higher LCOE.

An economic criterion that is related to the investment cost, but still carries significant value for making solar energy a viable option is LCOE. It has many definitions, however the most common one is: - “LCOE is a measure of average net present cost of electricity generation for an energy generating plant over its lifetime” (Sing & McCulloh, 2017). LCOE for solar power is calculated with equation 1, this equation has been derived by (Kost, et al., 2021).

$$LCOE = \frac{sum\ of\ costs\ over\ plant\ lifetime}{sum\ of\ energy\ produced\ over\ plant\ lifetime} = \frac{I_0 + \sum_{t=1}^{i} \frac{M_t}{(1+i)^t}}{\sum_{t=1}^{i} \frac{E_t}{(1+i)^t}} \quad (1)$$

Where the parameters are:

- I_0 – investment cost [€]
- M_t – maintenance and operation cost [€]
- E_t – energy generated [kWh]
- i - discount rate
- t – time period of calculation

This equation takes into consideration the investment costs, maintenance and operation costs, electricity produced, as well as the discount rate and lifetime of the power plant, all calculated in a specific time interval (most commonly one or several years). It is important to take into consideration the degradation of the PV modules. After a certain period of use, the PV modules start to degrade, lowering their efficiency which results is less energy produced per year and a higher LCOE. Degradation rate of PV modules is influenced by factors such as the quality of equipment used on plant. High operation costs over the plants' lifetime increase LCOE, and these values are therefore proportional. The end goal is to keep the LCOE to a minimum to make solar energy a viable renewable energy source compared to other low LCOE renewable energy sources like hydropower.

Net present value (NPV) is significant to project investors. It is utilized to evaluate profitability potential of the project, which in this case is a PV plant. The definition of NPV is that it is the difference between the present value of cash inflows and cash outflows in a specific time period. It is calculated with equation 2. (Jagerson, 2022)

$$NPV = \sum_{t=1}^{n} \frac{R_t}{(1+i)^t} - I_0 \qquad (2)$$

Where the parameters are:

- R_t – net cash flow [€]
- i – discount rate
- I_0 – initial investment cost [€]
- t – time period of calculation

A positive NPV is desired and projects with a higher NPV are more desirable for investors.

Internal rate of return (IRR) is closely related to NPV and is a metric important for the investor of the project. IRR is used to estimate the return of investments and it takes into consideration the time preference of investments. In reality, IRR is the discount rate that makes the NPV equal to zero, therefore it is calculated with equation 3. (Fernando, 2022)

$$0 = NPV = \sum_{t=1}^{n} \frac{R_t}{(1 + IRR)^t} - I_0 \quad (3)$$

Where the parameters are:

- R_t – net cash inflow [€]
- I_0 – initial investment cost [€]
- t – time period of calculation

When comparing projects, usually projects with the highest IRR are the most desirable for investors.

Table 1. Economic criteria

Economic criteria			
Criterion	Type	Goal	Unit
Initial investment cost	Quantitative	Minimize	€
Cost of operation	Quantitative	Minimize	€/year
Levelized cost of electricity	Quantitative	Minimize	€/kWh
Net present value	Quantitative	Maximize	€
Internal rate of return	Quantitative	Maximize	%

4.2.2 Technical criteria

Technical criteria for decision making take into consideration the technical aspect of the plant and this criteria group contains both quantifiable and non-quantifiable criteria.

Technical criteria in this group are:

- Total installed power
- Annual energy output
- Shading effect of PV modules
- Specific yield
- Total land area covered
- Convenience of expansion
- Ease of cable layout
- Ease of maintenance

Total installed power is a significant aspect that affects the final energy output of the plant itself. It can differ significantly depending on PV module technology that is used as well as the number modules. Total installed power is DC power, measured in kWp (kilo-watt-peak) and all PV modules have a factory rated power.

Most PV plant project have a set performance goal that needs to be fulfilled by the engineering team before the plant is even constructed. Annual energy output of the system is a key aspect of all PV plants, and this aspect fulfils the set performance goal of investors. Higher energy output implies higher revenue, which is a very significant factor for investors of the project. Annual energy produced is related to LCOE and indirectly to other economic criteria like NPV and IRR, which are significant for investors. This parameter is used in LCOE calculation. A higher energy output will result is a lower LCOE value, making solar energy a greater competitor to other renewables. A higher energy output can be achieved by using equipment with a higher efficiency factor, PV modules and inventers being the most important ones.

Shading effect of the PV module is a significant aspect of energy production. Exposure to sunlight during the entirety of the sunlight period of the day will result in a larger energy output, while shading will significantly reduce the performance of PV modules. Proper PV module row placement, distance between rows, orientation of modules and the tilt angle of the modules are some of the factors that affect shading of modules.

Specific yield is a criterion that takes many factors into consideration. It calculated as the total energy generated by the plant per installed power, and it is calculated with equation 4.

$$Yield_{sp} = \frac{E_{plant,tot}}{P_{plant,ins}} \quad (4)$$

Where the parameters are:

- $E_{plant,tot}$ – total energy generated by the PV plant [kWh]
- $P_{plant,ins}$ – installed power of PV plant [kWp]

It is measured in kWh/kWp (kilo-Watt-hour/kilo-Watt-peak). This criterion takes into consideration the shading effect of the module, the modules sensitivity to high operating temperatures and low light conditions, effectiveness of tracking technology and losses in the inverter. It gives engineers a quantifiable parameter for actual operating results and shows and compares different solar technologies while taking into consideration sub-optimal working conditions.

All alternatives are going to be reviewed are created in a plant design program PVsol. These programs form alternative software solutions with vastly different designs which use the same provided land area in different ways. Modules are mounted in different ways with different distance between rows, row angles and module tilt angles all producing a different energy output. These differences result in a different use of land that is meant for the solar plant, with some configuration using the space more efficiently than others. Total area covered by the modules is an important aspect that ties closely to total installed power. More area covered in most cases implies that more modules are installed and therefore more power installed.

Apart from the total covered area by solar modules, different layouts can provide easier expansion opportunities than others. This is a factor that comes into play if investors would like to expand the project and install more power, which in many new utility-scale PV plant is the case. Arrays that are placed in-line and parallel are easily expandible because no major layout changes need to be made and expansion is straight-forward.

In-line and parallel arrays provide easier setups for cables and power lines in the construction process as well. If arrays are mounted in different angles due to landscape or other factors, cable layout management can become expensive and complicated, therefore layouts with straight parallel arrays are preferable in the design process.

Maintenance and cleaning are two aspects of plant operation that need to be taken into consideration. As stated in previous segments, soiling of the modules can greatly affect their efficiency and the total energy production, so regular cleaning of modules is key for optimal performance. Cleaning can be needed in any time, sometimes caused by soiling from an unexpected weather condition, therefore ease of maintenance is an aspect that needs to be considered. Repair maintenance and regular maintenance are essential for optimal plant operation and simple, low-cost maintenance is well appreciated. Ease of maintenance on a plant can also bring the operation cost of the plant down significantly.

Table 2. Technical criteria

Technical criteria			
Criterion	Type	Goal	Unit
Total installed power	Quantitative	Maximize	kWp
Annual energy output	Quantitative	Maximize	kWh/year
Shading effect of PV modules	Qualitative	Minimize	-
Specific yield	Quantitative	Maximize	kWh/kWp
Total land area covered	Qualitative	Maximize	-
Convenience of expansion	Qualitative	Maximize	-
Ease of cable layout	Qualitative	Maximize	-
Ease of maintenance	Qualitative	Maximize	-

4.2.3 Environmental criteria

Environmental awareness is one reason renewable energy sources are used for energy production currently. Even though PV plant do not produce any greenhouse gas emissions during their operation phase, they still have an environmental impact that needs to be taken into consideration.

Environmental criteria in this group are:

- Reduction of greenhouse gas emission
- End-of-life waste management

- Impact on local vegetation

The first criteria that needs to be taken into consideration is the total amount of greenhouse gases that is reduced by using electricity generated by solar plants. By burning fossil fuels to produce electricity a certain amount of greenhouse gasses is produced. The first criteria will take into consideration how much of greenhouse gas emissions is reduced by using a specific alternative of a PV plant compared to a conventional coal-fuelled plant, for the same amount of generated electricity. This criterion is important, as it ties indirectly to environmental preservation and following emission regulations. Many regulations regarding greenhouse gas emissions in the energy sector are currently in order in the EU, with a final goal of decarbonising the energy sector by at least 55% by 2030 and making it climate neutral by 2050. (European Commission, 2021)

An average expected lifetime of PV modules is about 25-30 years (IRENA, 2016). After this period the PV modules need to be handled properly, therefore an end-of-life plan for the PV modules needs to be established. IRENA has predicted that by 2030 the waste generated from end-of life PV modules will be about 80 million tonnes, which is a significant amount of waste that needs to be handled. By 2050 this amount is predicted to be around 60-78 million tonnes (IRENA, 2016). All PV modules include toxic materials such as cadmium and lead, therefore the disposal process is somewhat difficult and the total amount of panels that need to be disposed is a factor in the final alternative choice. The mounting mechanisms and other equipment need to be recyclable or reusable in some way as well. If that is not possible a proper harmless disposal plan needs to be established for the substructures as well.

