

# Masters Program in **Geospatial Technologies**



## **Geoprocessing Toolbox for Renewable Energy**

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for the Degree of *Master of Science in Geospatial Technologies*

# Geoprocessing Toolbox for Renewable Energy

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## **DECLARATION OF ORIGINALITY**

I declare that the work described in this document is my own and not from someone else. All the assistance I have received from other people is duly acknowledged, and all the sources (published or not published) are referenced.

Castellón, February 2024

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## Abstract

Sustainable energy is necessary to reduce dependence on fossil fuels and address climate change. To establish renewable energy power plants (REPPs), it is important to consider effective procedures that yield abundant energy while sustaining the environment. Among others, Geographic Information Systems (GIS) and Multi-Criteria Decision-Making (MCDM) tools are commonly used for site selection and impact analysis of photovoltaic power plants. However, existing research lacks a single, convenient application for these processes. This study aimed to develop a user-friendly toolbox within the ArcGIS Pro environment for site selection and environmental and social impact analysis for photovoltaic power plants (PVPP). We used a literature review method to look at previous research on selecting sites for photovoltaic power plants using GIS and MCDM methods. Then, we used a design-and-creation method to develop a toolbox in ArcGIS Pro that combines methods for selecting PVPP sites and analyzing their effects using ArcGIS Python libraries. GIS-based methods were found to be used only in the normalization and alternative evaluation stages of MCDM. The results show that not all stages of MCDM employ GIS-based methods. Two script tools were created: PVPP site selection and PVPP impact analysis for finding optimal sites and analyzing the social and environmental impacts of photovoltaic power plants, respectively. The developed tools were tested and validated by conducting a study on the province of Castellón in the Valencian community. 10 suitable sites were identified and analysed for their environmental impacts. The Pathfinder application was used to validate the results of the PVPP site selection tool. 6 sites of the developed PVPP site selection tool intersect with 6 sites identified by the Pathfinder application as optimal locations for PVPP development. However, the study lacks validation for PVPP impact analysis, as there are no existing tools for impact assessment of photovoltaic power plants. Future work could involve field studies to validate the tool's effectiveness in different geographical locations and integrate other factors for photovoltaic site selection.

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# Chapter 1: Introduction

## Background

Globalization has significantly increased energy dependency in daily human activities, resulting in a higher demand for energy resource extraction (Azarpour et al., 2022; Shao et al., 2020). Researchers indicate that fossil fuels (FF) are the primary source of energy production globally, accounting for 80% of the total (Shao et al., 2020). However, the extraction, processing, and use of these FFs produce approximately 80% of carbon dioxide emissions and two-thirds of greenhouse gases (Shao et al., 2020). These findings suggest a need to seek alternative energy sources to reduce carbon footprint and mitigate the adverse effects of climate change (Azarpour et al., 2022; Saraswat et al., 2021; Shao et al., 2020).

Continuously using non-renewable energy has harmed the environment, increased energy fluctuation prices, and caused natural resource exhaustion (Saraswat et al., 2021; Shao et al., 2020). On the other side, renewable energy (RE), including solar, wind, hydropower, ocean, geothermal, and bioenergy, is promisingly raising their significance in global energy production and ensuring environmental sustainability (Saraswat et al., 2021; Shao et al., 2020). Moreover, renewable energy resources are widely accessible worldwide and abundant in nature.

One of the Sustainable Development Goals (SDGs) set up by the United Nations is the promotion of affordable and clean energy, as outlined in Goal 7. Nevertheless, the development of renewable energy facilities remains a multifaceted task (Rediske et al., 2020). The establishment of renewable energy necessitates the careful selection of a specific location and, afterward, the connection of the renewable energy power plant to pre-existing electrical grids, all while considering the imperative of preserving the natural ecosystem (Rediske et al., 2020). The implementation of these essential procedures necessitates substantial technological resources and might be a time-intensive endeavour, consequently impeding the expeditious development of renewable energy power plants (REPP) (Rediske et al., 2020).

The European Parliament established a new objective in 2018 related to the utilization of renewable energy; this objective indicated that a minimum of 32% of the European Union's overall energy consumption should be derived from renewable sources (Vargas-Salgado et al., 2022). The use of photovoltaic power plants, combined with other renewable sources, will be crucial in achieving the stated objective (Vargas-Salgado et al., 2022).

Photovoltaic power plants operate by means of the conversion of solar energy into electrical energy through the utilization of photovoltaic cells (Susanto, 2021). Photovoltaic facilities offer a sustainable and environmentally friendly source of electricity, as they harness solar radiation without the need for conventional fuel sources (Susanto, 2021). Referring to (Verdugo et al., 2017), the cost viability of

photovoltaic (PV) systems has been linked to the decrease in costs associated with PV modules and related equipment.

According to (Gómez-Navarro et al., 2021), the proportion of renewable energy in Spain's overall energy production was 32.2% in 2017, with solar photovoltaic energy accounting for 3.2% of this total. The Valencian community generates a mere 3.8% of the overall renewable energy production (Gómez-Navarro et al., 2021). Although Valencia's current contribution to solar PV energy is low, the region's climate is ideal for generating PV energy (Gómez-Navarro et al., 2021).

The Valencian community exhibits a yearly in-plane irradiation potential ranging from 2000 to 2100 kWh/m<sup>2</sup> for solar panels set on a stationary structure with a tilt angle of 36 degrees and directed towards the south (Vargas-Salgado et al., 2022). The Spanish government's recent revision of the regulations in 2018 and 2019 is evidence of a political will to facilitate stakeholder engagement in renewable energy projects (Gómez-Navarro et al., 2021). This can be attributed to Spain's comparatively elevated electricity rates within the European Union, averaging at 0.22€/kWh (Gómez-Navarro et al., 2021).

To encourage the use of photovoltaic power plants (PVPP), technology is serving as a benchmark in providing solutions for constructing and sustaining PVPP (Kocabaldır & Yücel, 2023a). One of the technological tools employed in this sector is Geographic Information System (GIS) (Gao et al., 2022; Kocabaldır & Yücel, 2023a). GIS is an essential tool in designing, planning, and developing renewable energy projects, as it helps in various stages of the REPP project's life cycle. GIS, as a container system to combine and execute geospatial algorithms, is utilized in the PVPP context to solve geospatial problems such as the identification of suitable lands in a territory and assess the possible environmental impacts associated with their development (Gao et al., 2022; Kocabaldır & Yücel, 2023a).

The integration of refined algorithms into a unified tool is crucial to accelerate the development of photovoltaic power plants and the field of renewable energy in general. By combining selected geospatial algorithm with non-geospatial methods into a single, the resulting unified GIS-based application or tool can drastically facilitate the execution of the site selection process for photovoltaic power plants, resulting in more accurate and reliable results. This is particularly important because site selection studies require a comprehensive evaluation of multiple factors, such as land availability, solar resource potential, grid connectivity, and environmental constraints (Demir et al., 2023a; Fard et al., 2022; Habib et al., 2020a; Zambrano-Asanza et al., 2021a). By integrating these factors into a unified tool, the process becomes more efficient and effective, ultimately contributing to the improvement of the decision-making process for site selection as part of the complex and general workflow involved in the development of photovoltaic power plants.

Currently, there is a gap in research when it comes to combining available methods for site selection and impact analysis into a single and convenient tool. In addition, existing tools on the market often fail to consider all the relevant information and required functionality, such as carbon footprint, cost analysis, and environmental assessment,



to carry out reliable site selection processes in a guided and unified manner. This leads to a fragmented approach where different tools need to be used separately, resulting in inefficiencies and potential inaccuracies. By integrating these methods into a unified tool, the site selection process becomes more comprehensive and streamlined for PPVP planners and GIS specialists. This not only saves time and resources, but also ensures that all relevant factors are considered, leading to more informed decision-making in the development of photovoltaic power plants.

This study aims to fill this gap by 1/ identifying the necessary criteria and GIS-based methods and algorithms for both site selection and environmental and social impact analysis and 2/ further integrating these selected methods and algorithms into a user-friendly toolbox within the ArcGIS Pro environment. The province of Castellón in the Valencian community has been chosen as the study area to validate this tool's effectiveness.

### Research Objective and Research Questions

The main objective of this research project is to develop a user-friendly toolbox within the ArcGIS Pro environment for site selection and environmental and social impact analysis of solar photovoltaic power plants. To achieve this objective, the following specific questions will be addressed:

1. What methods, based on multi-criteria decision making (MCDM) and GIS, are commonly used to select photovoltaic power plant sites?
2. How can a toolbox be developed within ArcGIS Pro, integrating PV power plant site selection and impact analysis methods using ArcGIS Python libraries?

The expected outcome of this research is a toolbox integrated in ArcGIS Pro that performs both the site selection and environmental and social impact analysis of photovoltaic power plants.

### Relevance of the study

The motivation for this study stems from the growing need to transition to renewable energy sources that can reduce greenhouse gas emissions and mitigate the impacts of climate change. Solar photovoltaic power plants have emerged as a promising solution due to their ability to harness clean and abundant solar energy (Bošnjaković et al., 2023). By developing a user-friendly toolbox within the ArcGIS Pro environment, this study aims to support the planning and development of solar photovoltaic projects, enabling decision-makers to make informed choices based on technical and non-technical factors.

The developed toolbox aims to provide a practical and user-friendly solution for the site selection and impact analysis of solar photovoltaic power plants. Government organizations, energy companies, geospatial scientists, and environmental consultants are among the stakeholders who will benefit from its use in the planning and development of solar photovoltaic projects. By considering both physical, social, economic, and environmental factors, the toolbox will assist decision-makers in

choosing the most suitable site for a solar photovoltaic power plant, thereby promoting the development of sustainable and efficient solar photovoltaic projects.

## Thesis Structure

This thesis is organised into five main chapters. This chapter introduces the background of the study; it defines the main problem, the research objective, and related research questions. It concludes with a thorough explanation of the motivation behind conducting the study.

Chapter 2 is split into two main subsections. The first subsection defines key terms used throughout the study. The second subsection provides a comprehensive background review, discussing relevant theories and previous studies related to site selection analysis and impact analysis for photovoltaic power plants, multi-criteria decision-making (MCDM), and GIS tools.

Chapter 3 discusses the methodology used for data collection and analysis. It starts by introducing the study area and providing an overview of the paradigm or structure of the research design. It gives detailed information on the data and methods used to address each specific research question. Finally, it concludes with a discussion.

The fourth component of the research process involves presenting results and discussion. Chapter 4 demonstrates a step-by-step demonstration of the tool. With the help of figures and tables, it presents the main findings, and discuss results, and analyse different interpretations for PPVP on the use of toolbox applied to the study area.

The fifth chapter concludes with a summary of the main points discussed throughout the research process. It explains how the developed tool addresses the research objectives, discusses the study's limitations, and provides recommendations for future research.

## Chapter 2: Background

This chapter first includes a section with definitions of key terms and concepts used throughout this document. The following section delves into the site selection analysis and impact analysis of photovoltaic power plants to better contextualize the state of the art on the research topic.

### Definition of key concepts

**Renewable energy:** Renewable energy refers to energy derived from naturally replenishing sources such as sunshine, geothermal heat, water, and wind (Mendoza-Rivera et al., 2023). Renewable energy sources are often characterized by their superior cleanliness and sustainability compared to non-renewable fossil fuels, which not only lack the ability to replenish themselves but also contribute to the release of detrimental greenhouse gases (Mendoza-Rivera et al., 2023). Renewable energy is applicable for several purposes, such as generating electricity, providing heating and cooling, facilitating transportation, and serving other uses (Mendoza-Rivera et al., 2023).

**Photovoltaic power plants:** These are solar power plant installations that use solar panels to turn sunlight into energy by harnessing the photovoltaic effect in semiconductor materials, hence generating electrical power (Pandey et al., 2019).

**Geoprocessing Toolbox:** The geoprocessing toolbox is a composite noun consisting of the words "geoprocessing" and "toolbox". Geoprocessing, from an ArcGIS standpoint, refers to a GIS procedure that involves manipulating data from an input dataset and producing an output dataset as a result (ArcGIS Pro Documentation, 2024) (Dobesova, 2011). Geoprocessing procedures typically include several spatial analysis tasks such as generating a mosaic dataset, transforming images, overlaying geographic features, processing topology, computing variables (such as the magnitude and duration of a storm across space and time), and analysing and converting data (ArcGIS Pro Documentation, 2024). A toolbox in ArcGIS is a container that holds toolsets and geoprocessing tools (ArcGIS Pro Documentation, 2024). The data is stored either as a .tbx file on a disc or as a table in a geodatabase (ArcGIS Pro Documentation, 2024).

**Script tool:** It is a customized tool that allows users to run a script (typically written in Python) to perform specific geoprocessing tasks or automate workflows within the ArcGIS environment (ArcGIS Pro Documentation, 2024). It extends the functionality of ArcGIS tools by incorporating user-written scripts for specialized analyses or processes (ArcGIS Pro Documentation, 2024).

**Site selection:** A systematic process to determining and selecting the optimal (geographical) site for a new facility or project (Singh et al., 2020). The process entails assessing several aspects and criteria to identify the most suitable location that fulfills its requirements and goals (Singh et al., 2020). The objective is to choose a site that optimises the likelihood of achieving success while reducing both risks and expenses.

Site selection is a multifaceted process that involves detailed examination and evaluation of elements like market demand, accessibility, infrastructure, labour availability, closeness to clients, competition, and other pertinent variables (Singh et al., 2020) (Singh, et al., 2020). Geographic Information Systems (GIS) and analytical

methodologies, such as the Analytic Hierarchy Process (AHP), may aid in site selection by offering tools and processes for analysing data, representation, and making decisions (Demir et al., 2023a; Singh et al., 2020).

**Multi-criteria decision-making (MCDM):** It is a widely used decision-making method that takes into account and assesses numerous criteria or elements simultaneously to make well-informed decisions among different possibilities (Shao et al., 2020). The process entails evaluating and assigning importance to several factors to make a choice that is most congruent with the overall goals or interests (Shao et al., 2020). Multi-Criteria Decision Making (MCDM) is extensively used across several domains, such as business, engineering, environmental planning, and resource management (Shao et al., 2020).

## Background Review

### Site selection for PVPP

To establish renewable energy power plants (REPPs), it is necessary to gather comprehensive ground data related to the specific area of interest or site. This data encompasses several aspects, such as physical, environmental, economic, and social factors (Y. Wang et al., 2022). By leveraging the expertise of professionals in the respective domain, the process of collecting and analysing relevant data aids decision-makers in establishing the critical factors necessary for identifying an appropriate location for a REPP (Y. Wang et al., 2022).