While PV plants make a positive environmental impact in terms of clean energy production, their construction process and overall layout on the selected location can have a significant impact on the surrounding microclimates that effect vegetation growth. Increase of in surface temperature and air temperature as well as changes in land irradiation and humidity take place in locations where PV modules are placed over vegetation. These changes effect local vegetation poorly and to reduce impact, PV plant layouts need to be designed to keep optimal air flow and shade to keep temperatures on the same level as before the placement of PV modules. (Vervloesem, et al., 2022).

Table 3. Environmental criteria

Environmental criteria			
Criterion	Type	Goal	Unit
Reduction of greenhouse gas emission	Qualitative	Maximize	-
End-of-life waste management	Qualitative	Minimize	-
Impact on local vegetation	Qualitative	Minimize	-

4.3 Multicriteria method selection

In many past scientific reports MCDM models have been developed regarding PV plants. One of the most repeatedly used methods in literature has been AHP, as can be seen in the literature review. This method has been proved useful by engineers and analysts in literature because of its ability to handle complex decision problems. The AHP deconstructs difficult decisions into a sequence of simple comparisons which are ranked in a hierarchy. It creates a hierarchical structure for the decision problem with higher levels of the hierarchy representing the end goal and lower levels are consisted of all possible alternatives (figure 10). In the case of this model, the end goal is a best possible design solution, while all design alternatives are located in the lowest hierarchy level.

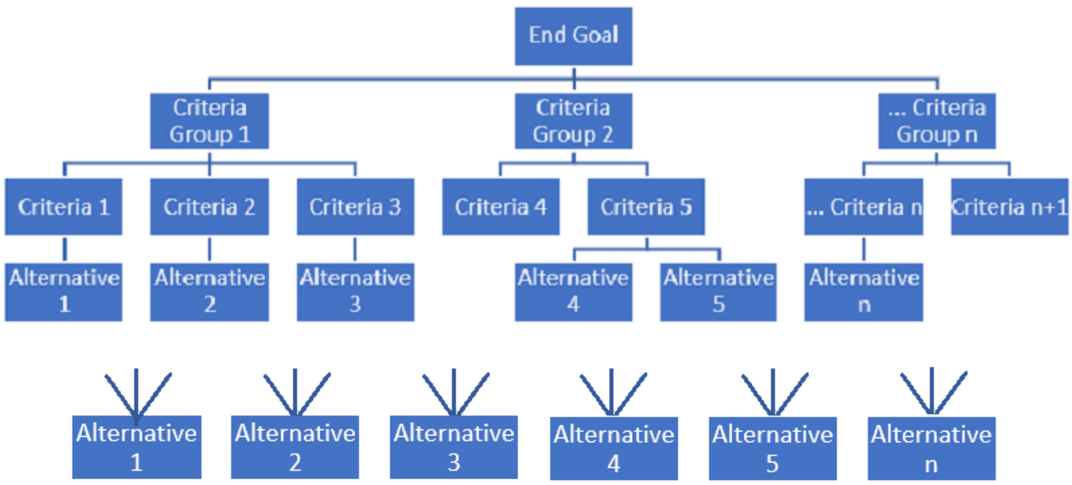

Figure 10. AHP hierarchy

In AHP, the criteria are organized in criteria groups that are relevant to each other in nature. These sub-criteria can be relevant in many different manners, in an example for this model, the criteria group is “Economic criteria”, while criteria are “LCOE”, “Initial investment cost” and “Cost of operation”. Alternatives are listed on the lowest part of the hierarchy, and they are influenced and connected to all criteria. It is important to know that AHP hierarchies can have many different criteria groups and alternatives (n number of criteria).

Apart from past examples in literature, AHP has been chosen as the appropriate method in this case because of its advantages compared to other methods, which are:

- Both qualitative and quantitative aspects of the problem or criteria can be considered
- Simplification of a complex task by using a hierarchical framework
- It measures consistency in judgement – consistency ratio (CR)
- Comparison matrices allow the criteria weights to be derived from pairwise comparison
- Large number of criteria can be used and listed in criteria groups similar in nature

The development process of a AHP model is done in several steps. The steps are shown in figure 11.

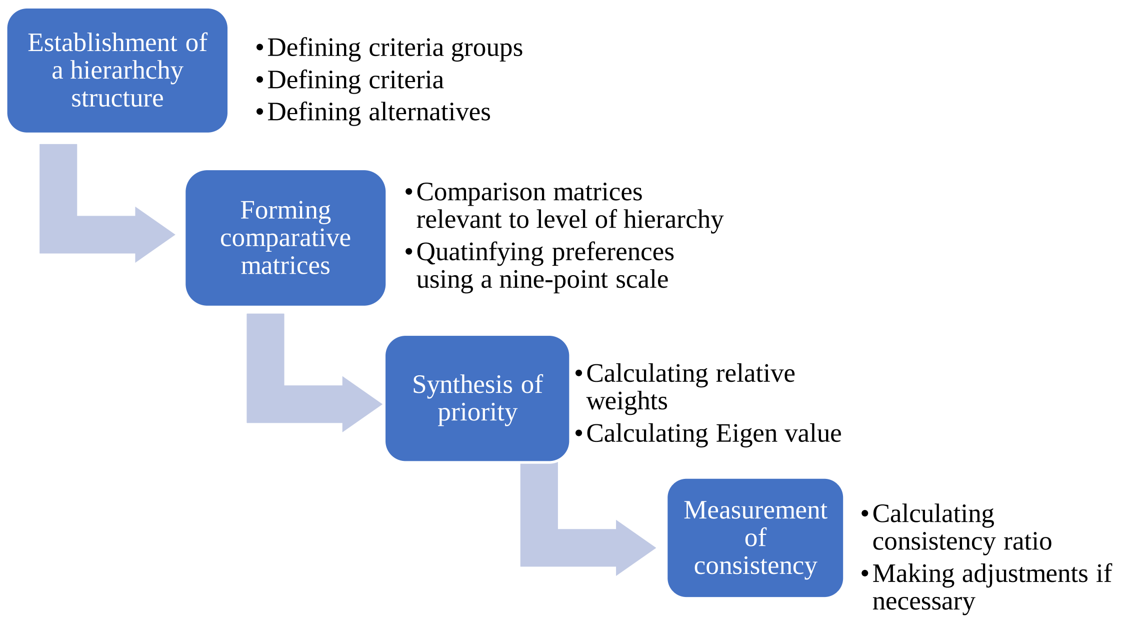

Figure 11. AHP model development steps

After these steps, the criterion weights and relative weights are obtained, after which the ranking process of the alternatives takes place.

First step of the AHP model creation is visualising the hierarchy structure itself. At the highest point of the hierarchy is the end goal, a best conceptual solution. Next step down of the hierarchy are criteria groups that have been listed in paragraph 4.2, and below that the criteria which have been listed in the sub-paragraphs of 4.2. In the lowest portion of the hierarchy, alternatives are listed, in this case four alternatives are listed. This hierarchical structure is shown on figure 12.

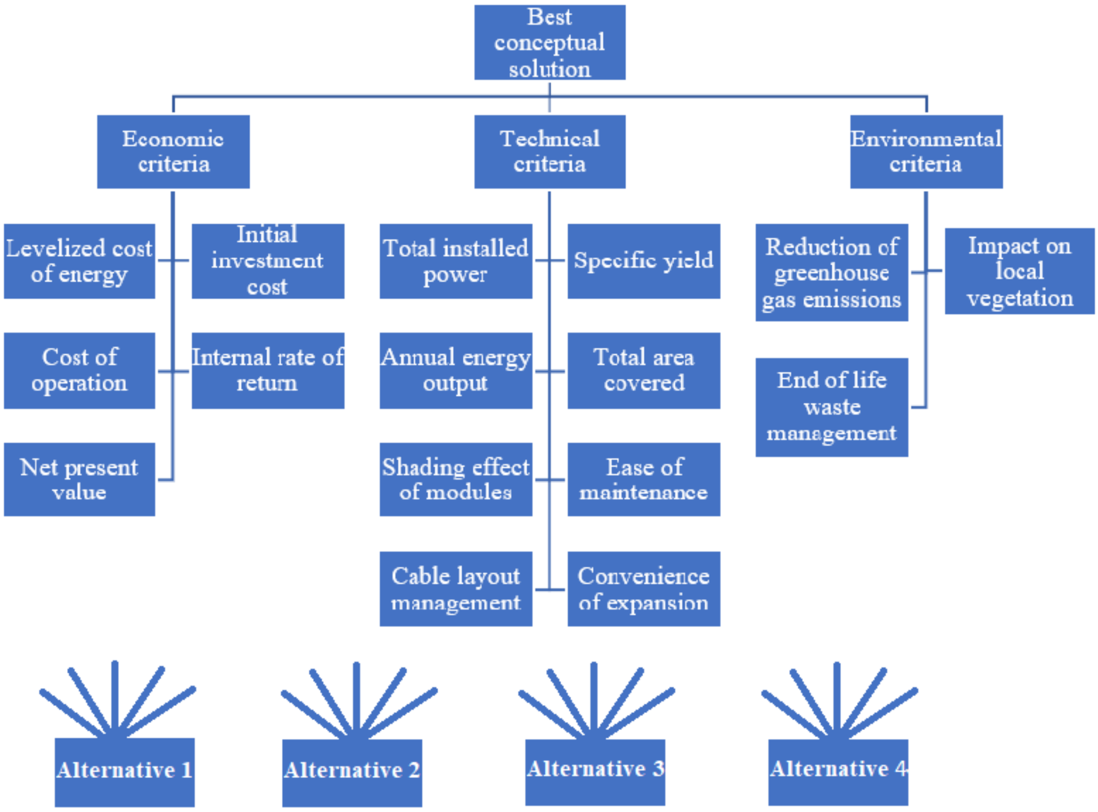

Figure 12. AHP model hierarchy for this problem

After a hierarchical structure has been established, the following step is forming the comparison matrices. Comparison matrices will be established between criteria of all individual criteria groups and between the criteria groups themselves. An example of a comparison matrix is presented in table 4.