There is a growing trend among researchers to develop models that can effectively ascertain the optimal sites for photovoltaic power plants (PVPP) (Demir et al., 2023a; Fard et al., 2022; Habib et al., 2020a; Zambrano-Asanza et al., 2021b). The use of GIS facilitates the implementation of a method referred to as multi-criteria decision-making (MCDM), which serves as a prevalent tool for site selection. MCDM enables the integration of data from multiple fields, such as physical, environmental, and social aspects, resulting in a comprehensive outcome that accounts for all inputs (Demir et al., 2023a; Fard et al., 2022; Habib et al., 2020a; Zambrano-Asanza et al., 2021b). The presence of these algorithms has enabled increased participation of stakeholders in PVPP establishments.

Researchers have employed several MCDM methods to determine the optimal location for establishing a solar power plant. These methods include the Analytic Hierarchy Process (AHP), Weighted Linear Combination (WLC), Step-wise Assessment Ratio Analysis (SWARA), Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), fuzzy logic models, the Decision-Making Trial and Evaluation Laboratory (DEMATEL), hybrid techniques, and Elimination and Choice Expressing Reality (ELECTRE), among others (Demir et al., 2023a; Tercan et al., 2021; Zambrano-Asanza et al., 2021b). Researchers typically select a certain method based on the specific geographical area of interest or the level of complexity of the criteria being studied. Consequently, it becomes necessary to assess the capabilities of these chosen methods.

## Economic, Social, and Environmental Impact analysis for PVPP

In addition to the physical selection of a location, assessing costs associated with a site is a crucial factor in developing solar photovoltaic (PV) facilities. The financial side of the RE project holds significant importance for all contributors engaged in the process, as highlighted by researchers (Aslani & Wong, 2014). In the context of project cost analysis, scholarly research indicates that decision-makers and investors rely on three key factors to assess the viability of renewable energy projects: the overall project cost, the cost associated with carbon footprint, and the return-on-investment cost (Aslani & Wong, 2014) (Steffen, 2020).

To assess the sustainability of solar PV facilities, it is imperative to incorporate the carbon emissions cost across their whole life cycle (Smoot, 2023). The World Nuclear Association (WNA) reports that solar PV utility plants generate an estimated 48 grams of carbon dioxide (CO<sub>2</sub>) throughout its life cycle (WNA, 2022).

The carbon footprint cost for renewable energy can be categorized into three main phases (Smoot, 2023): The initialization of the REPP (it involves all activities that emits carbon, like construction and transportation of materials), the operating phase (it involves the daily operational activities of the plant), and the building back phase (it involves all activities that emits carbon while demolishing or renovating the REP) (Smoot, 2023). Calculating the overall cost of carbon footprint reveals the degree of sustainability of a project, providing decision-makers with insight into the project's environmental viability.

According to (Smoot, 2023), the carbon footprint associated with PVPPs can be classified into three primary stages. The initialization phase encompasses all activities that contribute to carbon emissions, such as constructing and transporting materials. The operating phase involves the daily operational activities of the plant. Lastly, the building back phase includes all activities that emit carbon during the demolition or renovation of the PVPPs (Smoot, 2023). Determining the total expenses associated with the carbon footprint allows for an evaluation of the long-term feasibility of a project, thereby offering decision-makers valuable information regarding its environmental sustainability.

Besides calculating the cost, renewable energy needs an impact analysis on social and environmental factors. One of the techniques used in the environmental analysis of the renewable energy industry is life cycle assessment (LCA) (Tsoutsos et al., 2005; N. Zhang et al., 2022). LCA is a process that evaluates different factors involved in creating a product and its possible effects throughout its entire life cycle, starting from sourcing raw materials, production, usage, and ending with disposal (N. Zhang et al., 2022).

In the study of (N. Zhang et al., 2022), they conducted the life cycle assessment (LCA) on large-scale renewable energy projects between 2001 and 2019, specifically looking at the environmental aspect in California. The result shows that it is necessary for the local authorities to learn from the previous environmental impact of renewable energy projects to plan for future renewable energy extraction (N. Zhang et al., 2022). Simultaneously, it is also crucial to consider other potential metrics (ozone depletion potential, photochemical ozone formation potential, and acidification potential) that negatively impact the environment other than global warming (N. Zhang et al., 2022).

According to (Karytsas et al., 2020), there are still fewer official metrics for measuring the social impacts of renewable energy; the social indicators can help decision-makers to develop more informed strategies and policies and enhance people's social conditions. To ensure efficient planning, processes, and activities, it is essential to examine the steps involved in social impact measurement thoroughly. These steps include setting the objective and working group, selecting performance indicators, tracking the progress and data quality, and documenting the process (Karytsas et al., 2020).

## GIS Tools

GIS tools are applied in different fields, including renewable energy, urban planning, environmental management, and transportation. In the following section, we will discuss some of the studies that have developed or utilized GIS tools as a means of addressing complex research problems.

Spatial clustering is an extensively explored subject across diverse disciplines, often with limited tools implementing specific approaches (Ayudiani & Akbar, 2017). The authors introduce a user-friendly spatial clustering tool for accommodating various methods and techniques to address this gap. Emphasizing extensibility, the tool employs the template method design pattern, structuring the algorithm's skeleton as an abstract class, allowing for easy integration of new algorithms (Ayudiani & Akbar, 2017). The authors also explore the analysis of spatial clustering processes, incorporating the definition of spatial weight and spatial autocorrelation analysis (Ayudiani & Akbar, 2017). The output of the analysis is conveyed through a map visualization, providing a comprehensive insight into the results (Ayudiani & Akbar, 2017).

In summary, the proposed spatial clustering tool embodies key principles in GIS tool development (Ayudiani & Akbar, 2017). Its user-friendly design and extensibility through the template method pattern resonate with the goals of creating adaptable geoprocessing toolboxes. The incorporation of map visualization further enhances its suitability for GIS environments, offering professionals a valuable and accessible tool for diverse spatial analyses.

In another recent study by (Gairaa et al., 2023), they highlight the significance of diversifying energy sources and integrating solar energy for sustainable exploitation. They emphasize optimal site selection for solar PV power plants based on multiple criteria, including solar potential, proximity to power infrastructure, environmental considerations, climatic conditions, location, economic factors, and orography (Gairaa et al., 2023). The use of GIS tools is recommended to analyse location parameters and assess their impact on overall performance (Gairaa et al., 2023). They conclude by urging site suitability studies in Algeria to support policymakers in planning profitable PV power plants (Gairaa et al., 2023).

The emphasis on the use of GIS tools in the study of (Gairaa et al., 2023) is clearly defined as one of the major approaches to defining optimal sites for solar energy. With modern technology, tools can be built with commercial and open-source software packages such as ArcGIS, GRASS, and QGIS. However, each of these software packages has no defined tool specific for site selection. The user needs to create models or use

single tools one after the other to accomplish the whole process, which is sometimes time-consuming and prone to errors and mistakes.

The study of (Custodio et al., 2019) presents OpenGIS, a GIS-based planning tool that aims to evaluate the effects of distributed energy resources on distribution networks and investigate possible remedies for thermal and voltage issues. The tool showcases its capabilities using an actual low-voltage network in the UK, including home PV installations (Custodio et al., 2019). The increasing use of distributed energy resources, such as PV systems, batteries, and electric cars, will significantly change distribution networks (Custodio et al., 2019). Consequently, the significance of sophisticated tools like OpenGIS becomes evident.

Another GIS tool has been created by (Muñoz & García, 2021) to evaluate the effects of floods on the electricity industry. The tool encompasses evaluating flood risk, assessing asset exposure and susceptibility, computation of cost assessment, and determining electrical network reliability indices. The application is shown using a practical case study conducted in Barcelona, where several flooding situations are analysed, and the effectiveness of water management methods is evaluated (Muñoz & García, 2021). The tool aims to aid decision-makers in both strategic planning and operational choices by providing vital insights to mitigate concerns caused by severe flooding occurrences in the electrical network.

(Muñoz & García, 2021) tool was designed specifically for assessing and monitoring environmental impacts. Combining GIS capabilities with related scientific research, the developed tool provides an effective means to tackle global challenges. It highlights that the integration of spatial data and advanced analytical capabilities in GIS tools enables a more thorough understanding of environmental issues, leading to improved solutions and informed decision-making in the face of complex challenges.

A framework is essential for developing digital tools for managing urban or environmental data. It provides a structured approach that guides the development process and ensures the tools are effective and aligned with user needs. Noennig described four key elements necessary for developing tools that may be used in urban research, planning, and decision-making settings (Noennig, 2022). It includes user requirements, solution types, interaction level, and data provision (Noennig, 2022). Each element is described concerning the current study below.

Along the same lines, capturing user requirements is critical in developing digital tools for urban or environmental data. A comprehensive understanding of the needs and challenges of the user side is essential to ensure that the tools are designed to meet their specific needs. By recording, structuring, and defining user requirements, developers can create user-friendly, efficient, and practical tools addressing users' challenges (Noennig, 2022). For example, in the current site selection project for PVPP, understanding the user requirements can help restructure the process, reduce errors, and make the tool more user-friendly and accessible.

Another crucial factor when it comes to developing digital tools for urban or environmental data is to consider existing software modules or toolboxes that can be used as a foundation. These modules or toolboxes can provide valuable resources and functionalities to be utilized in developing the envisioned tool (Noennig, 2022). For

example, besides ArcGIS Pro used in the current study, other software modules such as related R packages, Python libraries, or QGIS can be used for data analysis and visualization. These software modules offer a wide range of tools and functionalities that can be integrated into the envisioned tool, enhancing its capabilities and flexibility.

The envisioned tool for site selection analysis for PVPP requires users to carry out various interactions to utilize its capabilities effectively. Users would need to select appropriate criteria for site selection, normalize data, weigh criteria appropriately, and make informed decisions based on the analysis results. These interactions involve complex decision-making processes that require users to deeply understand the site selection analysis methodology and the specific requirements for PVPP. The tool can be developed to support users throughout the process by providing a comprehensive understanding of the interactions involved, making it more user-friendly and facilitating accurate results (Noennig, 2022).

Finally, data availability and accessibility are crucial considerations in the development of the envisioned tool. By understanding data formats, quality, quantity, and other specific aspects, developers can design the tool to seamlessly accommodate and process the available data (Noennig, 2022). For example, ensuring that the tool supports both vector and raster data witnesses that the tool can handle the main data types required for site selection analysis for the PVPP. By addressing data availability and accessibility, the tool can provide accurate and reliable analysis results, enabling users to make informed decisions in the site selection process.

## Python for ArcGIS Pro

Programming skills have become increasingly vital for GIS professionals across various fields, with many GIS job offers now require proficiency in programming (Zandbergen, 2020). Python stands out as a key language in this context. The rising interest in Python within the geospatial community has driven efforts to develop Python tools, utilize third-party packages from the open-source geospatial community, and explore Python's application in emerging areas like web GIS (Dobesova, 2011; Zandbergen, 2020).

ArcGIS Pro, a desktop software application designed for working with local datasets, supports Python as a scripting language (Dobesova, 2011). The inclusion of the ArcPy package in the software further enhances Python's role by providing access to all tools within ArcGIS Pro, including those from its extensions (Zandbergen, 2020). The integration of Python scripting with ArcGIS Pro facilitates efficient task automation (Dobesova, 2011; Zandbergen, 2020). In line with these capabilities, the current study aims to create new geoprocessing tools that not only expand ArcGIS Pro's functionality but also seamlessly integrate into the software's interface. Python script tools and Python toolboxes play a pivotal role in achieving this goal (Dobesova, 2011; Zandbergen, 2020).

Early developments in geospatial scripting languages included the Arc Macro Language (AML), and the workstation Arc/Info architecture, which served as an introduction to ESRI GIS software (M. Zhang et al., 2014). AML was specifically developed to interface with the Arc/Info geodatabase, offering users a scripting language to automate geospatial procedures (M. Zhang et al., 2014). Subsequently, with the advent of ArcView, the Avenue programming language was introduced as an additional choice for



geographic scripting (M. Zhang et al., 2014). Avenue provided users with the ability to configure and perform iterative processes inside the ArcView GIS environment (M. Zhang et al., 2014).

The purpose of ESRI's ArcPy Python module is to function as a software development kit (SDK) to enable geospatial scripting and automation inside the ArcGIS platform (M. Zhang et al., 2014). ArcPy provides an extensive collection of tools, functions, classes, and modules that allow users to develop geospatial processes of varying complexity using Python programming (M. Zhang et al., 2014). The incorporation of Python into ArcGIS offers a robust and adaptable platform for doing geospatial research, managing data, and automating map creation (M. Zhang et al., 2014). ArcPy has become an essential element for GIS experts, enabling them to use the functionalities of Python for efficient and configured geoprocessing operations inside the ArcGIS software environment.

The use of scripting in geospatial data processing offers several key benefits. Firstly, it allows for the automation of repetitive tasks, such as data conversion, saving significant time and effort (Dobesova, 2011). Secondly, scripting enables scalability in processing large datasets, efficiently handling large amounts of data, and performing complex analyses (Dobesova, 2011). Thirdly, scripting provides flexibility through the customization of workflows and algorithms to meet specific needs (Dobesova, 2011). Lastly, scripting offers a higher level of efficiency and accuracy compared to manual work by eliminating the risk of human errors and ensuring reliable results (Dobesova, 2011).

In addition, the advantage of scripting in geospatial data processing becomes evident when dealing with the diversity of tools and formats in commercial and open-source GIS software (M. Zhang et al., 2014). Systems like ArcGIS, GRASS, QGIS, and GeoTools offer unique algorithm components, each with its processing capabilities (M. Zhang et al., 2014). However, these tools often employ different product formats, creating interoperability challenges and a significant gap between software platforms (M. Zhang et al., 2014).

Additionally, no single tool encompasses all necessary geoprocessing functions or supports all spatial data formats. To overcome these limitations and harness the strengths of various tools, scripting languages play a crucial role in seamlessly integrating components from different software packages (Zandbergen, 2020). By employing scripts, users can bridge the gaps between disparate tools, creating a cohesive and customized geospatial processing workflow that efficiently leverages the strengths of multiple platforms, ultimately enhancing flexibility and functionality in data analysis and management (Zandbergen, 2020; M. Zhang et al., 2014).

## Chapter 3: Methods and Data

The following section provides details on the methodology applied to develop the geoprocessing toolbox while addressing the research questions. It consists of five sections.

Section 1 describes the characteristics of the study area, including any relevant background information. Section 2 describes the methodological structure used to develop the toolbox and analyse the data. Section 3 concentrates on the data used to test the tools developed. Section 4 describes method used to address the first research question. Section 5 discusses the methods used to develop a geoprocessing toolbox for PVPP to answer the second research question.

### 3.1 Study Area

The primary objective of this research is to develop a toolbox and ensure its practical applicability; it must be tested using real data within a tangible context. For this purpose, the province of Castellón in the Valencian Community, Spain, was selected. Castellón is a province situated on the eastern coast of Spain, near the Mediterranean Sea. It shares its borders with the provinces of Valencia, Teruel, and Tarragona. The province of Valencia is located to the south of Castellón, while the province of Teruel lies to the west. The province of Tarragona is on the northern side. Figure 1 shows the location of Castellón Province on the map.

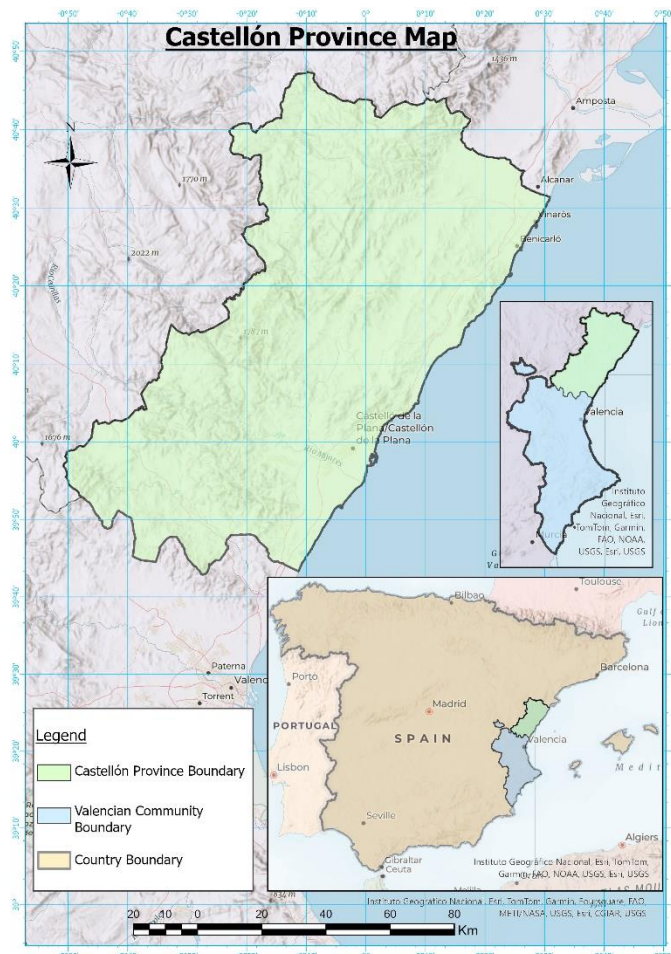


Figure 1: Study Area Map

According to Eurostat (2023), the population of Castellón province is 582,218, with a density of 88 people per square kilometer across a total area of 6,689.56 square kilometers (Eurostat, 2023). The population of the province of Castellón follows a classic pyramidal distribution by age groups, with a relatively balanced gender ratio.

Understanding the land use and land cover in the province of Castellón is crucial for assessing its potential for solar energy development. The dominance of rangeland, trees, flooded vegetation, crops, and built-up areas can have implications for installing photovoltaic power plants. For example, as shown in Figure 2, tall trees covering 34.7% of the total area may limit the available space for solar panels. In contrast, the abundance of vacant land and built-up areas may provide suitable locations for solar energy infrastructure. Additionally, the proximity of these areas to existing grid infrastructure can facilitate the connection of new potential sites to the electricity grid (ESRI, 2022).

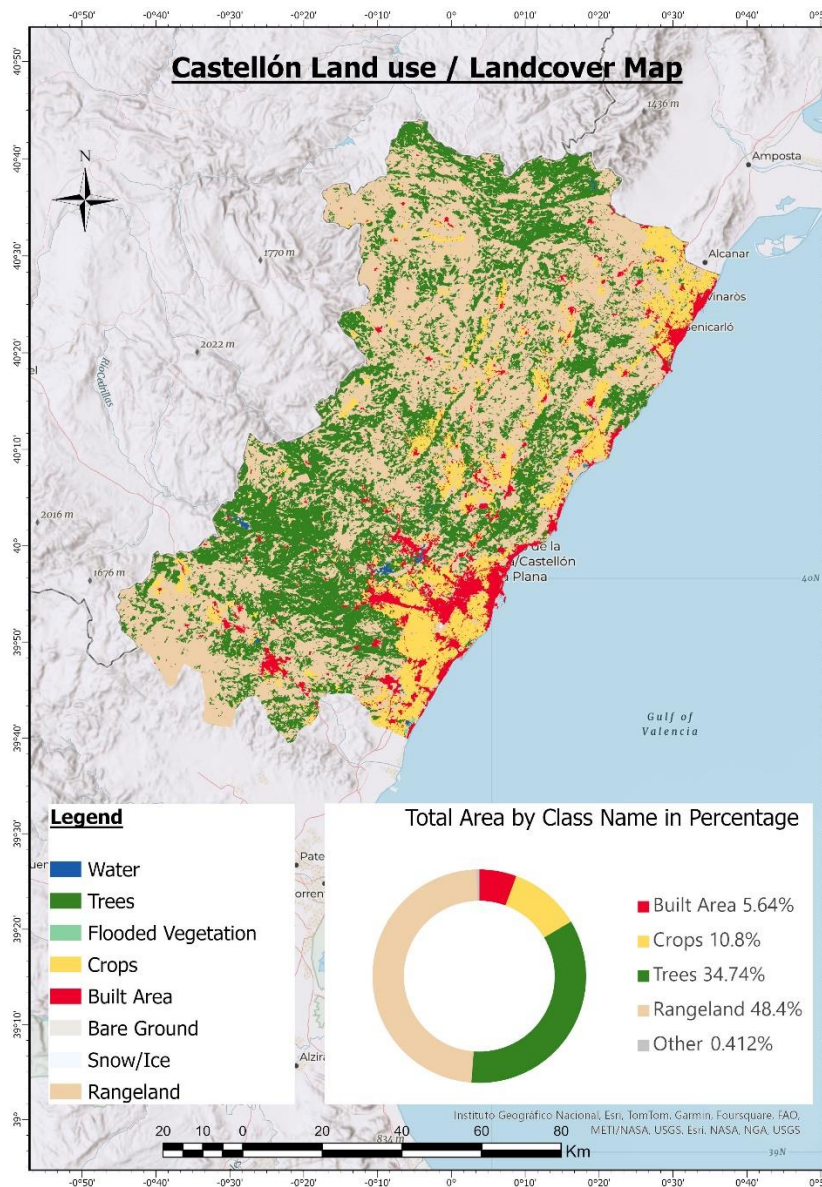


Figure 2: Castellón Landuse/Landcover map

The Esri global land use/land cover dataset is a widely recognized and trusted source of land use and land cover data. It is a comprehensive dataset that provides detailed information on different land cover classes, allowing for accurate analysis of land use patterns. This dataset is regularly updated to ensure that the information is current and reflects the most recent changes in land cover (ESRI, 2022). The figure 2 above shows the 2022 land use and land cover map for the province of Castellón. It shows eight classes including water, trees, flooded vegetation, crops, built area, bare ground, snow/ice, and rangeland. Rangeland is the most prevalent, covering more than 48%.

The province of Castellón features a significant solar resource potential, with average solar radiation levels ranging from 1200 to 1700 kWh/m<sup>2</sup>. Based on Energypedia's solar radiation classes, the province of Castellón falls into the moderate and high classes (energypedia, 2018). This high solar resource availability indicates the province's suitability for installing photovoltaic power plants. Additionally, historical data shows that the region in which the province of Castellón lies has experienced successful solar energy production, with several solar farms contributing to the local energy grid (IEA, 2020).

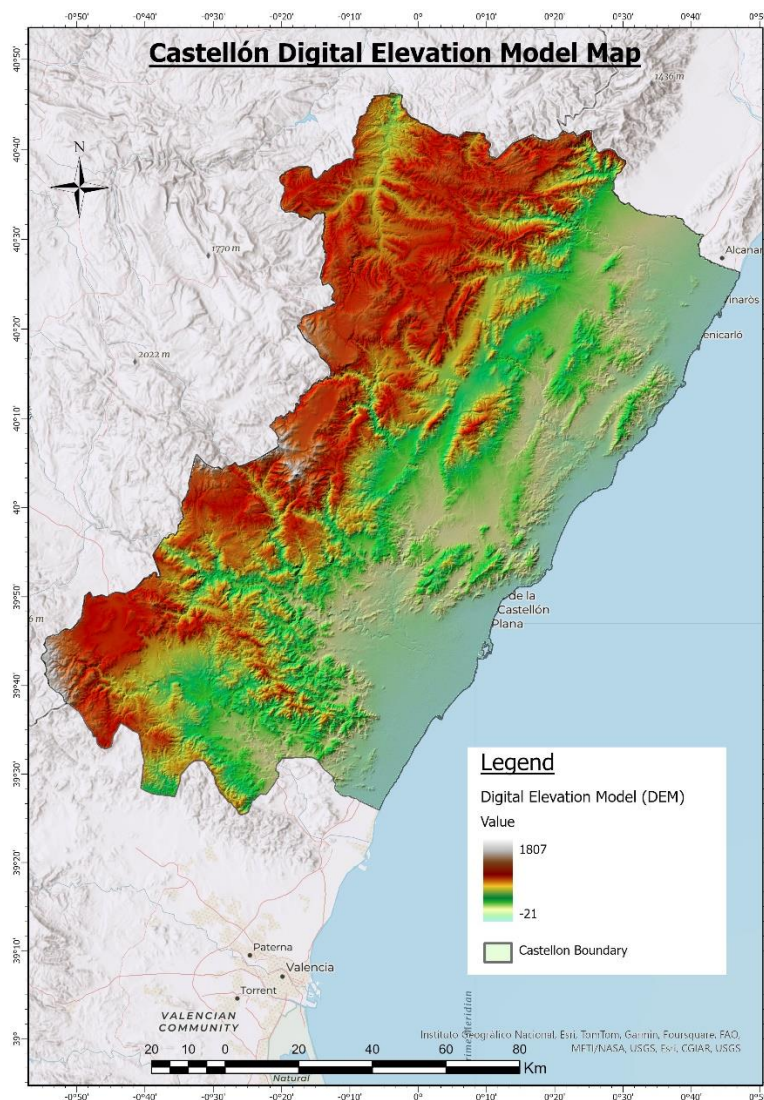


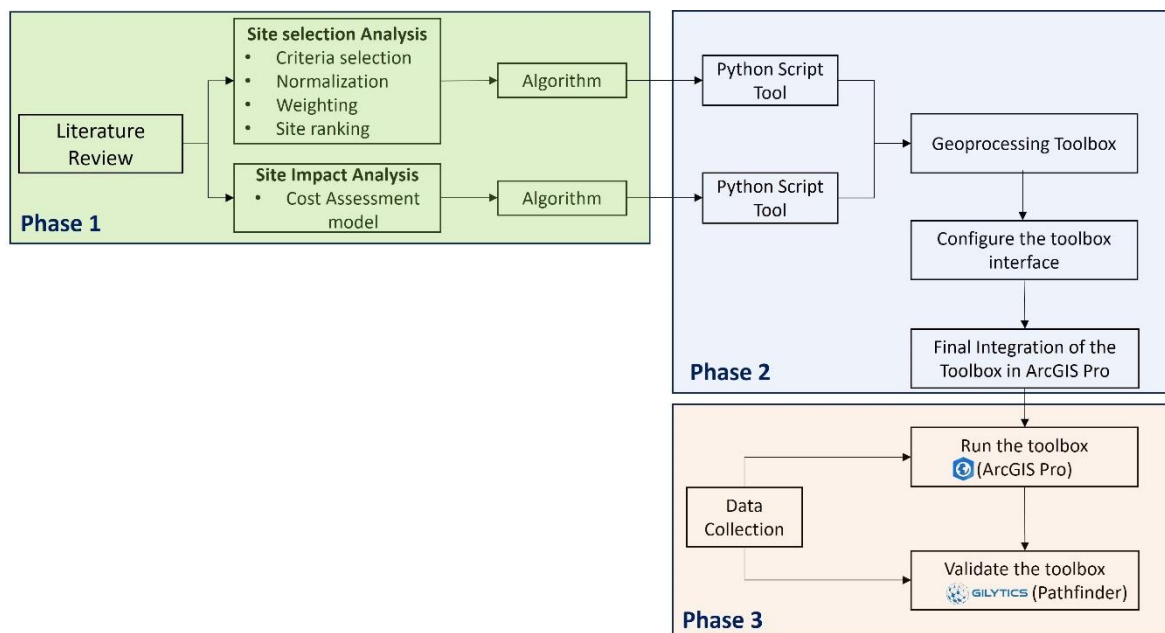
Figure 3: Castellón Digital Elevation Model (DEM) map.

The region of Castellón has a topography that favours PVPP installations. As Figure 3 shows, the province of Castellón has an elevation ranging from -21 to 1807. The different elevations allow for the installation of solar panels at optimal angles to capture the maximum amount of sunlight throughout the day. Additionally, the flatness of the terrain in certain areas of Castellón makes it easier to set up and maintain solar panel arrays. This topography also makes it easier for these photovoltaic power plants to transmit the electricity they generate to nearby towns and cities.

The potential for solar energy development in Castellón offers numerous benefits to the province and its residents. By harnessing the abundant solar resource, Castellón can make significant progress towards its renewable energy targets, reducing reliance on fossil fuels and contributing to global efforts to mitigate climate change. Furthermore, establishing photovoltaic power plants and associated infrastructure will create job opportunities in the region, stimulating the local economy and promoting sustainable growth. Solar energy development can also enhance energy security by diversifying the energy mix and reducing dependence on external sources. Overall, investing in solar energy in Castellón is a promising pathway toward a cleaner, more sustainable future.