Table 4. Comparison matrix example

	Criterion 1	Criterion 2	Criterion 3	Criterion 4	Criterion 5
Criterion 1	**1**	a	b	c	d
Criterion 2	1/a	**1**	e	f	g
Criterion 3	1/b	1/e	**1**	h	i
Criterion 4	1/c	1/f	1/h	**1**	j
Criterion 5	1/d	1/g	1/i	1/j	**1**

A comparison matrix is constructed with criteria along the vertical columns and horizontal rows and their value of preference in the table (values a-j in table 4). When compared to each other, criterions are defined with a number 1-9, dependant on preferences when comparing one criterion other. Each number represents a different meaning that is assigned by the user of the model or derived from experts' opinion on the topic. The values are explained in table 5. (Saaty, 2008)

Table 5. Definition of comparison matrix values (Saaty, 2008)

Intensity of importance	Definition
1	Equally preferred
3	Moderately preferred
5	Strongly preferred
7	Very strongly preferred
9	Extremely preferred
2, 4, 6, 8	Intermediate values

After matrix establishment, normalized weights and Eigen value are calculated. Normalized or relative weights are calculated by dividing each entry with the sum of its column, after which each entry is expressed as a percentage of its sum. The normalized principal Eigen vector (also known as priority vector) is calculated by averaging all values for every row. (Teknomo, 2006)

By doing this any small inconsistencies in decision-making are corrected. To check for these inconsistencies, Principal Eigen value (λ_{max}) needs to be calculated. To obtain this value a sum of products between each element of Eigen vector and the sum of columns of the reciprocal matrix. (Teknomo, 2006)

To check consistency in judgment, consistency ratio is calculated. Consistency ratio (CR) is calculated taking into consideration the Principal Eigen value λ_{max} and random consistency index (RI). Value of RI is obtained from table 6 and it is relative to the amount of criteria (n).

Table 6. Random consistency index values (Golden & Wang, 1990)

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

Consistency ratio takes consistency index (CI) into consideration. CI is calculated using equation 5.

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{5}$$

Where the parameters are:

- λ_{max} – maximal principal Eigen value
- n – size of matrix

After obtaining the value for CI, CR is calculated using equation 6.

$$CR = \frac{CI}{RI} \tag{6}$$

Where the parameters are:

- CI – consistency index
- RI – random consistency index

For the judgement to be consistent, the CR should be below 10%, if that is not the case, weight values of criteria need to be altered to adjust the CR below the set value.

Following these steps are comparison matrices for all alternatives and criteria, followed by ranking of alternatives in relation with all criteria group and criteria weights.

5 Practical application

Renewable energy sources, mainly hydro energy, have been in use as an energy source in Bosnia and Herzegovina for several years. The potential for utility scale energy production using solar energy has only been researched for the past 10-15 years. Solar energy production potential has been noticed in some regions of the country, making solar energy a viable option, and giving it a competitor status to hydro energy, which is a well-established and often used energy source in Bosnia and Herzegovina. Many companies have started designing utility scale PV plants recently, one of which is the author of a project that will be used in this model.

This developed model is further applied on a practical problem on a project by a public energy generating company based in Bosnia and Herzegovina, which is named "Company 1", for privacy reasons requested by the company. The project is an ongoing project, that is estimated to be built in the near future, on already provided land in Bosnia and Herzegovina. For privacy reasons, requested by Company 1, the said project is referred to as "Project 1" instead of the given project name. All technical data for the project as well as design alternatives have been provided by the company for accurate model implementation. Sections of figures, which have been provided by Company 1 and have sensitive information or classified data is blurred.

5.1 Technical description of PV plant project

Many different locations for construction of a solar plant have been researched by Company 1, one of which is the location that has been chosen for the construction of this project. Irradiation measuring equipment has been placed in various locations throughout Bosnia and Herzegovina to determine an optimal location for a project in 2010 and after 67 months of weather research, a location has been chosen. Solar potential research for the region that Project 1 in being constructed on has been found sufficient in terms of irradiation and ease of access, with solar irradiance having an average value of 1.530 [kWh/m^2]. (Company 1, 2021)

The location of the project near a local mine and the land provided for the project is a former waste-rock and sand disposal location for that mine. Orientation of the location is northwest-southeast, and it is accessible to heavy machinery and trucks with local tarmac roads, as can be seen on figure 13. The provided location is in close proximity to the electrical grid lines, making it easily connectible to the grid.

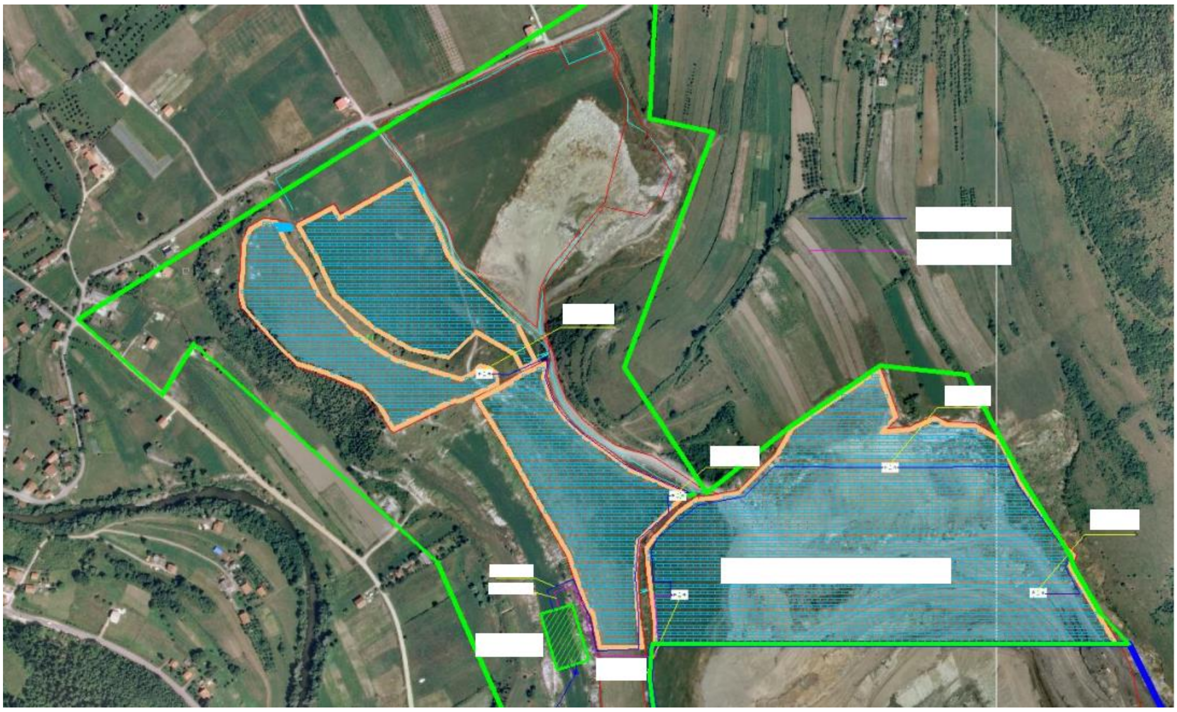

Figure 13. Project 1 location (Company 1, 2021)

The provided land has an area of 27 hectares divided in 4 sections (figure 13) and is relatively flat, with the different between the lowest and highest point of the ground being about 6 meters (figure 14). The landscape is covered in low rising grass, a very small amount of trees and no other major vegetation or animal habitats. Land preparation will not require major landscape alterations, therefore construction of the PV plant will only slightly impact the local flora and fauna.

Figure 14. Project 1 landscape photo (Company 1, 2021)

The energy generated by this project will be transported via local electrical substations and power lines. Updates will be needed for some local electricity substations to make the grid connection optimal and make the supply for major industrial areas possible. For all expenditures planned an additional electrical substation will need to be built. Project 1 will have an estimated installed power (AC) of 22 MW. It is important to say that for this project a fixed supplier of major PV plant components is used, therefore all alternatives will have the same model of PV module, inverter and other equipment.