### 3.2 Methodology

The study workflow is divided into three phases (Figure 4). Phase 1 starts with identifying GIS-based methods for site selection of PVPP by following a Multi-Criteria Decision Making (MCDM) approach. The MCDM approach involves identifying and evaluating multiple criteria that are important for the selection of PVPP sites. These criteria could include solar irradiation, land availability, proximity to transmission lines, and environmental impacts. Each criterion is assigned a weight based on its importance, and the sites are evaluated and compared based on these weighted criteria to determine the optimal site location. The study uses the MCDM approach to systematically assess and prioritize potential PVPP sites based on these criteria.



#### Figure 4: Study Methodology Workflow

Secondly, a site impact analysis model is defined, specifically designed to assess the cost of each site regarding the overlaying social or environmental features. This model considers factors such as population density, proximity to residential areas, environmental sensitivity, and potential ecological impacts. By overlaying these features on the selected sites, the model calculates a cost value for each site, which helps identify the most suitable location for the PVPP.

For each method, we identify its respective algorithm or function. The selected algorithm for PVPP site selection includes linear scaling, reclassification, Analytic Hierarchy Process (AHP), and Weighted Linear Combination (WLC). These algorithms are typical tools available in the ArcGIS environment that allow us to evaluate the suitability of different sites based on multiple criteria.

In phase 2, first, we arrange these algorithms into a Python script following the Multi-Criteria Decision-Making (MCDM) approach, which combines the algorithms' outputs to determine the most suitable site for PVPP development. Second, we identify and transform the corresponding GIS tools, such as the Overlay Analysis tool and the Intersection tool, into a Python script structure to conduct the site impact analysis, which assesses the selected site's potential environmental and social impacts.

Using the ArcGIS geoprocessing functionalities, each Python script is configured and converted into a Python script tool, which is then stored in a geoprocessing toolbox. These tools enable users to input their data, perform data transformations, and easily store the output in a desired directory. This saves time and effort and ensures consistency and reproducibility in data processing.

The geoprocessing toolbox provides a user-friendly interface for accessing and executing the tools, making it easy for users to find and use the needed functionalities. By storing the tools in a toolbox, users can also share their custom tools with others, allowing for collaboration and consistency in spatial analysis workflows.

Additional changes and updates are made to the geoprocessing tools during the tool's integration into ArcGIS Pro. These changes aim to optimize the tool's performance and ensure seamless integration with ArcGIS Pro. For example, modifications may be made to the tool's algorithms or data processing methods to enhance efficiency. By making these adjustments, the tool can effectively leverage the capabilities of tools in the ArcGIS Pro software while maintaining a user-friendly interface for easy adoption and utilization.

Phase 3 emphasizes the validation process. We begin by collecting data specific to the site selection of PVPP, such as technical, economic, environmental, and social factors. The data is then used to run the tools in ArcGIS Pro, which generates potential sites and impact costs based on the user's input parameters. In addition, Pathfinder (a web tool created by Gilytics that operates on the cloud and assists GIS organisations in participatory development of infrastructure. It allows for efficient planning of renewable energy sources, including wind, photovoltaic, and solar) and is used to obtain optimal sites using similar data and approaches to locate sites suitable for PVPP. The results of both tools are then compared to showcase the effectiveness of the new toolbox. This

comparison includes evaluating the accuracy and reliability of the results, ensuring that the tool provides reliable outputs for site selection of PVPP.

### 3.3 Data

The table below describes the data used to identify suitable sites and assess the environmental impact of photovoltaic power plants in Castellón province.

Data	Description	Source	Credits
Ecological corridors	Ecological and functional connectors and corridors	<a href="http://gva.es">ICV (gva.es)</a>	Green Infrastructure and Landscape Service - Regional Ministry of Territorial Policy, Public Works and Mobility - Generalitat Valenciana
High cultural value	Spaces of high cultural value in the province of Castellón	<a href="http://gva.es">ICV (gva.es)</a>	Green Infrastructure and Landscape Service - Regional Ministry of Territorial Policy, Public Works and Mobility - Generalitat Valenciana
Natural Park	Natural parks	<a href="http://gva.es">ICV (gva.es)</a>	Servicio de Gestión de Espacios Naturales Protegidos - Conselleria d'Agricultura, Medi Ambient, Canvi Climàtic i Desenvolupament Rural
Protected Landscape	Zoning of the P.R.O.G. of the Protected Landscape of La Ombria del Benicadell, including public areas, recreational areas, private forest areas, private agricultural areas in production,	<a href="http://gva.es">ICV (gva.es)</a>	Servicio de Organización y Técnicas de Gestión

	degraded private areas and impact buffer areas		
RAMSAR	Areas of Natural Heritage and Biodiversity incorporated into the approved Municipal Green Infrastructure, protected by international instruments	<a href="http://icv.gva.es">ICV (gva.es)</a>	Green Infrastructure and Landscape Service - Regional Ministry of Territorial Policy, Public Works and Mobility - Generalitat Valenciana
ZEPAs and ZECs	Special protection areas for birds in the province of Castellón	<a href="http://icv.gva.es">ICV (gva.es)</a>	Ministry of Agriculture, Environment, Climate Change and Rural Development - Generalitat Valenciana
Humid areas	Areas of wetlands of the province of Castellón	<a href="http://icv.gva.es">ICV (gva.es)</a>	Servicio de Gestión de Espacios Naturales Protegidos - Conselleria d'Agricultura, Medi Ambient, Canvi Climàtic i Desenvolupament Rural - Generalitat Valenciana
River channels	River channels	<a href="http://icv.gva.es">ICV (gva.es)</a>	General for Territorial Planning and Landscape - Regional Ministry of Territorial Policy, Public Works and Mobility - Generalitat Valenciana
Risks	Areas with natural hazards incorporated into the approved Municipal Green Infrastructure, which are critical	<a href="http://icv.gva.es">ICV (gva.es)</a>	Green Infrastructure and Landscape Service - Regional Ministry of Territorial Policy, Public Works and Mobility -



	of the incidence (natural or induced) of these risks.		Generalitat Valenciana
Livestock roads	Livestock elements of the Inventory of the network of livestock routes of the Valencian Community	<a href="http://icv.gva.es">ICV (gva.es)</a>	Institute of Cartography of Valencia
Area delimited by territorial planning	Areas delimited by territorial, environmental and urban planning	<a href="http://icv.gva.es">ICV (gva.es)</a>	Institute of Cartography of Valencia
Landscape interest	Areas of scenic interest	<a href="http://icv.gva.es">ICV (gva.es)</a>	Green Infrastructure and Landscape Service - Regional Ministry of Territorial Policy, Public Works and Mobility - Generalitat Valenciana
Municipal places (municipal natural landscapes)	Areas of interest of the Municipal Natural Sites	<a href="http://icv.gva.es">ICV (gva.es)</a>	VAERSA, Valenciana de Fomento Energética de Residuos S.A.
Strategic forest floor of PATFOR	Delimitation of the Strategic Forest Land according to the criteria of the Forest Territorial Action Plan of the province of Castellón (PATFOR)	<a href="http://icv.gva.es">ICV (gva.es)</a>	SERVICIO DE ORDENACIÓN Y GESTIÓN FORESTAL - Conselleria d'Agricultura, Medi Ambient, Canvi Climàtic i Desenvolupament Rural - Generalitat Valenciana
ZEPA and ZEC CD zoning	Special Protection Areas for Birds (SPAs) in the province of Castellón	<a href="http://icv.gva.es">ICV (gva.es)</a>	Ministry of Agriculture, Environment, Climate Change and Rural Development - Generalitat Valenciana
Highways, Minor Roads,	Road's infrastructures	<a href="https://download.geofabrik.de/">https://download.geofabrik.de/</a>	OpenStreetMap Data

Railway, and Roads			
Clay	Areas with soft and very soft clay type soils	<a href="http://icv.gva.es">ICV (gva.es)</a>	Valencian Institute of Building - Ministry of Housing and Bioclimatic Architecture - Generalitat Valenciana
Urban soil	Spaces on urban land and developable land incorporated into the approved Municipal Green Infrastructure, for their functions of connection and landscape integration of urban spaces and the IV in the exterior of urban fabrics (LOTUP)	<a href="http://icv.gva.es">ICV (gva.es)</a>	Green Infrastructure and Landscape Service - Regional Ministry of Territorial Policy, Public Works and Mobility - Generalitat Valenciana
GHI	The average yearly sum of global horizontal irradiation (GHI) covering a period of 25 recent years (1994 - 2018)	<a href="http://global-solar-atlas.com">Global Solar Atlas</a>	World Bank Group and Global Solar Atlas (GSA)
Flooding danger 1- 7 PATRICOVA	Flood hazard is defined as the probability of occurrence of a flood, within a given period of time and in a given area. There are 6 hazard levels, levelled from 1 to 6 from highest to lowest hazard and a seventh level of geomorphological hazard.	<a href="http://icv.gva.es">ICV (gva.es)</a>	Dirección General de Ordenación del Territorio, Urbanismo y Paisaje - Conselleria d'Habitatge, Obres Públiques i Vertebració del Territori - Generalitat Valenciana
Photovoltaic power potential	the amount of power generated per unit	<a href="http://global-solar-atlas.com">Global Solar Atlas</a>	World Bank Group and Global Solar Atlas (GSA)

(PVOUT)	of the installed PV capacity over the long-term.		
DEM (source of Slope and Orientation rasters)	Digital terrain model in raster format	<a href="http://gva.es">ICV (gva.es)</a>	Valencian Cartographic Institute
Castellon administrative boundary	Castellon administrative boundary	<a href="https://www.arcgis.com/home/item.html?id=5eb88decbff54520b49c785241c07bf4">https://www.arcgis.com/home/item.html?id=5eb88decbff54520b49c785241c07bf4</a>	ESRI
Gas pipeline, Oil pipeline, and Electrical lines	Energy equipment of the province of Castellón (year 1998) from the former COPUT, including information on power lines, gas pipelines and pipelines.	<a href="http://gva.es">ICV (gva.es)</a>	Antigua Conselleria d'Obres Públiques, Urbanisme i Transport (COPUT) - Generalitat Valenciana

Table 1: Data Description

### 3.4 Literature review for PVPP site selection methods.

To answer the first research question -- What methods, based on multi-criteria decision-making (MCDM) and GIS, are commonly used to select and analyse the impact of photovoltaic power plant sites? -- a literature review research method was used. The literature review method involves conducting a thorough search of relevant literature about a particular topic or area of study to gain a complete perspective of the current state of the art of the selected topic. Additionally, the literature review method helps identify gaps or limitations in previous studies, providing opportunities for further investigation and improvement in the current research. In this work, the focus of the review was the selection and analysis of photovoltaic power plant sites using MCDM and GIS. By conducting a literature review on the study topic, one can gain insights into how MCDM techniques have been successfully applied in similar studies related to site selection. Therefore, this gained knowledge can inform the methodology of the current study, ensuring that it builds upon existing research and contributes to the field's understanding of site selection for PVPP using MCDM.

Methodologically speaking, the selected sources for the review were journal articles published between 2020 and 2024 and indexed in renowned scientific databases such as Science Direct and IEEE Xplore. These studies either used MCDM or GIS methods or a combination of both methods for site selection analysis of solar and photovoltaic power plants. Both databases were chosen because they are both accessible and known for supporting the academic advancement of publications on the topic of renewable resources.

For the search, the key terms used were "site selection analysis," "solar power plants," "photovoltaic power plants," "MCDM methods," and "GIS methods." The search yielded a total of 21 relevant articles that met the search criteria. The analysis of these articles provided valuable insights into the current trends and advancements in the field of site selection analysis for solar and photovoltaic power plants using MCDM and GIS methods.

### 3.5 Methods to develop a geoprocessing toolbox.

To answer the second research question, -- How can a toolbox be developed within ArcGIS Pro, integrating PV power plant site selection and impact analysis methods using ArcGIS Python libraries? -- a design-and-creation method was employed to develop the toolbox. As mentioned in the problem statement, there is no unified tool that supports all the GIS-based methods for choosing a photovoltaic power plant site using the MCDM approach. The current research aims to address this gap by developing a tool within the ArcGIS Pro environment.

The design-and-creation method transforms theoretical concepts and techniques into practical tools that can be used within the ArcGIS Pro environment (Cross, 1993). The methods transformed involve algorithms required for site selection and impact analysis, which are implemented using ArcGIS Python libraries. Additionally, user-friendly interfaces were created to ensure ease of use for non-technical users.

The creation process will use existing geoprocessing tools, such as buffering, overlay analysis, reclassify tools, and other programming functions and conditions, such as loop structures or conditional statements, to enhance the tool's functionalities. In addition, the design-and-creation method has an iterative structure that enables further refinement and improvement.

The toolbox was developed in the ArcGIS Pro environment because most of the already existing tools for site selection are found inside the ArcGIS geoprocessing tools. For example, the "Weighted Overlay Tool" allows users to assign weights to different factors, such as land use or soil type, and then multiply each weight with its respective layer, which is then summed up to a raster file output.

Additionally, ArcGIS provides a user-friendly interface for developing toolboxes, with drag-and-drop functionality and a visual programming environment that allows users to easily create custom tools. Furthermore, the ArcPy library in ArcGIS contains a wide range of pre-existing script functions that can be used to build tools, reducing the need for coding from scratch. Furthermore, the extensive documentation and support available for ArcGIS make it easy for users to find resources and troubleshoot any issues they may encounter during the toolbox development process.

The toolbox that is developed in ArcGIS Pro can be shared with others easily via different methods. One of the options involves publishing the toolbox to ArcGIS Online, a cloud-based platform that enables users to access and use the toolbox from anywhere with an internet connection (Zandbergen, 2020). Another option is to save the toolbox on an accessible network drive within an organization. Additionally, the toolbox can also be shared as a standalone executable file that can be installed on other computers and

used without requiring ArcGIS Pro (Zandbergen, 2020). These options make sure that the toolbox can be shared and used by other users, encouraging teamwork and productivity.

Zandbergen's research focused on developing a geoprocessing toolbox using the Python programming language and outlined six steps necessary to build a script tool inside a toolbox (Zandbergen, 2020). Zandbergen's work provided valuable insights into the process and served as a guide for developing the geoprocessing toolbox in the current study. By incorporating Zandbergen's research, the study aims to build upon his framework and develop the PVPP site selection toolbox's functionality.

Figure 6 depicts the workflow of Zandbergen's steps for creating script tools. Part 1, shaded in blue, involves the initial processes of creating script files and creating a custom toolbox that will store the script tools in ArcGIS Pro. Once the first part is complete, the workflow continues in part 2, shaded in yellow, which involves modifying the script, configuring the toolbox, and testing the script tool. In the next paragraphs, each step of Zandbergen's workflow will be discussed in the context of the current study.

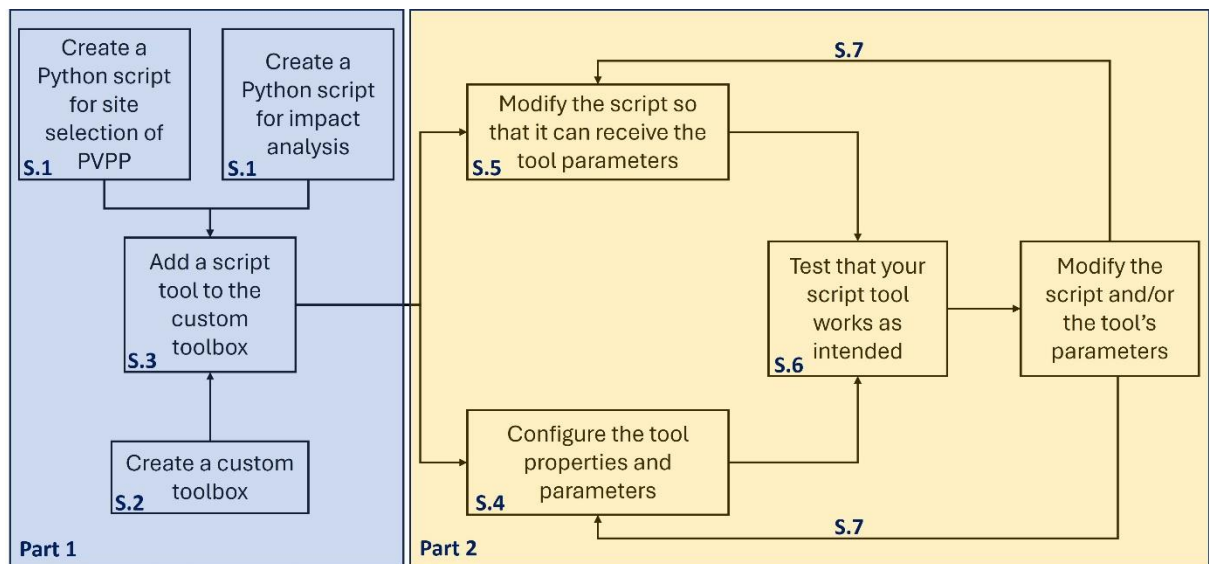


Figure 5: Script Tool Development Workflow

**Step 1. Creating Python Scripts (S.1)**

The site selection analysis consists of multiple operations in which the result of one operation becomes the input of the next operation. Scripting can support this process, particularly while using ArcGIS tools to run these operations in a sequential workflow. In ArcGIS Pro, it is possible to transform a Python script (.py) into a tool that runs as a geoprocessing tool. The script tool has similar capabilities as other tools; it has an open dialog box where ArcGIS users can interact; it can be used in other tools or models; and it is also possible to share the tool within the teams, organization, or outside the organization (Zandbergen, 2020).

**Step 2. Create a custom toolbox (.tbx file) (S.2).**

The process of creating a new custom toolbox in ArcGIS Pro was done by opening the Catalog pane from the View tab in the Windows group. After the Catalog pane was opened, the toolbox option was selected, right clicked on, and then choosing a new

Toolbox. A specific folder was chosen to save the toolbox on my local disk, and gave the toolbox a name PVPP toolbox.

Step 3. Add a script tool to the custom toolbox (S.3).

Two script tools were created, namely PVPP Site Selection and PVPP Impact Analysis. The process used to create both tools were similar. The first step involves opening the PVPP toolbox in the Catalog pane, right-clicking to the PVPP toolbox, and then choosing “New Script”. Both tools are named according to their intended functionality.

Step 4. Configure the tool properties and parameters (S.4).

After the script tool is created in a geoprocessing toolbox, the tool properties and parameters are configured. Firstly, to accept the Python script created earlier, the tool properties are changed to link the Python file containing all the developed scripts. Secondly, the tool parameters are set. Users interact with the tool through parameters in a tool dialog box.

Step 5. Modify the script so that it can receive the tool parameters (S.5).

The tool will start to work properly when the Python script can interpret the parameters set for the tool. To achieve this, the scripts are modified using mainly two functions: the `GetParameterAsText()` and `GetParameter()` functions of ArcPy. Both functions retrieve the information of the tools using the parameter index. The `GetParameterAsText()` reads the parameters information as a text string while the `GetParameter()` reads them as a list.

Step 6. Test that your script tool works as intended (S.6).

The tool was tested by adding actual data from the province of Castellón. The data consists of vector and raster data usually used in the site selection of photovoltaic power plants. The testing process ensures that the script and tool are communicating smoothly and shows the success of the development. Both script tools, PVPP site selection, and PVPP impact analysis, were tested and obtained the results.

In addition to validating the tool results and accuracy, similar data were employed in the Pathfinder web application, where the parameters were equally set. The results were also observed and compared. The PVPP site selection was the only validated tool. The PVPP impact analysis was not validated due to the lack of a similar tool in the Pathfinder application.

Step 7. Modify the script and/or the tool’s parameters (S.7).

Since the toolbox supports iterative behaviour, the modification of the tools, scripts, and toolbox can be continued when necessary. The ArcGIS Pro encourages such behavior, whereby the tool can be shared with others, thus supporting feedback.

To develop the second tool for analyzing the social and environmental impacts of PVPP sites, this study built on an existing cost model in the Pathfinder application. The Pathfinder application is a web-based tool used in the field of renewable energy, including but not limited to optimal site selection and grid connection (Gilytics AG, 2024). The Pathfinder web-based application considers factors such as transmission lines and access roads to calculate the total cost of a particular path. While this model has been valuable for evaluating the impacts of project routes, it cannot assess the impacts of specific sites, which is the main focus of this research. By building upon the

existing cost model and adapting it to determine the impacts of PVPP sites, this study aims to fill this gap by providing a tool for analyzing the social and environmental implications of PVPP sites.

The existing cost model provided a foundation for understanding the cost or impact that environmental, socioeconomic, and technical features have on the route, such as transmission lines or access roads. Figure 6 and Table 2 show how the Pathfinder model calculates the total cost of a particular path over different layers, which could be environmental or social features.

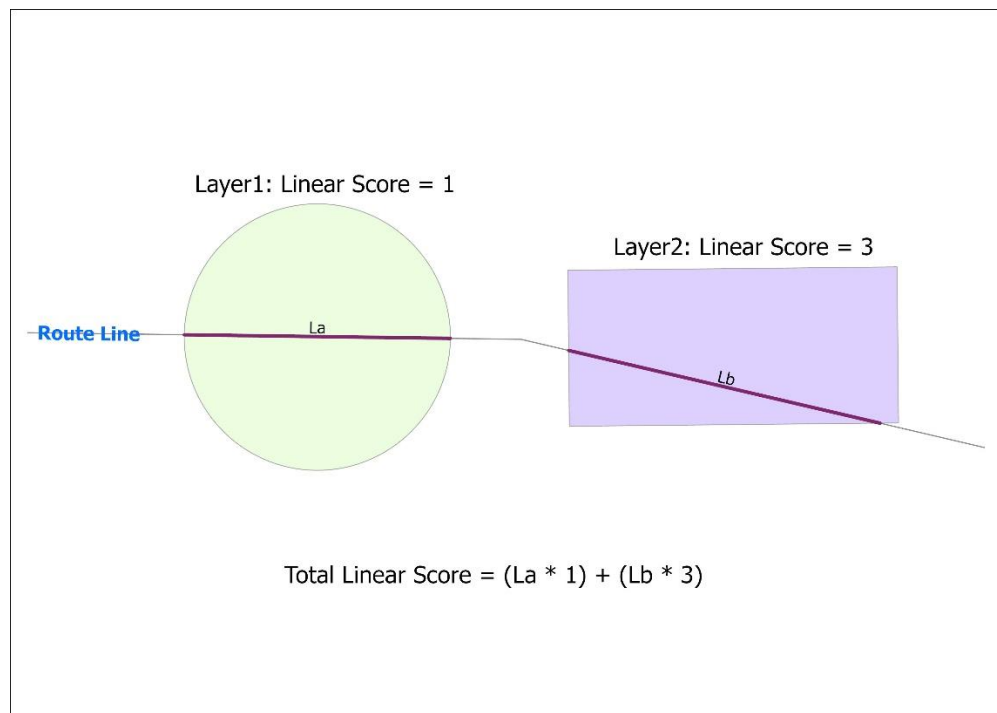


Figure 6: Cost assessment illustration model by Pathfinder.

This is how the data would like in the Pathfinder Application.

Name	Crossed	Layer Weight	Total Score
Layer 1: Agricultural (Km)	6	1	6
Layer 2: Farmland (Km)	2.3	3	6.9

Table 2: Cost assessment results in Pathfinder

The model incorporates global properties, such as the base cost per route length unit, and layer-specific properties, such as the importance score for the environmental impact layer (Gilytics AG, 2023). By multiplying the per-layer score values by the crossing length, the model determines the total cost of the linear route (Gilytics AG, 2023).

For this study, the foundation parameters used in the creation of the tool will be the cost per site area unit and the importance score for each environmental or social impact layer. These parameters serve as the basis for assessing the impact of these features on the PVPP sites. By assigning a cost value to each unit of site area and a score to each

impact layer, the tool will be able to evaluate the overall environmental and social implications of the PVPP sites.



## Chapter 4: Results and Discussion

The result section is divided into two sections. Section 1/ describes and discusses the MCDM and GIS-based methods for PVPP site selection identified through a literature review. Section 2/ demonstrates tools developed for PVPP site selection and impact analysis. The main idea of this study is to create a toolbox in the ArcGIS environment, which is used in the site selection analysis of photovoltaic power plants and in assessing the impact the resulting sites have on the environmental and social features.

### 4.1 PVPP site selection methods.

Through a thorough analysis of the use of MCDM and GIS tools in the selected studies, the most common methods were identified, which highlights the significance of some methods in comparison to others. This process offers good insights that one can use in our own studies to address the main research questions. Table 3 classifies eligible studies according to whether MCDM and GIS are used in isolation or in combination. Notably, 20 of the 21 studies reviewed used both MCDM and GIS in the site selection analysis. The MCDM provides a hierarchical structure, while GIS offers spatial analysis capabilities. This highlights the importance of combining both tools in order to enhance the site selection analysis.

Source	Use of MCDM and GIS	Reference
Science Direct	Both GIS and MCDM	(Agyekum et al., 2021; Almasad et al., 2023; Colak et al., 2020; Demir et al., 2023b; Elboshy et al., 2022; Habib et al., 2020b; Hasti et al., 2023; Islam et al., 2024; Kocabaldır & Yücel, 2023b; Marques-Perez et al., 2020; Qiu et al., 2022; Rekik & El Alimi, 2024; Rios & Duarte, 2021; Villacreses et al., 2022; Zambrano-Asanza et al., 2021a)
	MCDM only	None
	GIS only	None
IEEE	Both GIS and MCDM	(Ahmetović et al., 2022; Genç & Karipoğlu, 2021; Rahayani & Nair, 2023; Rekik & El Alimi, 2023; Tempa & Singh, 2020)
	MCDM only	(C.-N. Wang et al., 2021)
	GIS only	None

Table 3: MCDM and GIS Methods

For each eligible study in Table 1, we examined how the MCDM approach was applied in combination with GIS tools, resulting in three different stages, as discussed in the section below.

### Stage 1: The criteria identification or criteria selection

At this stage, the installation of a renewable energy power plant involves identifying factors that lead to a successful use of available resources in terms of the physical structure of the space, the economic viability of the project, environmental sustainability, and social considerations.

There are mainly two categories of criteria that influence the suitability of sites to install photovoltaic power plants: evaluation and exclusion criteria (Agyekum et al., 2021; Islam et al., 2024; Kocabaldır & Yücel, 2023a; Rios & Duarte, 2021; Shao et al., 2020; Zambrano-Asanza et al., 2021b). On the one hand, the exclusion criteria are factors that are totally prohibited while doing the analysis. These factors are usually called restrictive criteria. They are excluded from the suitability analysis results of the site selections. Examples could be anything that would affect the well-being of society or might instead increase the cost of installation or maintenance of the photovoltaic infrastructure. In addition, factors that would destroy the ecosystem or harm biodiversity are also considered exclusion criteria (Agyekum et al., 2021; Islam et al., 2024; Kocabaldır & Yücel, 2023a; Rios & Duarte, 2021; Shao et al., 2020; Zambrano-Asanza et al., 2021b).

On the other hand, evaluation criteria are factors that are necessary to effectively ensure a suitable spot for a photovoltaic power plant. It includes solar irradiation, slope, proximity to transport infrastructure, average annual cloudy days, and land availability. These factors are usually grouped into four categories: technical, economic, social, and environmental (Agyekum et al., 2021; Islam et al., 2024; Kocabaldır & Yücel, 2023a; Rios & Duarte, 2021; Shao et al., 2020; Zambrano-Asanza et al., 2021b).

At this stage, there is no specific GIS tool or method employed to identify criteria. However, GIS tools are used to process the collected data into formats that can be easily integrated into other stages. For example, if proximity to road infrastructure is one of the criteria necessary to install a photovoltaic power plant, then data on roads as lines in a vector format is collected. Using a buffer analysis tool, a GIS tool, the road data is converted into polygons with the specified proximity distance. The new road (output) data will then be used as an input in the normalization stage of MCDM.

### Stage 2: The Criteria Normalization

At this step, the data for each criterion are collected and normalized based on a specific method. Due to the variety of the data used in the site selection of photovoltaic, the data are standardized in the same format by applying normalization methods. This ensures that all the data can be compared and analysed effectively. The normalization process helps to eliminate any bias in the data, allowing for the accurate evaluation of each criterion's importance in the site selection process (Shao et al., 2020). The qualitative data are transformed into numeric data to support the calculations, allowing mathematical models to be applied (Shao et al., 2020).

Table 4 illustrates the normalization method applied in the reviewed studies. They are categorized into three sections. Section one includes studies that used GIS tools to normalize the data collected. Section two contains studies that used other statistical methods to standardize the data. Section three comprises studies that did not mention any normalization method.