The equipment that has been chosen for Project 1 has the following specifications:

- PV modules have an estimated power of 540Wp and dimensions 1.133 x 2.256 mm
- Inverters are centralized container-design units with an integrated transformer (0,66/35 kV)
- Fixed angle of modules – no tracking mechanism

The modules will be mounted at a 30^{o} angle against the horizon and the module arrays will be facing the south.

The equipment specifications used in all alternatives have been provided by Company 1 in the technical description (Company 1, 2021).

5.2 Multicriteria decision making model implementation

The MCDM model that has been developed in this thesis is fit to be implemented for instances, where there are no more than four alternatives. The model has been divided into five main groups spread across multiple sheets:

1. Comparison matrices of criteria groups with respect to the goal
2. Comparison matrices of sub criteria with respect to the corresponding group
3. Comparison matrices of alternatives with respect to each criterion
4. Supplementary sheet – Economic criteria calculation
5. "Summary" sheet – Overview of results and ranking of alternatives

The supplementary sheet is aimed for assistance in calculation of economic parameters LCOE, NPV and IRR, in case the used does not have direct data. The parameters are calculated using equations (1), (2) and (3), as well as the information for the initial investment cost and annual energy output. Information provided in this sheet is used as references for comparing alternatives based on economic criteria in the following sheets.

Traditionally, AHP models use a set of criteria which are not dependant on each other, however in this case, some criteria are contained in other criteria and are therefore dependant. This will be resolved during criteria weight determination, where preference will be given to certain criteria based on companies' needs and financial limitations.

5.2.1 Criteria groups and criteria comparison matrices

In the first steps the weighing of criteria groups has been done. A comparison matrix 3x3 has been assembled (table 7). Technical criteria are most preferred, being moderately more preferred than economic criteria and strongly preferred to environmental criteria. The preferences this comparison matrix have been adjusted to fit the needs for the company.

Table 7. Criteria groups comparison matrix

	Economic criteria	Technical criteria	Environmental criteria
Economic criteria	**1**	1/3	3
Technical criteria	3	**1**	6
Environmental criteria	1/3	1/6	**1**

After this step, each criteria groups' criteria have been compared to others, determining the weights of all criteria. This can be seen on the following tables.

Table 8. Economic criteria comparison matrix

	Initial investment cost	Cost of operation	Levelized cost of electricity	Net present value	Internal rate of return
Initial investment cost	**1**	5	1/4	1/4	1/4
Cost of operation	1/5	**1**	1/5	1/9	1/9
Levelized cost of electricity	4	5	**1**	1/2	1/2
Net present value	4	9	2	**1**	1
Internal rate of return	4	9	2	1	**1**

The most preferred economic criteria are NPV and IRR, which are equally preferred to each other. These parameters take into consideration the initial investment cost as well as the cash flow and are indirectly associated with some working parameters like annual energy production. They are followed by LCOE, which is followed by initial investment cost. The least preferred economic criterion is cost of operation.

Table 9. Technical criteria comparison matrix

	Total installed power	Annual energy output	Shading effect	Specific yield	Total land area covered	Convenience of expansion	Ease of cable layout	Ease of maintenance
Total installed power	**1**	1/2	2	1/2	3	3	3	3
Annual energy output	2	**1**	3	1	5	6	6	4
Shading effect	1/2	1/3	**1**	1/3	2	3	3	2
Specific yield	2	1	3	**1**	5	6	6	4
Total land area covered	1/3	1/5	1/2	1/5	**1**	2	2	1
Convenience of expansion	1/3	1/6	1/3	1/6	1/2	**1**	1	1/3
Ease of cable layout	1/3	1/6	1/3	1/6	1/2	1	**1**	1/3
Ease of maintenance	1/3	1/4	1/2	1/4	1	3	3	**1**

The most significant technical criteria are specific yield and annual energy output. Annual energy output is a parameter that effects many other criteria, mostly economic ones. A higher energy output carries a potential for higher profit and a higher amount of clean energy distributed in the grid. This parameter as well as total installed energy are included in the formula for specific yield (equation 4), which delivers an important ratio of produced energy and installed power. These criteria are followed by the remaining qualitative criteria, which are layout based. The least preferred ones are ease of cable layout and convenience of expansion

Table 10. Environmental criteria comparison matrix

	Reduction of greenhouse gas emissions	End of life waste management	Impact on local vegetation
Reduction of greenhouse gas emissions	**1**	1	6
End of life waste management	1	**1**	6
Impact on local vegetation	1/6	1/6	**1**

Reduction of greenhouse gas emission and end of life waste management are equally preferred environmental criteria, and they are both strongly preferred to impact on local vegetation. This is due to the magnitude of criteria effect. While impact on local vegetation is important, greenhouse gas emissions impact a larger part of the environment that is not geographically limited to only the location of the PV plant. PV plant end of life results in a significant amount of electronic and metal waste quantified in multiple tonnes. Some of this waste can be recycles and some of it cannot and ends up in large landfills, impacting a large amount of the environment. Toxic waste materials, which are located inside PV cells, impact not only the local waste plant, but can also potentially harm underground water sources and excrete toxic fumes into to atmosphere if not handled properly.

5.2.2 Alternatives

Information regarding alternatives and their differences have been provided in the technical description (Company 1, 2021). Alternatives have been derived from PVsol, a software dedicated for PV plant design. Each alternative has a specific set of parameters displayed in table 10.

Apart from these parameters the layout description of each alternative is available:

- Alternative 1 – Distance between PV modules 5.4m, available area filled out by modules completely. Modules mounted in arrays and standalone.
- Alternative 2 - Distance between PV modules 5.4m, modules mounted in arrays on mounting mechanisms. Modules mounted only in arrays.
- Alternative 3 – Distance between PV modules 6.7m, available area filled out by modules completely. Modules mounted in arrays and standalone.
- Alternative 4 - Distance between PV modules 6.7m, modules mounted in arrays on mounting mechanisms. Modules mounted only in arrays.

Alternatives 1 and 3, as well as 2 and 4 are similar, with the main difference being distances between modules. A larger distance between modules will result in better irradiation throughout the day and better accessibility to modules, however less modules installed. The other difference between these alternatives is the way the intended area was used for mounting PV modules. Alternatives 2 and 4 have PV modules mounted in arrays only, resulting in a simple and accessible design, that is beneficial for simple maintenance and a simple cable layout. The layout design in alternatives 1 and 3 is slightly different. In these alternatives the modules are mounted in arrays, however the unused space, mainly around the borders of the intender area, are filled by standalone PV modules. This layout design results in a more efficiently used area and higher modules count, therefore more power installed. The trade-off in this design is sacrifices for a slightly more complex maintenance, cable layout and making the layout inconvenient for expansion.

Table 11. Alternatives of Project 1

<table>
<tr><th></th><th>Investment cost
(million €)</th><th>Number of PV modules</th><th>Installed power (DC)
(kWp)</th><th>Installed power (AC)
(MW)</th><th>Specific yield
(kWh/kWp)</th><th>Energy production
(MWh/year)</th></tr>
<tr><td>Alternative 1</td><td>18.38</td><td>50355</td><td>27191.5</td><td rowspan="4">22</td><td>1.331</td><td>36219</td></tr>
<tr><td>Alternative 2</td><td>16.9</td><td>46575</td><td>25150.5</td><td>1.34</td><td>33731</td></tr>
<tr><td>Alternative 3</td><td>16.05</td><td>43200</td><td>23328</td><td>1.368</td><td>31908</td></tr>
<tr><td>Alternative 4</td><td>15.653</td><td>41175</td><td>22234.5</td><td>1.368</td><td>30417</td></tr>
</table>

A wide range of initial investment cost are present in alternatives, as well as the number of PV modules and technical parameters regarding energy production. Apart from these provided parameters, some economic parameters have been calculated.

Maintenance and operation cost is calculated with equation 7. It has been derived from information from Company 1, where maintenance engineers expect the maintenance and operation cost to be equal to 2% of the initial investment cost.

$$M_t = 0.02 * I_t \tag{7}$$

All four alternatives use the same equipment, therefore this value is constant across all four alternatives. It is expected that this cost will grow every year by 2% for every alternative as well.

The lifetime expectancy for all four alternatives is 25 years. The equipment that is used is predicted to have a degradation rate of 2% by the end of the first operational year, after which it will degrade by 0.5% in the following years. This will impact the energy output of the PV plant by reducing it towards the end of its lifetime.

This information is used in the supplementary sheet to gain data about LCOE, NPV and IRR for the project, as there was no data about these criteria provided by the company. These criteria are calculated with a discount rate of 6%. To gain access to the cash flow, it is considered that all of the electricity generated by the PV plant is sold at a price of 0.057 €/kWh. (FERK, 2021)

Table 12. Economic parameters of alternatives

	NPV	IRR	LCOE
Alternative 1	€ 609,037.57	6.4%	€ 0.05559
Alternative 2	€ 872,204.23	6.6%	€ 0.05484
Alternative 3	€ 722,803.15	6.5%	€ 0.05510
Alternative 4	€ 1,242,424.75	6.9%	€ 0.05374

Information from table 12 will be further used in economic criteria comparison matrices for LCOE, NPV and IRR criteria matrices.