Categories	Methods	References
Using GIS	Fuzzy membership function	(Rekik & El Alimi, 2024)
	Reclassification	(Colak et al., 2020; Islam et al., 2024; Kocabaldir & Yücel, 2023b; Tempa & Singh, 2020)
	Reclassification and linear scaling	(Rekik & El Alimi, 2023; Villacreses et al., 2022)
No GIS	Fuzzy membership function	(Ahmetović et al., 2022; Almasad et al., 2023; Hasti et al., 2023)
	Expert scoring	(Agyekum et al., 2021; Elboshy et al., 2022; Marques-Perez et al., 2020; Rahayani & Nair, 2023; C.-N. Wang et al., 2021)
	Linear scaling	(Zambrano-Asanza et al., 2021a)
No normalization method is mentioned		(Demir et al., 2023b; Genç & Karipoğlu, 2021; Habib et al., 2020b; Qiu et al., 2022; Rios & Duarte, 2021)

Table 4: Criteria Normalization Methods

### Reclassification

Reclassification involves setting ranges or classes of the criterion values, where each class is assigned a new value according to a particular scale range. The main objective of this method is to transform the quantitative criteria into generally classifiable qualitative criteria. This reduces the complexity of some of the raster information and speeds up other processing raster calculations. In the reviewed literature (table 4), 4 studies used reclassification as a normalization method, whereas 2 studies used it with the linear scaling method (Colak et al., 2020; Islam et al., 2024; Kocabaldir & Yücel, 2023b; Tempa & Singh, 2020).

The reclassification method is available in ArcGIS as a "reclassify tool." It supports the reclassification of raster data. The tool allows the user to set thresholds and corresponding classes. It also allows options for handling missing values (ArcGIS Pro Documentation, 2024). The tool can be automated to work with a batch of files (ArcGIS Pro Documentation, 2024). In addition, this tool is available in the ArcPy Python library; thus, it makes it convenient to create new tools and efficiently perform repetitive tasks.

### Fuzzy membership function

This tool determines the level of satisfaction of each criterion in relation to a potential site, on a scale from 0 to 1 (Ahmetović et al., 2022; Almasad et al., 2023; Hasti et al., 2023). Some studies solely use this method for normalization. The tool includes various functions, such as linear and sigmoidal functions, which users can choose based on the nature of the criteria values (Shao et al., 2020). The selection of the appropriate function is crucial, as it determines how the values of the criteria are transformed and weighted in further calculations. In the reviewed studies, the Fuzzy membership method was used in four studies, but it was only used once with the help of GIS software.

The ArcGIS version of this tool has the same functionalities of allowing membership types, namely, the Gaussian, Small, Large, MSSmall, MSLarge, and linear algorithms (ArcGIS Pro Documentation, 2024). The output is a floating-point raster with values ranging from 0 to 1 (ArcGIS Pro Documentation, 2024). The tool can also be retrieved from the ArcPy library, allowing users to incorporate it into their Python scripts and workflows.

### Linear scaling

According to (Shao et al., 2020), the linear scaling method is defined by the formula below:

$$x_{ij}^* = \frac{x_{ij}}{x'_j}$$

where  $x'_j = \max \{x_{ij}\}$  or  $x'_j = \min \{x_{ij}\}$  or  $x'_j = \frac{1}{n} \sum_{i=1}^n x_{ij}$ ; and  $x'_j > 0$

In the reviewed literature, linear scaling was used in three studies: twice with a GIS application and once independently. Linear scaling is available in the Rescale by Function tool in the ArcGIS Pro environment. The tool has multiple transformation functions, including linear transformation, which possesses the same functionality as the linear scaling method (ArcGIS Pro Documentation, 2024).

The tool requires the user to input data as a raster file, which is then transformed into a continuous scale. The advantage of using this tool over the reclassification methods is that it doesn't require the user to group the data into classes (ArcGIS Pro Documentation, 2024). It automatically calculates the scaling based on the minimum and maximum values of the input raster (ArcGIS Pro Documentation, 2024). This saves time and effort for the user, as they do not have to define class ranges manually. In addition, it supports both linear and non-linear algorithms, allowing various types of transformations to be applied to the input raster dataset (ArcGIS Pro Documentation, 2024).

### Expert scoring

Expert scoring is a frequently used method for normalizing qualitative data. The experts are selected based on their experience and knowledge in the specific domain related to the subject being studied (Agyekum et al., 2021; Elboshy et al., 2022; Marques-Perez et

al., 2020; Rahayani & Nair, 2023; C.-N. Wang et al., 2021). Their opinions are used to assess the pre-selected criteria. Their opinions are usually given in a qualitative format. Following that, additional analyses are performed to transform the qualitative data into quantitative data.

Based on the literature examined, expert scoring was utilized in five studies. This highlights why it is more often used in photovoltaic site selection. One reason is the multidimensionality of the site selection process, which combines data from various sectors, including technical, social, environmental, and economic sectors. In this situation, experts in each category provide more insights than individual judgments.

### Stage 3: Criteria Weighting and alternative evaluation.

At this level, the data is already commonly standardized in a raster format. The next step is to clarify the level of importance for each criterion. The processing is called weighting because criteria are ranked based on their significance in the site selection process. At this stage, there is no specific GIS tool available to support determining the weight coefficients; however, there are other statistical methods that support this process of finding weight coefficients, like the analytical hierarchy process (AHP). AHP is one of the prominent methods for weighting criteria in site selection analysis. Of the 21 studies reviewed, 15 used AHP as a single method to determine the weight of criteria for site selection analysis, and 6 used it in conjunction with other methods.

The AHP is performed in two steps. Pairwise comparison and Weighted Linear Combination (WLC). In the pairwise comparison, experts provide an opinion on the weight to which each criterion should adhere using a judgment matrix on a scale of 1 to 9. Then, based on the judgment matrix, a consistency test is performed to check whether the judgment made was reasonable or incorrect, which ultimately results in a final weight assigned to each criterion.

The second step involves performing the WLC after assigning weight coefficients to each criterion, as described in the formula below by (Shao et al., 2020).

$$S_i = \sum_{j=1}^n w_j x_{ij}, i = 1, 2, \dots, m$$

They are GIS tools that support WLC behaviours of integrating multiple criteria into a single output raster layer, such as weighted overlay, weighted sum, and fuzzy overlay tools. The weighted overlay and weighted sum tools support assigning the weight coefficient to different criteria and combining the values to produce a suitability map. On the other hand, fuzzy overlay allows only rasters with fuzzy membership values, which are merged using operators to create the suitability map. Each of the tools is explained separately below.

#### Fuzzy Overlay

The fuzzy overlay tool in ArcGIS is part of the spatial analyst extension. It combines multiple fuzzy membership rasters using a fuzzy operator into a single output raster (ArcGIS Pro Documentation, 2024). The rasters have a membership value typically between 0 and 1, which indicates the level to which a cell belongs to a particular category class (ArcGIS Pro Documentation, 2024). The fuzzy operator includes And, Or, Sum, Prod, and Gamma (ArcGIS Pro Documentation, 2024). The tool generates an

output raster whose cell value represents the combined influence of all the input rasters based on the chosen fuzzy operator.

### Weighted Overlay

The weighted overlay tool is a spatial analysis technique used to combine raster layers into a single output raster layer (ArcGIS Pro Documentation, 2024). The input rasters can represent different criteria in site selection analysis; they must be standardized into a common scale and assigned weights of importance (ArcGIS Pro Documentation, 2024). To create the output, all the input layers are combined by multiplying each cell value in a layer by its corresponding weight and then adding up the weighted values throughout all the layers (ArcGIS Pro Documentation, 2024).

### Weighted Sum

The Weighted Sum tool in ArcGIS is a tool that combines multiple raster layers into a single output raster layer based on assigned weights (ArcGIS Pro Documentation, 2024). It is similar to the Weighted Overlay tool, but there is a key difference between the two. The Weighted Sum tool supports both integer and floating-point rasters, whereas the Weighted Overlay tool only supports integer rasters (ArcGIS Pro Documentation, 2024). Additionally, the Weighted Sum tool does not allow normalizing the input raster layer (ArcGIS Pro Documentation, 2024).

In addition, ArcGIS has an inbuilt tool that facilitates locating potential sites from a suitability map. This tool is called the "Locate Regions Tool," which is in the Spatial Analyst toolbox. This tool uses the output of the overlaid weighted rasters to propose potential sites with a particular shape and size that depends on the user specification (ArcGIS Pro Documentation, 2024). It thus improves the manual process of visually inspecting the suitability map and manually identifying potential sites.

## 4.2 Toolbox development demonstration

A toolbox was developed in the ArcGIS Pro software. The toolbox contains two script tools: the PVPP site selection tool and the PVPP impact analysis tool. Both script tools were built from Python scripts. The ArcPy library was the main library used because it contains all the functionalities and capabilities of the geoprocessing environment that support the creation of tools and toolboxes in the ArcGIS Pro environment.

The ArcGIS Pro software was chosen because it supports the integration of GIS methods used in the MCDM analysis of photovoltaic site selection into a unified tool. Additionally, it has the capability of extending the functionalities of GIS tools used at different stages of MCDM, including criteria identification, normalization, weighting, and finding an alternative solution. The main workflow was to arrange all the tools necessary into a Python script, develop a geoprocessing script tool from the Python script, and integrate the tool inside the toolbox.

Additionally, ArcGIS Pro supported the development of the PVPP impact analysis tool. The tool was developed based on the Pathfinder model of assessing the cost of routes based on the overlaying features. All the algorithms needed were developed and integrated into a Python script and later as a tool in the ArcGIS Pro software. The final tool interface and input parameters of the PVPP site selection and PVPP impact analysis tools are explained in detail below.

## A. PVPP Site Selection Interface

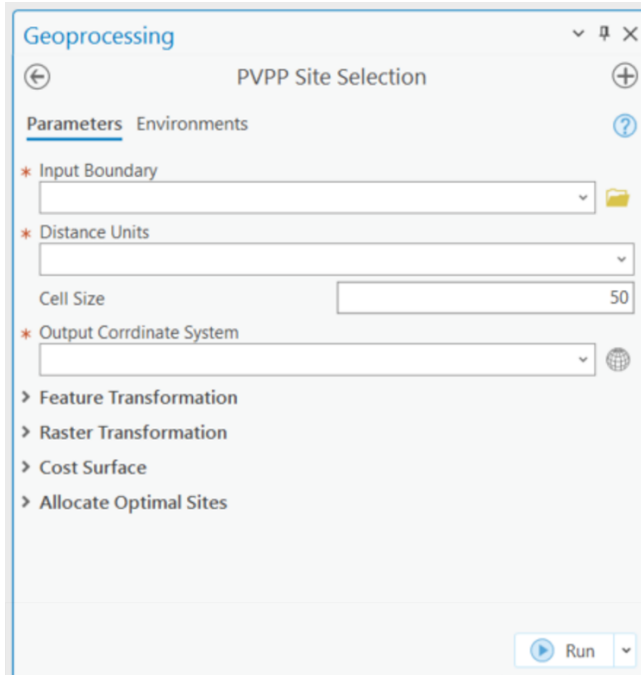


Figure 7: PVPP site selection tool interface.

The PVPP Site Selection tool can be grouped into five parts. Figure 7 shows the first interface the user sees when opening the tool. The tool interface looks like the normal interface of all ArcGIS geoprocessing tools. The tool shows a title in the upper part, the middle section shows the parameter layout, and at the bottom, the tool shows a Run button. The user should use the parameter layout section to enter either input from the data or directly type the information. In addition, the Run button is used to start the execution of the tool.

### Part 1

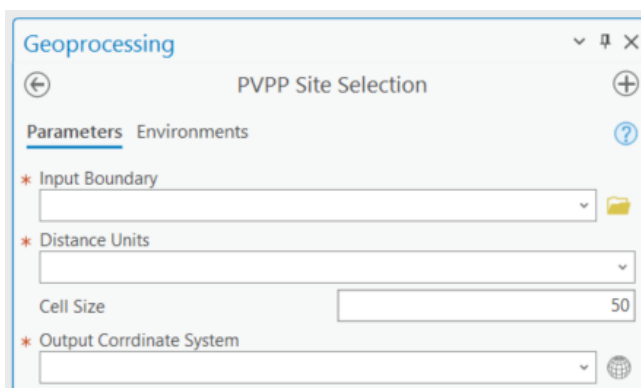


Figure 8: The PVPP site selection part 1 interface.

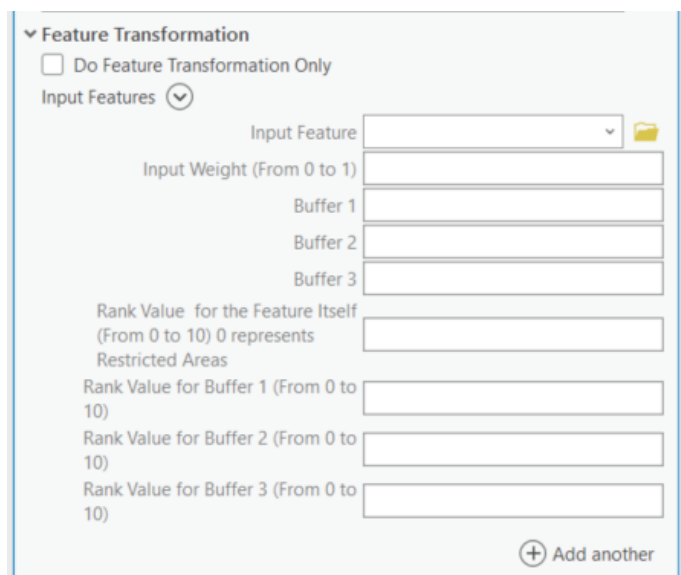
The first part of the tool consists of four parameters (Figure 8). The four parameters address the general essential input data that a user needs to specify ahead of time. It includes the input boundary, which is a polygon feature that represents the delimitation boundary of the study area, such as the city boundary, upon which the photovoltaic site selection is going to be applied. It includes a distance unit parameter, which shows a list

of imperial units, such as meters or feet, that the user must choose from. The selected unit will be used in all the analyses that request an imperial unit as an input feature.

Additionally, the first part includes a cell size parameter. The parameter supports only numerical numbers from 1 to 100. The cell size information supports all the analyses that involve raster transformations, for example, converting a vector feature to a raster feature dataset. Setting a cell size will ensure that the tool output reflects the specified details. The last parameter in the first part is an output coordinate system parameter. It supports the projected coordinate system. Users can specify it directly, or they can use the available list from the software by clicking on the globe button located on the left side of the parameter. This will ensure an accurate spatial reference in the input data.