5.2.3 Economic criteria comparison matrices

The provided initial investment cost has enabled calculation of the remaining criteria and parameters needed for comparison matrices.

Alternative 1 hold the highest investment cost of 18.38 million € and is therefore the least preferred alternative of the group. Alternative 2 has the second highest investment cost of 16.9 million €, which is closely followed by alternative 3 with and investment cost of 16.05 million €. Alternative 4 hold the lowest investment cost and is therefore the most preferred alternative regarding this sub-criterion.

Table 13. Initial investment cost comparison matrix

Criteria	Alternative 1	Alternative 2	Alternative 3	Alternative 4
Alternative 1	**1**	1/3	1/5	1/6
Alternative 2	3	**1**	1/2	1/3
Alternative 3	5	2	**1**	1/2
Alternative 4	6	3	2	**1**

Cost of operation in this model has been calculated as a percentage of the initial investment cost. Cost of operation hold a value of 2% of the initial investment, its value is proportional to the initial investment cost and therefore its comparison matrix is similar to the matrix in table 13.

Table 14. Cost of operation comparison matrix

Criteria	Alternative 1	Alternative 2	Alternative 3	Alternative 4
Alternative 1	**1**	1/3	1/5	1/6
Alternative 2	3	**1**	1/2	1/3
Alternative 3	5	2	**1**	1/2
Alternative 4	6	3	2	**1**

Levelized cost of electricity is calculated in the supplementary sheet alongside NPV and IRR. Calculation shows that alternative 4 holds the lowest LCOE of 0.05374 €/kWh and is therefore the most preferred alternative. Alternative 2 has the next lowest value of 0.05484 €/kWh, closely followed by Alternative 3 with a LCOE of 0.05510 €/kWh. The least preferred alternative is alternative 1, which holds the highest LCOE value of 0.05559 €/kWh. (Table 12.)

Table 15. LCOE comparison matrix

Criteria	Alternative 1	Alternative 2	Alternative 3	Alternative 4
Alternative 1	**1**	1/3	1/3	1/8
Alternative 2	3	**1**	2	1/4
Alternative 3	3	1/2	**1**	1/5
Alternative 4	8	4	5	**1**

Margins of NPV values between some alternatives are very significant. Alternative 4 carries an NPV value of 1.24 million €, which is double the amount of alternative 1 which holds a value of only 609 thousand €. This makes alternative 4 extremely preferred more to alternative 1. Alternatives 2 and 3 hold values of 872 thousand € and 722 thousand € respectively.

Table 16. NPV comparison matrix

Criteria	Alternative 1	Alternative 2	Alternative 3	Alternative 4
Alternative 1	**1**	1/4	1/2	1/9
Alternative 2	4	**1**	2	1/5
Alternative 3	2	1/2	**1**	1/7
Alternative 4	9	5	7	**1**

IRR results from table 12 show that alternatives 1, 2 and 3 have a considerably lower IRR value compared to alternative 4. This makes alternative 4, the most preferred alternative for this criterion. Alternative 1 has the lowest value for IRR, therefore it is least preferred, followed by alternative 3 and alternative 2.

Table 17. IRR comparison matrix

Criteria	Alternative 1	Alternative 2	Alternative 3	Alternative 4
Alternative 1	**1**	1/3	1/2	1/6
Alternative 2	3	**1**	2	1/3
Alternative 3	2	1/2	**1**	1/4
Alternative 4	6	3	4	**1**

5.2.4 Technical criteria comparison matrices

Value for the total installed power of the PV plant project have been provided by the company related to this project and are in table 11. Alternative 1 has the most power installed 27.19 MWp, making it the most preferred alternative. It is followed by alternative 2 with 25.15 MWp, alternative 3 23.3MWp and finally alternative 4 with 22.23 MWp installed.

Table 18. Total installed power comparison matrix

Criteria	Alternative 1	Alternative 2	Alternative 3	Alternative 4
Alternative 1	**1**	3	6	8
Alternative 2	1/3	**1**	3	4
Alternative 3	1/6	1/3	**1**	2
Alternative 4	1/8	1/4	1/2	**1**

Annual energy output values are provided by the s well. Alternative 1 produces 36.2 MW/year, which is the most energy per year compared to other alternatives. Alternative 2 is the second highest producer with 33.73 MWh/year, followed by alternative 3 with 31.9MWh/year MWh. Alternative 4 produces the least energy per year, producing 30.4 MWh/year.

Table 19. Annual energy output comparison matrix

Criteria	Alternative 1	Alternative 2	Alternative 3	Alternative 4
Alternative 1	**1**	3	6	8
Alternative 2	1/3	**1**	2	4
Alternative 3	1/6	1/2	**1**	2
Alternative 4	1/8	1/4	1/2	**1**

Shading effect is mainly affected by the layout of the plant and the distance between PV module arrays. Alternatives 3 and 4 have a larger distance between arrays and are therefore more preferred. Alternative 4 has a layout where the PV modules are only mounted in arrays, making the layout less cluttered and more simple and therefore slightly more preferred than alternative 3. The same is valid for alternatives 1 and 2, making alternative 2 the least sought-after option for this criterion.

Table 20. Shading effect comparison matrix

Criteria	Alternative 1	Alternative 2	Alternative 3	Alternative 4
Alternative 1	**1**	1/2	1/4	1/6
Alternative 2	2	**1**	1/3	1/4
Alternative 3	4	3	**1**	1/2
Alternative 4	6	4	2	**1**

Specific yield takes into consideration the annual energy output, installed power and combines them into a single parameter. Values for this parameter have been provided by the company as well. Alternatives with the highest specific yield are alternatives 3 and 4, yielding 1.368 kWh/kWp. They are equally preferred to each other however more preferred to alternatives 1 and 2, which yield 1.331 and 1.34 kWh/kWp respectively.

Table 21. Specific yield comparison matrix

Criteria	Alternative 1	Alternative 2	Alternative 3	Alternative 4
Alternative 1	**1**	1/2	1/6	1/6
Alternative 2	2	**1**	1/4	1/4
Alternative 3	6	4	**1**	1
Alternative 4	6	4	1	**1**

Information about total land area covered by the PV modules have not been provided by Company 1, therefore it is weighted based on the layout descriptions and the number of modules installed. More compact layouts with less distance between arrays use the provided area more efficiently. Alternatives 1 and 3 use standalone modules to fill the space even further. For this criterion, alternative 1 is the most preferred alternative, due to use of standalone modules to fill in space and the shortest distance between modules. It has the highest number of modules installed as well (table 11). Alternative 4 has the longest distance between arrays and least modules installed and is therefore the least preferred.

Table 22. Total land area covered comparison matrix

Criteria	Alternative 1	Alternative 2	Alternative 3	Alternative 4
Alternative 1	**1**	2	5	7
Alternative 2	1/2	**1**	3	4
Alternative 3	1/5	1/3	**1**	2
Alternative 4	1/7	1/4	1/2	**1**

Mounting PV modules in straight arrays makes additional expanding of plants more convenient, therefore alternatives 2 and 4 are the most preferred, with alternative 4 being slightly more preferred due to a larger distance between arrays, which is beneficial for easier access for equipment needed for expanding.

Table 23. Convenience of expansion comparison matrix

Criteria	Alternative 1	Alternative 2	Alternative 3	Alternative 4
Alternative 1	**1**	1/3	1/2	1/6
Alternative 2	3	**1**	3	1/2
Alternative 3	2	1/3	**1**	1/3
Alternative 4	6	2	3	**1**

Larger distance between arrays implies larger access area for cable layout during the construction period. Usually, cables are installed with a large cable wheel being rolled in between arrays to lay the cable down. If arrays are straight, well-spaced with no obstacles, the cable laying process is made easier, therefore the alternative with the largest distance between arrays and most simple design is the most preferred alternative, which is in this case alternative 4.

Table 24. Ease of cable layout comparison matrix

Criteria	Alternative 1	Alternative 2	Alternative 3	Alternative 4
Alternative 1	**1**	1/2	1/5	1/6
Alternative 2	2	**1**	1/3	1/5
Alternative 3	5	3	**1**	1/2
Alternative 4	6	5	2	**1**

Ease of maintenance and ease of cable layout have similar criteria regarding preferences, one of the most crucial ones being access to modules. Alternatives with a larger distance between arrays are more preferred, as are alternatives which only use array mounted modules. This enables easier access for cleaning machines and a simpler maintenance and cleaning process. Alternative 4 is best alternative regarding this criterion, because it uses an array mounted layout and has the largest space between arrays.