## Part 2

The second part involves the processing of the vector features by performing proximity analysis, normalizing the data, and assigning weights (Figure 9). The first parameter set as a Boolean type asks the user whether to do feature transformation only or not. The user might want to process the vector data only; thus, the tool supports this capability. The second parameter requests the user input feature, which could be a point, a line, or a polygon feature. The input feature can be dragged from the layers in the content pane, or it can be retrieved from a local disk.



The screenshot displays the 'Feature Transformation' section of a software interface. It includes a checkbox for 'Do Feature Transformation Only', an 'Input Features' dropdown menu, and several input fields for 'Input Feature', 'Input Weight (From 0 to 1)', 'Buffer 1', 'Buffer 2', 'Buffer 3', and three 'Rank Value' fields (for the feature itself and for each buffer). A '+ Add another' button is located at the bottom right.

Figure 9: The PVPP site selection part 2 interface.

The third parameter requests the weight coefficient of the input feature. The weight should be in a range between 0 and 1. The user specifies the input weight directly for each feature. The methods of finding a weight value are not introduced in this tool. However, the tool accepts the final weight values obtained, which are the ones that should be incorporated into this parameter.

Buffer 1, Buffer 2, and Buffer 3 are proximity analysis parameters that request a specific number in terms of distance. They perform a buffer analysis on the input feature. Though there is an exemption on point and line features, due to the nature of the site selection analysis, all point and line features must be converted into polygons to be properly analysed.



The rest of the parameters work on the ranking input feature. On a scale ranging from 0 to 10, the features are ranked with respect to the level of their importance. 0 represents features that should be excluded from the analysis, 1 represents features with low significance, and 10 represents features with high significance. If the input features were passed through a proximity analysis, then each buffer performed would also be ranked.

### Part 3

The third part of the tool consists of the raster transformation (Figure 10). The processing of the raster feature can be divided into two groups: reclassification and rescaling. Depending on the user's interest, they can choose to transform raster data from its natural values to a scale of 1 to 10, or they can choose to reclassify it into a set of classes. Both options are available in this tool.

Similarly to the vector transformation, the tool supports the choice of only performing raster analysis. The user can set that option in the first parameter. The second parameter allows adding the input raster to the tool by either choosing from the layers available in the content pane or by choosing from the local disk. The raster used in such analysis must at least have one band. Additionally, a weight value is assigned to the raster data based on its importance in the third parameter space. It should be a numeric value ranging from 0 to 1.

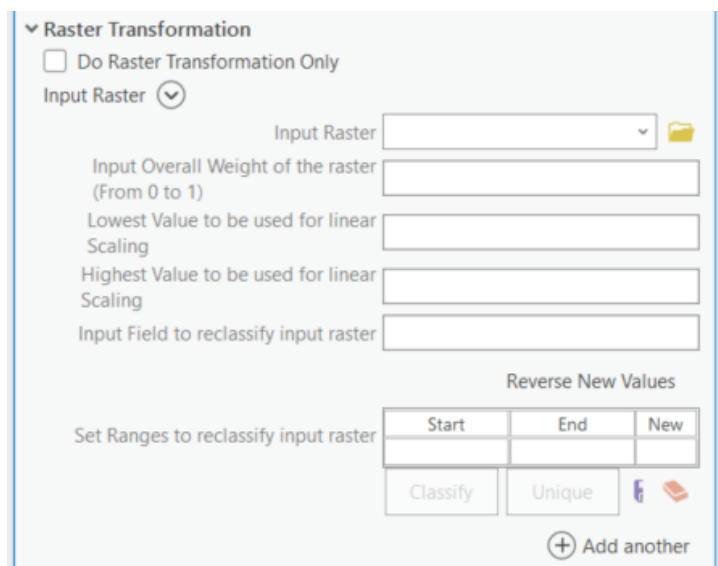


Figure 10: The PVPP site selection part 3 interface.

The third and fourth parameters accept numerical values used for rescaling the input raster feature. Both the lowest or minimum value of a raster and the highest or maximum cell value of a raster are entered in the respective parameter. These values are linearly transformed on a scale of 1 to 10. Figure 11 shows how a linear transformation works.

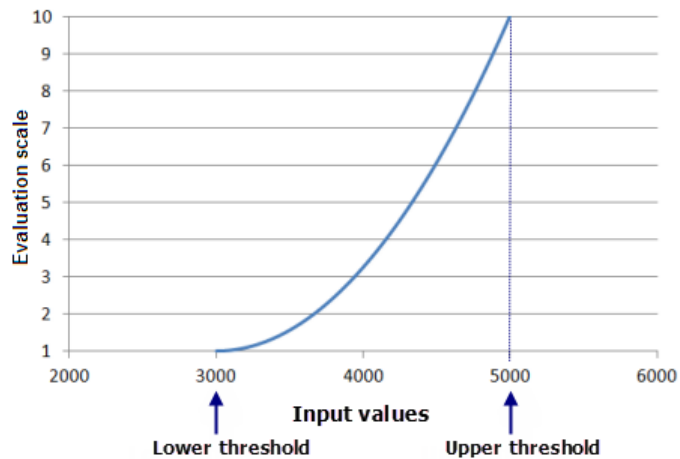


Figure 11: Linear Transformation Graph

The rest of the parameters are used to reclassify the input raster feature. The input field to reclassify is the name of a field in the attribute whose values are going to be reclassified. Depending on the user's choice, classes are defined, and a new value representing the level of importance is assigned, from 0 to 10. 0 represents restricted areas, and values from 1 to 10 represent low significance to high significance, respectively.

#### Part 4

The fourth part consists of one parameter, which computes the suitability analysis map (Figure 12). The parameter itself is an output parameter, meaning it is used to set the name of the output and the path where the suitability raster layer will be stored. To compute this analysis, a weighted sum tool was used. Every input feature and input raster is assigned a weight coefficient on a scale of 0 to 1, and it has an attribute field storing the ranking values in a range of 0 to 10. Firstly, the features with 0 values are excluded using the mask functionality in the environmental settings of the tool. The rest of the features are passed through the weighted sum tool, which multiplies the weight with the ranking value of each feature and combines all the features into a single raster.

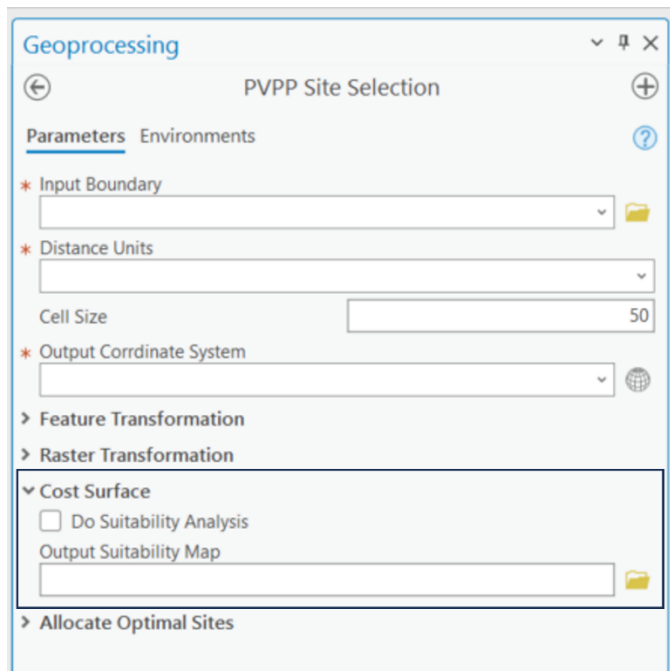


Figure 12: The PVPP site selection part 4 interface.

### Part 5

The fifth part of the PVPP site selection tool is to allocate optimal sites (Figure 13). At this level, all the above parts must be filled with data and relevant information. This part is structured to facilitate the user's ability to locate potential sites from the suitability map.

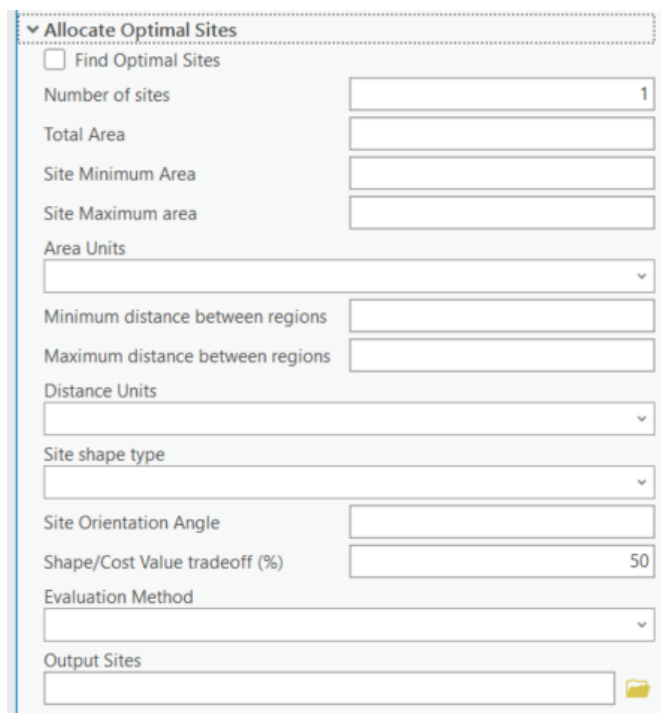


Figure 13: The PVPP site selection part 5 interface.

The user can dictate the outcome of the output using the available parameters, including the number of sites, the total area the site covers, the site minimum and maximum area, the area units such as square kilometers or miles, the minimum and maximum distance between sites, the shape of the site such as a square or a circle, the site orientation angle from 0 degrees to 360 degrees, the percentage at which shape should be maintained at the cost of the underlying cell values, ranging from 1 to 100, and the evaluation method that supports the selection of the best sites, among others. The output is a raster dataset, which can be stored in a file geodatabase or on a local disk.

### B. PVPP Impact Analysis Tool

The PVPP impact analysis tool has four parts (Figure 14). It was developed to assess the impact of sites on environmental and social factors. The result from the PVPP site selection tool is used as the main input in this tool.

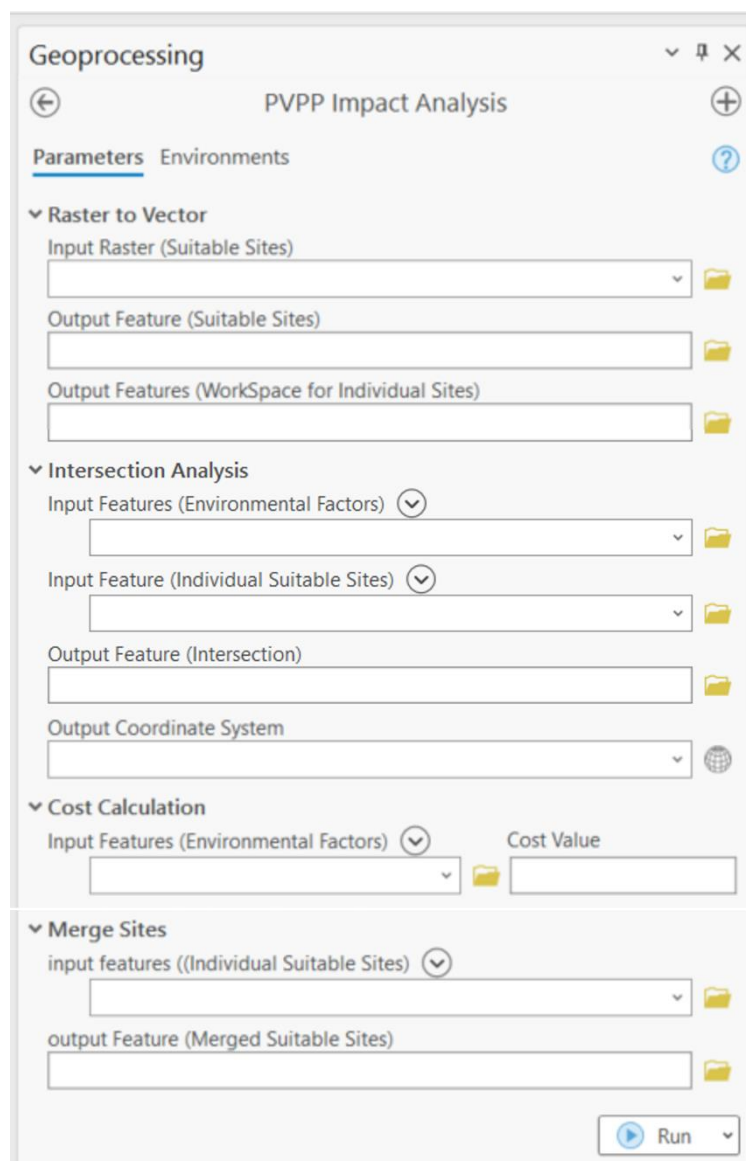


Figure 14: PVPP Impact Analysis tool interface.

The first part of the tool addresses the conversion of the potential sites from a raster format to a vector format. Additionally, the converted features are split into features. To achieve that, the user needs to specify three parameters set in the tool. The Input Raster (suitable sites) parameter helps the user select the raster layer that contains the sites in the content pane or retrieve the data in a local directory. The Output Feature (suitable sites) parameter helps the user set a path to where the vectorized feature will be stored. The Output Features (workspace for individual sites) parameter helps the user set a file geodatabase where all the individual sites will be stored. The raster to feature and split tools are used in the script file to support the tool operations.

The second part of the tool addresses the intersection analysis. Each of the optimal site polygon layers is overlaid with the other layers that represent areas that can be impacted in vector form. For example, the layer of site 1 intersects with layers such as "urban areas," "protected areas," and "high elevation areas." (which can be an elevation raster classified and vectorized). To support this process, four parameters were set inside the tool.

The first parameter, "Input Features (Environmental Factors)" accepts all the layers that will be assessed. They can be pulled from the content pane, the local file system, or the portal. The second parameter, "Input Feature (Individual sites)" is set to acquire the individual feature layers of sites. The third parameter, "Output Feature Intersection" can be used to set the output of the intersection analysis. The fourth parameter, "Output Coordinate system," is set for inputting the coordinate system of the user's choice.

The third part of the tool addresses the cost estimation analysis. To calculate the cost, an impact score, which could be different for each layer, is applied to the geometric area values of the intersection output. The results are added together, which gives the total impact score of each site. Two parameters were set to support this analysis. Firstly, the "Input Features (Environmental Factors)". It supports the output of the intersection analysis as input. Secondly, the "cost value" supports numerical values representing the cost of the environmental or social feature.