Table 25. Ease of maintenance comparison matrix

Criteria	Alternative 1	Alternative 2	Alternative 3	Alternative 4
Alternative 1	**1**	1/3	1/3	1/6
Alternative 2	3	**1**	2	1/3
Alternative 3	3	1/2	**1**	1/3
Alternative 4	6	3	3	**1**

5.2.5 Environmental criteria comparison matrices

Reduction of greenhouse gas emissions is a criterion tied to annual energy production. More energy generated from renewable sources and not fossil fuels, results in less greenhouse gasses emitted in the atmosphere, therefore alternatives with the highest energy production are the most preferred ones. Table 11 shows that alternative 1 is the highest producer and therefore the more preferred alternative for this criterion, while alternative 4 is the least preferred alternative.

Table 26. Reduction of greenhouse gas emission comparison matrix

Criteria	Alternative 1	Alternative 2	Alternative 3	Alternative 4
Alternative 1	**1**	3	5	6
Alternative 2	1/3	**1**	2	3
Alternative 3	1/5	1/2	**1**	2
Alternative 4	1/6	1/3	1/2	**1**

Number of installed PV modules directly correlates to the amount of material that is disposed in the end of PV plants life cycles. Alternative 1 has the most PV modules installed, while alternative 4 has the least PV modules installed, as can be seen on table 11. This makes alternative 4 the most preferred alternative.

Table 27. End-of-life waste management comparison matrix

Criteria	Alternative 1	Alternative 2	Alternative 3	Alternative 4
Alternative 1	**1**	1/3	1/6	1/8
Alternative 2	3	**1**	1/3	1/4
Alternative 3	6	3	**1**	1/2
Alternative 4	8	4	2	**1**

Looking at the number of installed modules and mounting mechanisms, alongside the layout, an estimate can be made for an impact on the local vegetation for the setup of the PV plant. A greater number of PV modules will also create more shade, creating a lack of sunlight and a problem for local plants. Alternative 1 is found to be the least preferred, and alternative 4 is the most preferred.

Table 28. Impact on local vegetation comparison matrix

Criteria	Alternative 1	Alternative 2	Alternative 3	Alternative 4
Alternative 1	**1**	1/2	1/3	1/4
Alternative 2	2	**1**	1/2	1/3
Alternative 3	3	2	**1**	1/2
Alternative 4	4	3	2	**1**

5.3 Overview of results

After the implementation of model, the summary of results can be found in the "Summary" sheet. For the final criteria ranking, the normalized weights of all groups, criteria and alternatives for each criterion have been considered. The results derived by the model are displayed in table 29.

Table 29. Results of model

Name	Priority
Alternative 1	0.253
Alternative 2	0.190
Alternative 3	0.203
Alternative 4	0.354

Alternative 4 has the highest priority and is highlighted in green. The ranking of alternatives is as follows:

1. Alternative 4 – priority 35.4% or 0.354
2. Alternative 1 – priority 25.3% or 0.253
3. Alternative 3 – priority 20.3% or 0.203
4. Alternative 2 – priority 19% or 0.190

In technical criteria, both alternatives 1 and 4 have been preferred more than the other alternatives. Alternative 1 has more installed power and more energy output, but a lower specific yield compared to alternative 4. Alternative 4 has a layout preferred more for maintenance, expansion and cable layout, therefore both performed well in terms of technical criteria.

These two alternatives are the most preferred alternatives for environmental criteria as well. Alternative 1 has the highest energy output and therefore the highest reduction of greenhouse gas emissions. Alternative 4 has thrived in other environmental criteria due to less modules installed, resulting in less impact on local vegetation and less waste in the end of the plants lifetime.

Deciding criteria group for this project have been economic criteria. Alternative 4 has been the most preferred alternative in all economic criteria due to its high NPV and IRR and low LCOE and costs. Alternative 1 is the least preferred alternative for economic criteria, performing significantly worse in all aspects than other alternatives.

Alternatives 2 and 3 have been the middle ground for most criteria. These alternatives did not stand out in any criteria as much as alternatives 1 and 4. They have performed similarly as well, with their final priority being fairly close.

Alternative 4 is the selected to be the best conceptual solution alternative for this project. The layout of alternative 4 is shown on figure 15.

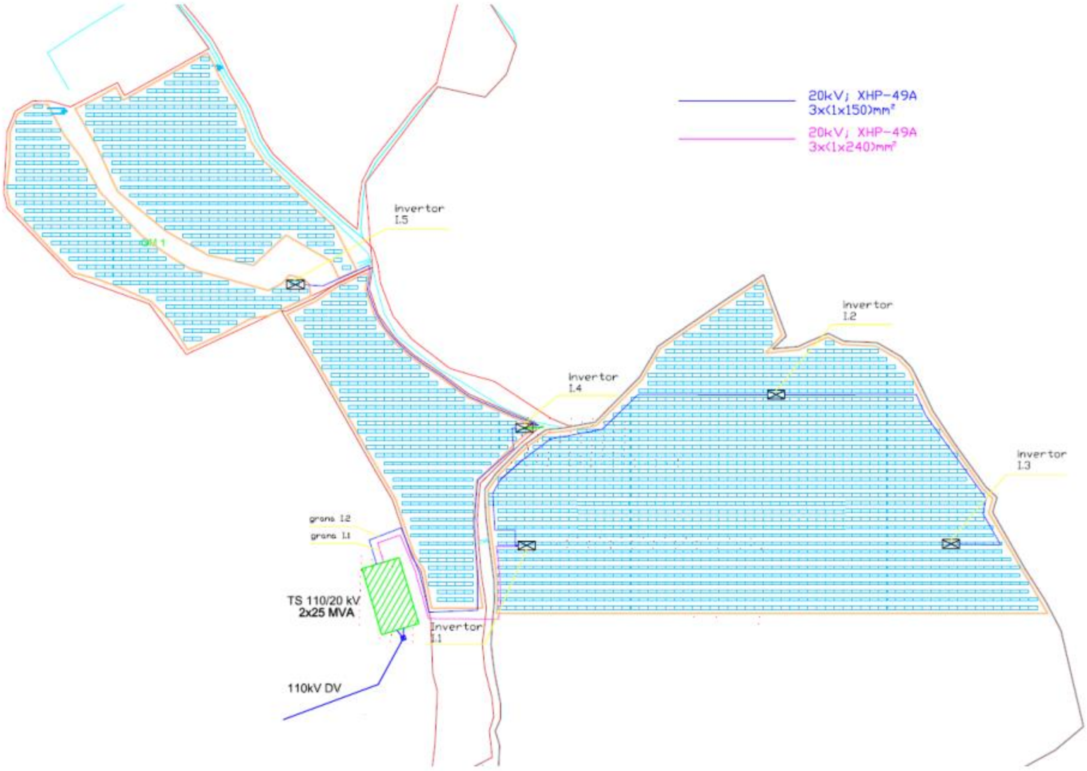

Figure 15. Selected alternative layout (Company 1, 2021)

This image has been derived from PVsol and has been provided by Company 1. The picture displays the array arrangement along with the positions of inverters and the cable layout.

6 Further development suggestions

The results provided by this AHP model are very sufficient, however the accuracy of this model can be further improved by changing a couple of key aspects regarding the parameters provided as well as the model itself.

Even though AHP is a well-established and widely used MCDM method, it has its disadvantages. The judgement factor when defining criteria weights and preferences in AHP is very subjective. When defining criteria weights, the user of the model has to assign a specific number that represents preference of one criterion to other. When assigning this number, a certain level of uncertainty is present, due to a need of more intermediate values that are not set on one specific number. The uncertainty of judgement of the user is not taken into consideration in AHP. One of the possible solutions for this problem is using fuzzy triangular number sets as a part of the AHP method. This method is an expansion of conventional AHP and it is called Fuzzy Analytical Hierarchy Process (FAHP). FAHP uses the same hierarchy process as traditional AHP as well as the same steps in the decision-making process, with the only difference being fuzzy triangular number. These number sets are defined as:

$$\text{Fuzzy number set} \rightarrow (l, m, n)$$

Where the letters represent:

- l – upper value of modal number m
- m – modal number of a fuzzy set
- n – lower value of modal number m

AHP uses crisp values that are shown in table 5, whereas values in FAHP are represented as fuzzy numbers displayed in table 30.

Table 30. Fuzzy Analytical Hierarchy Process scale (Majak & Karjust, 2018)

Intensity of importance	Fuzzy numbers	Definition
1	(1, 1, 1)	Equally preferred
3	(2, 3, 4)	Moderately preferred
5	(4, 5, 6)	Strongly preferred
7	(6, 7, 8)	Very strongly preferred
9	(9, 9, 9)	Extremely preferred

Fuzzy number sets represent a wider range that the user can use, and making the value not fixed on a specific value but rather on a range. By using fuzzy number sets, the judgement of preference is not fixed on one value, but rather on a range, giving the user more options as well as lowering the uncertainness of the user in difficult decision-making situations, removing one of the disadvantages of AHP.

Apart from the method that is being used the model's accuracy can be enhanced by getting the most accurate data and parameters of all alternatives. Project 1 has been modelled and developed in PVsol software, which does not quantify all parameters, such as shading effect and reduction of greenhouse gasses and total area covered by PV modules, but rather gives a layout examples and different parameters from which an expert derives an opinion that is used for weighting alternatives based on criteria. Using the most modern software made for designing large utility scale PV plants, provides the engineers with quantified data for these criteria, which can be used in the future in model implementation. The parameters that can be acquired by modern programs are the shading effect, greenhouse gas reduction as well as detailed layout drawings that can be used for cable layout and maintenance planning. One of the programs that gives out this data is PVsyst.

Another concept that can be implemented to this model is usage of different PV plants components in alternatives. By doing this, the alternatives are not only compared based on their layout and output parameters but based on PV module technologies that are used as well. This gives a wider range of choice to the user, when alternatives are compared based on technical criteria. Different PV module technologies and suppliers of PV plant components can influence the economic investments significantly, therefore the comparison based on economic criteria can differ even more if this concept is implemented.

7 Conclusions

The rise in use of renewables and development of new methods for renewable energy utilization are one of the most popular occurrences in the energy production sector in the 21st century. Development of different solar technologies, as well as the price decrease in already established technologies has resulted in sunlight becoming one of the most used renewable energy sources today for both private and utility scale energy production. As history has shown, new technologies often come with new problems engineers must solve, solar plant layout design being one of them. Modern software solutions have made this task simpler, however the decision-making problem for alternative selection is still present.

Most papers and reports regarding this problem have focused on different aspect of solar plant design, one of the most popular ones being optimal location selection. Some have focused on ideal renewable energy source selection as well, where models are used to compare different renewable energy sources to determine to most efficient one for an area. None of these already developed models have focused on the MCDM problem that is faced when designing the layout of the PV plant, while taking into consideration the economical aspect at the same time. In this thesis, a model was developed aimed to assist engineers and solve this MCDM problem a lot of engineers were facing.

A company that has run into this problem is Company 1, an energy company based in Bosnia and Herzegovina, which has several PV plant projects planned for the following years. One of their projects they are currently working on is Project 1, a 22MW utility scale PV plant that is going to be built in Bosnia and Herzegovina. The land for this project has been provided and the project is in its development phase. Four alternatives have been derived by engineers in PVsol, a solar plant design program and have been provided for model development. The aim of this being problem solving of the MCDM problem that has occurred.

The developed model uses a traditional MCDM method, AHP, which is a widely used well established MCDM method. Criteria groups and criteria on based of which the alternatives will be judged have been established to take into consideration the most significant characteristics of PV plants. Several economic, technical and environmental criteria have been taken into consideration and weight accordingly to the company's needs. Criteria have been chosen based on all significant aspects regarding the construction and operation of a PV plant and judgements of importance of the criteria have been set regarding demands of Company 1. The layout design problem is deconstructed into different levels and set in a hierarchy, making the decision-making process simple and straight-forward. Results obtained by this model are appropriate for any decision-making process involving PV plant layout design, as simple and priorities of all alternatives are provided. This concept of model can be used for any PV plant that is going to be designed in the future, and with further developments that are mentioned in chapter 6, the accuracy can be improved considerably.

This model can be incorporated with other models developed for solar plants. Engineers can use multiple MCDM models in their decision-making process to get the best location, best and most affordable technology to use as well as the best layout possible. Better results with MCDM models imply better designed and located PV plants, this can lead the way for solar energy to become the most preferred way to produce clean energy, further decarbonizing the energy sector.

References

Al Garni, H. Z. & Awasthi, A., 2018. *Solar PV Power Plants Site Selection: A Review,* Montreal: Concordia Institute for Information Systems Engineering.

Alsayed, M., Cacciato, M., Scarcella, G. & Scelba, G., 2014. *Multicriteria Optimal Sizing of Photovoltaic-Wind Turbine Grid Connected Systems,* s.l.: IEEE .

APS News, 2009. *April 25, 1954: Bell Labs Demonstrates the First Practical Silicon Solar Cell,* s.l.: American Physical Society.

Arnett, J., Schaffer, L., Rumberg, J. & Tolbert, R., 1984. *Design, installation and performance of the ARCO Solar one-megawatt power plant,* Athens: Photovoltaic Solar Energy Conference.

Beck, M. et al., 2019. *Combining PV and Food Crops to Agrophotovoltaic – Optimization of Orientation and Harvest,* s.l.: Fraunhofer Institute for Solar Energy Systems (ISE).

Bloomberg, 2014. *New Energy Science,* s.l.: Bloomberg.

Cen, J., 2019. *Saline solutions* , s.l.: PV Magazine Photovoltaic markets and technology.

Cherradi, N., 2019. *Solar PV technologies what's next ?,* Brussels: Bequerel Institute.

Company 1, 2021. *Project 1 - Project idea description and documentation,* s.l.: s.n.

Coulee Energy, 2021. *Bifacial Solar Panel Double Sided Solar Panels,* Ningbo: Coulee Energy China.

EESI, 2021. *Fossil Fuels Energy,* s.l.: EESI.

EIA, 2022. *Solar explained,* s.l.: U.S. Energy Information Administration.

El-Bayeh, C. Z. et al., 2020. *An Original Multi-Criteria Decision-Making* , s.l.: s.n.

Electrical Technology, 2018. *Solar Power Plant – Types, Components, Layout and Operation.* [Online].

European Commission, 2021. *Commission proposes new EU framework to decarbonise gas markets, promote hydrogen and reduce methane emissions,* Brussels: European Commission - Press release.

Extance, A., 2019. *The reality behind solar power's next star material,* s.l.: Nature - International Journal of Science.

FERK, 2021. *Odluka o regulisanju otkupne cijene energije,* Mostar: Regulatorna Komisija za Energiju u Federaciji Bosne i Hercegovine.

Fernando, J., 2022. *Internal Rate of Return (IRR),* s.l.: Investopedia.

Filatof, N., 2019. *The importance of staying cool,* s.l.: PV Magazine Photovoltaic markets and technology.

Fraunhofer ISE, 2019. *Photovoltaics report,* Freiburg: Fraunhofer ISE and PSE Conferences & Consulting GmbH.

Ghasempour, R. et al., 2019. *Multi-Criteria Decision Making (MCDM) Approach for ,* s.l.: International Journal of Renewable Energy Development (IJRED).

Goh, H. H. et al., 2021. *Using Multi-Criteria Decision Making (MCDM) and Choosing by Advantages (CBA) to Determine the Optimal Location for Solar Photovoltaic (PV) Farms,* s.l.: s.n.

Golden, B. L. & Wang, Q., 1990. *An Alternative Measure of Consistency,* New York: Springer Verlag.

Green, M. A., 2019. *Photovoltaic technology and visions for the future,* Sydney: School of Photovoltaic and Renewable Energy Engineering.

Haddad, B., Liazid, A. & Ferreira, P., 2017. *A multi-criteria approach to rank renewables for the Algerian electricity system,* s.l.: s.n.

Ibrahim, G. R. F., Mahmood, K. W. & Mahmud, M. M., 2021. *Multi Criteria Decision Analysis Technique for Solar Power Sites Selection in Duhok Governorate – Iraq,* s.l.: s.n.

IEA, 2021. *Solar PV,* Paris: IEA.

IRENA, 2016. *End-of-Life Management - Solar Photovoltaic Panels,* Abu Dhabi: International Renewable Energy Agnecy.

IRENA, 2019. *Future of Solar Photovoltaic,* Abu Dhabi: International Renewable Energy Agency .

IRENA, 2021. *Renewable Power Generation Costs in 2020,* Abu Dhabi: International Renewable energy Agency.

Jagerson, J., 2022. *Net Present Value (NPV) ,* s.l.: Investopedia.

Jeong, H. S., Choi, J., Lee, H. H. & Jo, H. S., 2020. *A Study on the Power Generation Prediction Model Considering Environmental Characteristics of Floating Photovoltaic System,* s.l.: Applied Sciences.

KIC InnoEnergy, 2015. *Future renewable energy costs: solar photovoltaics. How technology innovation is ,* s.l.: KIC InnoEnergy.

Kost, C. et al., 2021. *Levelized Cost of Electricity Renewable Energy Technologies,* Freiburg: Fraunhofer ISE.

Lee, A., 2022. *'Smooth operator': world's largest floating solar plant links with wind and storage,* s.l.: Recharge.

Majak, J. & Karjust, K., 2018. *Fuzzy AHP as a tool for prioritization of key performance indicators,* s.l.: s.n.

Marsh, J., 2018. *PERC solar cells: An overview,* s.l.: EnergySage.

Martin, J. R., 2019. *BayWa r.r. adds European floating solar momentum with double project completion ,* s.l.: PV Tech.

Moraes Lopes de Jesus, M. A. et al., 2019. *Anti-soiling coatings for solar cell cover glass: Climate and surface,* s.l.: s.n.

Rediske, G. et al., 2020. *Multi-criteria decision-making model for assessment of large photovoltaic farms in Brazil,* s.l.: s.n.

Ridha, H. M. et al., 2021. *Multi-objective optimization and multi-criteria decision-making methods for optimal design of standalone photovoltaic system: A comprehensive review,* s.l.: s.n.

Rühle, S., 2016. *Tabulated Values of the Shockley-Queisser Limit for Single Junction Solar Cells,* s.l.: Solar energy .

Saaty, T. L., 2008. *Decision making with the analytic hierarchy process,* Pittsbourgh: Katz Graduate School of Business.

Sangwongwanich, A., Yang, Y., Sera, D. & Blaabjerg, F., 2017. *Lifetime Evaluation of Grid-Connected PV Inverters Considering Panel Degradation,* s.l.: IEEE Transactions on Power Electronics.

Schindele, S. & Hogy, P., 2017. *Agrophotovoltaics: Harvesting the Sun for Power and Produce,* s.l.: Innovation 4E.

Sharavan, K. & Chunduri, K., 2018. *PERC solar cell technology,* s.l.: Taiyang.

Singh, S. N., Tiwari, P. & Tiwari, S., 2021. *Fundamentals and Innovations in Solar Energy,* s.l.: Springer Nature.

Sing, L. & McCulloh, M., 2017. *Levelized cost of electricity for solar photovoltaic and electrical energy storage,* s.l.: s.n.

Tavana, M., Arteaga, F. J. S., Mohammadi, S. & Alimohammad, M., 2017. *A fuzzy multi-criteria spatial decision support system for solar farm location planning,* s.l.: s.n.

Teknomo, K., 2006. *Analytical Hierarchy Process (AHP) Tutorial,* s.l.: s.n.

Tsanova, T., 2019. *German agro PV trial shows up to 186% land use efficiency,* s.l.: Renewables Now.

U.S. Department of Energy , 2007. *The History of Solar ,* s.l.: U.S. Department of Energy.

Vervloesem, J., Mercheggiani, E., Choudhury, M. A. M. & Muys, B., 2022. *Effects of Photovoltaic Solar Farms on Microclimate and,* s.l.: Sustainability.

Wang, C.-N.et al., 2021. *A Multicriteria Decision-Making Model for the Selection of,* s.l.: Mathematics 2021.

Zambrano-Asanza, S., Qoiros-Tortos, J. & Franco, J. F., 2021. s.l.: s.n.

Zhou, J. et al., 2020. *A geographical information system based multi-criteria decision-making approach for location analysis and evaluation of urban photovoltaic charging station: A case study in Beijing,* s.l.: s.n.

Zidane, T. E. K. et al., 2020. *Optimal Design of Photovoltaic Power Plant Using,* s.l.: Energies 2020.

ZR0

Ak. 2021/22

University of Sarajevo

Mechanical Engineering Faculty Sarajevo

Department for Industrial Engineering and Management

Topic title:	**Selction of the best conteptual solution alternative in the process of photovoltaic power plant preliminary design preparation**

Mentor/s:	**Zedina Lavić**
Scientific field:	**Industrial Engineering and Management**

Subject and explanation of topic:

The design of solar power plants is facilitated by the using of modern software applications. They provide different alternatives of conceptual solutions in terms of the number and layout of photovoltaic panels, the number of inverters, installed power, and annual production of photovoltaic power plants, including economical project performances. The designer has the task to select the best alternative of the technical solution, which should be further developed during the process of preliminary design preparation. Since the selection criteria are most often conflicting, i.e. some are maximized and some are minimized, the designer is faced with the problem of multicriteria decision making.

The work should provide a brief historical overview of the development and use, description and expected trends of further development and use of photovoltaic technology as well as a literature review concerning the models for solar power plants alternatives selection.

In the paper, the model for the selection of photovoltaic power plant alternative in the process of preliminary design preparation should be developed: the criteria for selecting the best alternative should be established and the appropriate method of multicriteria decision making should be used to select the best alternative of the conceptual solution of a photovoltaic power plant. The model should be applied to the practical problem: for a specific space, intended for the construction of a photovoltaic power plant, an overview of the alternatives provided by the software should be given and a selection of the best alternative made. A critical review of the results and a suggestion for further research should be provided.

Mandatory literature:

[1] Beck, M. et al. (2019), *Combining PV and food crops to agrophotovoltaic? Optimization of orientation and harvest*, Fraunhofer Institute for Solar Energy Systems (ISE), ResearchGate, https://doi.org/10.4229/27thEUPVSEC2012-5AV.2.25.
[2] Bodis, K., Kougias, I., Taylor, N., Jager-Waldau, A. (2019), *Solar Photovoltaic Electricity Generation: A Lifeline for the European Coal Regions in Transition*, Sustainability 2019, 11(13), 3703; https://doi.org/10.3390/su11133703
[3] Green, M.A. (2019), *Photovoltaic technology and visions for the future*, Progress in Energy I, Volume 1, Number 1, https://doi.org/10.1088/2516-1083/ab0fa8/pdf

Sarajevo, 12/09/2022

Appendices

Appendix 1. PV plant lifetime cash flow

Cash flow [€]				
Year	Alternative 1	Alternative 2	Alternative 3	Alternative 4
0	-18380000	-16900000	-16050000	-15653000
1	1655593.34	1547889.46	1461380.88	1469320.88
2	1637918.93	1531507.58	1445867.10	1453965.90
3	1620097.47	1514990.49	1430224.92	1438485.70
4	1602126.03	1498335.50	1414451.77	1422877.76
5	1584001.62	1481539.85	1398545.04	1407139.55
6	1565721.16	1464600.72	1382502.04	1391268.44
7	1547281.54	1447515.25	1366320.06	1375261.79
8	1528679.58	1430280.51	1349996.32	1359116.88
9	1509912.03	1412893.51	1333527.98	1342830.95
10	1490975.58	1395351.21	1316912.15	1326401.18
11	1471866.84	1377650.50	1300145.87	1309824.69
12	1452582.38	1359788.21	1283226.15	1293098.54
13	1433118.68	1341761.11	1266149.90	1276219.74
14	1413472.15	1323565.91	1248914.01	1259185.25
15	1393639.14	1305199.25	1231515.28	1241991.94
16	1373615.91	1286657.69	1213950.44	1224636.64
17	1353398.67	1267937.73	1196216.19	1207116.11
18	1332983.54	1249035.82	1178309.12	1189427.04
19	1312366.55	1229948.30	1160225.79	1171566.07
20	1291543.67	1210671.47	1141962.67	1153529.75
21	1270510.78	1191201.54	1123516.17	1135314.59
22	1249263.68	1171534.65	1104882.60	1116916.99
23	1227798.08	1151666.86	1086058.25	1098333.32
24	1206109.63	1131594.15	1067039.28	1079559.86
25	1184193.85	1111312.43	1047821.80	1060592.79

Appendix 2. Criteria group weights

Criteria group weights	
Criteria group	Weight
Economic criteria	0.251
Technical criteria	0.653
Environmental criteria	0.096
CR	2.35%

Appendix 3. Economic criteria weights

Economic criteria weights	
Criterion	Weight
Initial investment cost	0.094
Cost of operation	0.033
Levelized cost of electricity	0.202
Net present value	0.336
Internal rate of return	0.336
CR	4.69%

Appendix 4. Technical criteria weights

Technical criteria weights	
Criterion	Weight
Total installed power	0.151
Annual energy output	0.268
Shading effect	0.104
Specific yield	0.268
Total land area covered	0.061
Convenience of expansion	0.038
Ease of cable layout	0.038
Ease of maintenance	0.074
CR	2.14%

Appendix 5. Environmental criteria weights

Environmental criteria weights	
Criterion	Weight
Reduction of greenhouse gas emissions	0.462
End of life waste management	0.462
Impact on local vegetation	0.077
CR	0.00%

Appendix 6. Alternative comparison based on economic criteria results

Economic criteria *normalized values and CR*					
	Table 13	Table 14	Table 15	Table 16	Table 17
Alternative 1	0.064	0.064	0.061	0.056	0.079
Alternative 2	0.165	0.165	0.193	0.182	0.229
Alternative 3	0.292	0.292	0.133	0.098	0.137
Alternative 4	0.479	0.479	0.613	0.664	0.556
CR	1.70%	1.70%	4.11%	4.31%	1.67%

Appendix 7. Alternative comparison based on technical criteria results

Technical criteria *normalized values and CR*				
	Table 18	Table 19	Table 20	Table 21
Alternative 1	0.594	0.603	0.073	0.064
Alternative 2	0.244	0.223	0.124	0.111
Alternative 3	0.101	0.112	0.300	0.412
Alternative 4	0.061	0.062	0.503	0.412
CR	2.39%	1.24%	1.55%	0.55%
	Table 22	Table 23	Table 24	Table 25
Alternative 1	0.532	0.081	0.067	0.072
Alternative 2	0.288	0.293	0.112	0.234
Alternative 3	0.112	0.139	0.306	0.168
Alternative 4	0.068	0.486	0.514	0.525
CR	1.10%	2.44%	1.98%	3.74%

Appendix 8. Alternative comparison based on environmental criteria results

Environmental criteria *normalized values and CR*			
	Table 26	Table 27	Table 28
Alternative 1	0.574	0.052	0.096
Alternative 2	0.222	0.129	0.161
Alternative 3	0.126	0.311	0.277
Alternative 4	0.077	0.507	0.466
CR	1.89%	2.18%	1.46%