The fourth part of the tool addresses the merging of sites. At this level, each site should have a total impact cost. Therefore, the sites are merged into a single feature layer to facilitate the comparison analysis of the sites. Two parameters are set to support this merging process. "The input features (Individual suitable sites)", which retrieve all the individual layers of sites, and the " Output Feature (Merged Sites)", which helps the user set the name and the output location.

Below is the process through which each script tool was developed, with relevant details. The testing results are also demonstrated for both PVPP site selection and PVPP impact analysis tools, and in addition, the validation phase of the PVPP site selection tool is also presented and discussed.

## Step 1: Creating Python Script

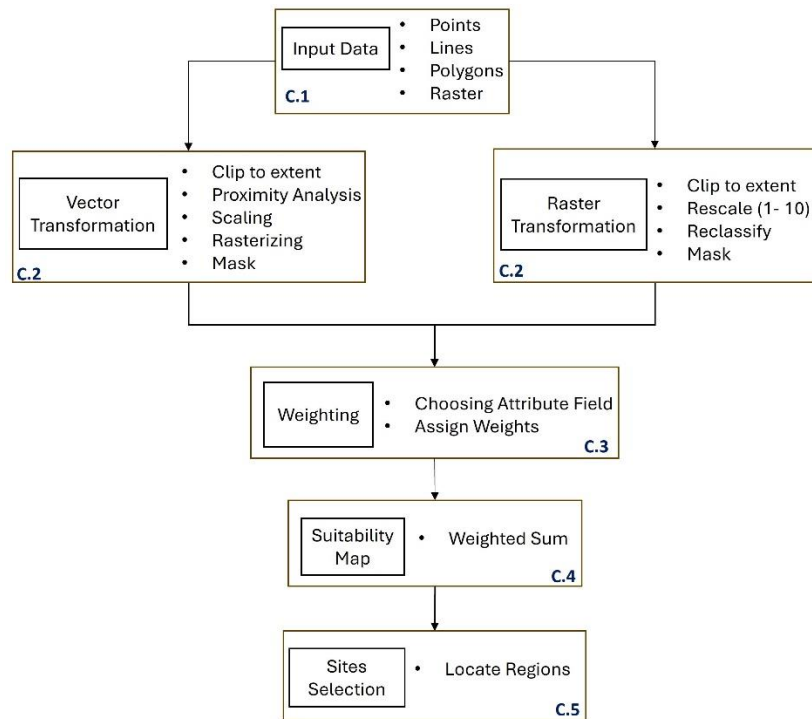


Figure 15: PVPP site selection tool Workflow.

Using a Python editor application PyCharm 2023 2.3, the scripts for selecting sites for photovoltaic power plants and analysing the social and environmental impacts were developed. First, a Python script for site selection of PVPP was created using the ArcPy library, and the script's structure was divided into five main categories (Figure 15). The first category (C.1) consists of setting the variables that store input data. This includes vector features (points, lines, and polygons) and raster features like the digital elevation model (DEM) or global horizontal irradiation (GHI).

The second category (C.2) consists of data processing. At this level, vector features and raster features are handled separately. The process of transforming vector features involved clipping (Clip Analysis Tool) all the features to the extent of the study area, performing proximity analysis (Multiple Ring Buffer Analysis Tool) on features like points and lines, converting (Feature to Raster Conversion Tool) features into raster data, normalizing (Calculate Field Tool) the features into a reasonable scale, and finally excluding the features with restricted areas. All the layers are projected into the same coordinate system with the Project Tool.

Besides that, raster features are also processed by taking input rasters and clipping them to cover the study area. These are then either reclassified (Reclassify Tool) into a set of classes or scaled linearly (Rescale by function Tool). Both tools normalized the data in the range of 1 to 10. Then, areas that are restricted are excluded from the dataset. All the input raster layers are projected into the same coordinate system with the Project Raster Tool. Additionally, rasters are set to a similar resolution size.

The third category (C.3) involves the weighting process. With the support of the Gilytics expert opinions (Table 5), all the features were assigned a weight coefficient on a scale of 0 to 1.

The fourth category (C.4) involves performing a weighted overlay analysis (Weighted Sum Tool), which includes multiplying each assigned weight coefficient for each raster feature by the normalized value and summing them all together. The output is the suitability map, ranking from 1 to 10. Where 1 means less suitable areas and 10 means highly suitable areas.

The fifth category (C.5) involves locating sites (Locate Regions Tool). From the suitability map obtained in the fourth category, we use the locate regions tool to identify the best regions that meet certain criteria, such as shape, the angle of orientation, the total area, and the distance between sites.

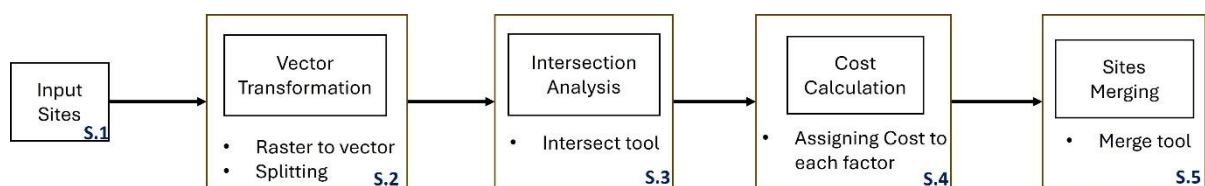


Figure 16: PVPP impact analysis tool Workflow.

Secondly, an impact analysis Python script was created using the ArcPy library to assess the potential sites' environmental and social impact. As described earlier, the tool was developed based on the cost assessment model of the Pathfinder application, which is used to calculate the cost a route has on the overlaying features.

The script developed can also be divided into five sections (Figure 16). The first section (S.1) involved importing the library and setting variables that store the path of data that are going to be used in the analysis. It also involves setting the environmental parameters of the script. At this level, the input data are the outputs of the previous script (potential sites for PVPP), which are sites located in the most suitable areas favoring photovoltaic power plants.

The second section (S.2) involves converting the sites from a raster format to a vector format using the Raster to Feature Tool. The output of the vectorization is then used as an input in the Split tool by splitting the sites into individual features.

The third section (S.3) involves the intersection analysis, where each individual site feature is overlaid (Intersection Tool) with environmental features such as water bodies, forest areas, soil classification, and parks, and social features such as population distribution. The intersection indicates the site's impact on the overlaying feature.

The fourth section (S.4) calculates each site's total impact cost. To find it, we take the geometric area values of the intersections (for instance, in square meters), apply an impact score (using Calculate Field) to these values—which can vary for each feature—and add the results to get a total impact score.

The fifth section (S.5) involves combining individual sites into a single feature layer using the merge tool. This merging of sites would support further analysis and comparison of the site's total impact cost. A site with high-cost values indicates a high environmental or social cost and is less preferable, while a site with low-cost values would indicate a low environmental or social cost and is more preferable.

## Step 2: Create a custom toolbox (.tbx file).

The PVPP toolbox was developed in the ArcGIS Pro software (Figure 17), with version 3.2.0. The steps followed to create the toolbox involved navigating to the Catalog pane, right-clicking the Toolboxes folder, choosing a new toolbox (.atbx), setting the name of the toolbox, and setting the directory path to a folder where the toolbox will be saved. The new toolbox was named PVPP Toolbox.

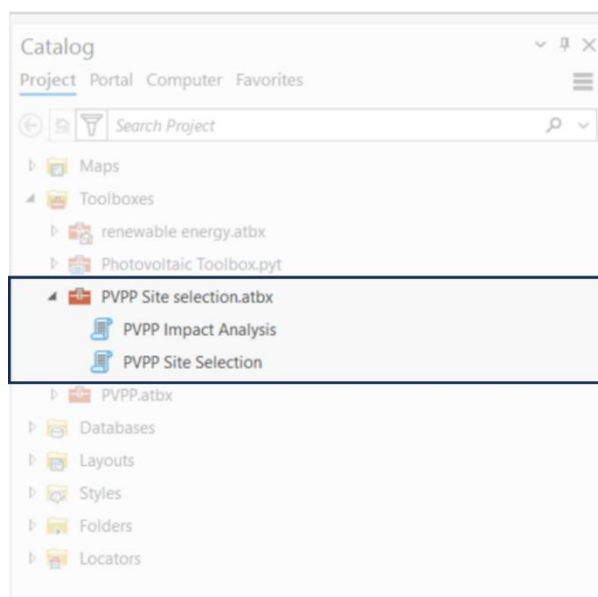


Figure 17: PVPP Site Selection Toolbox in ArcGIS Pro

## Step 3: Add a script tool to the custom toolbox.

Two script tools were created, namely PVPP Site Selection and PVPP Impact Analysis. The process used to create both tools was similar. The first step involves opening the PVPP toolbox in the Catalog pane, right-clicking on the toolbox, and then choosing New Script. Both tools are named according to their intended functionality.

## Step 4: Configure the tool properties and parameters.

After the script tools are created in a geoprocessing toolbox, the tool properties and parameters are configured. Firstly, for the tool to accept the Python script created earlier, the tool properties are modified to link the Python file containing all the developed scripts into the tool (Figure 18). Secondly, the tool parameters are set. Users interact with the tool through parameters in a tool dialog box.

On the PVPP Site selection script tool, 24 parameters were set (Figure 19), while in the PVPP impact analysis script tool, 11 parameters were also set. The process involves setting a name and label of a parameter, choosing a data type, choosing whether the parameter is an input or an output parameter, choosing if the parameter is required or



optional to the user, choosing a category, setting a filter, and setting default values where they are necessary. Figure 9 shows an example of the parameters set for the PVPP site selection script tool.

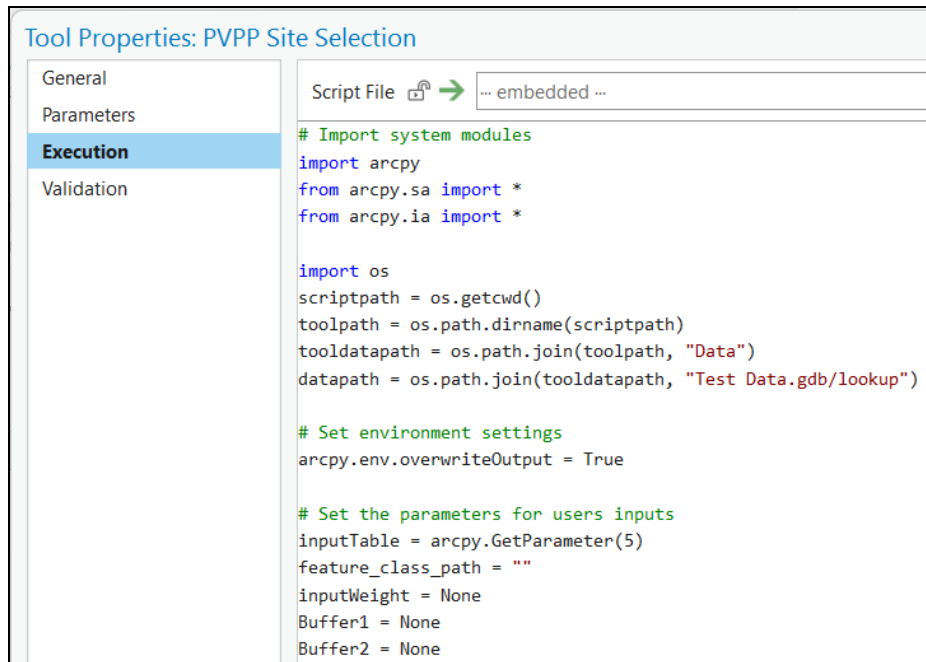


Figure 18: Tool properties modification.

	Label	Name	Data Type
0	Input Boundary	InputBoundary	Feature Layer
1	Distance Units	Distance_unit	String
2	Cell Size	Cell_Size	Long
3	Output Corrdinate System	Output_Corrdinate_System	Coordinate System
4	Do Feature Transformation Only	Perform_Vector_Analysis	Boolean
5	Input Features	Input_Features	ValueTable
6	Do Raster Transformation Only	Perform_Raster_Analysis	Boolean
7	Input Raster	Input_Raster	ValueTable
8	Do Suitability Analysis	Do_Suitability_Analysis	Boolean
9	Output Suitability Map	Output_Suitability_Map	Raster Layer,Raster...
10	Find Optimal Sites	Find_Optimal_Sites	Boolean
11	Number of sites	Number_of_sites	Long
12	Total Area	Total_Area	Double
13	Site Minimum Area	Site_Minimum_Area	Double
14	Site Maximum area	Site_Maximum_area	Double
15	Area Units	Area_Units	String
16	Minimum distance between regions	Minimum_distance_between_regions	Long
17	Maximum distance between regions	Maximum_distance_between_regions	Long
18	Distance Units	Distance_Units	String
19	Site shape type	Site_shape_type	String
20	Site Orientation Angle	Site_Orientation_Angle	Long
21	Shape/Cost Value tradeoff (%)	Shape_Cost_Value_tradeoff	Long
22	Evaluation Method	Evaluation_Method	String
23	Output Sites	Output_Sites	Raster Layer
*			String

Figure 19: PVPP site selection tool parameters.

### Step 5: Modify the script so that it can receive the tool parameters.

The scripts were modified to support the tool requirements. Both the PVPP site selection and PVPP impact analysis script tools were modified to accept the `GetParameterAsText()` and `GetParameter()` ArcPy functions. Both functions help to retrieve information the user enters in the tool dialog box. This information is then stored as variables in the script file, which thus facilitates easy use in the script geoprocessing analysis. Figure 20 shows an example of where the script was modified to use `GetParameterAsText()` and `GetParameter()`. Each parameter in the tool has an index number (0, 1, 2,...), which the `GetParameterAsText()` and `GetParameter()` functions use to retrieve its information.

```
# Description: Perform an environmental and social impact assessment cost
import arcpy

arcpy.env.overwriteOutput = True

# Set user parameters for converting optimal sites into vector features and split them
OptimalSites = arcpy.GetParameterAsText(0)
OptimalSitesVectorized = arcpy.GetParameterAsText(1)
IndividualSitesWorkspace = arcpy.GetParameterAsText(2)
```

Figure 20: Python script example.

After modifying both tools, the tool interface is automatically updated to display the input parameters corresponding to the variables in the script. This allows the user to enter values for each parameter when running the tool. Additionally, any changes made to the variables in the script will be displayed in the tool interface, ensuring uniformity between the script and the tool.

### Step 6: Testing the script tool.

The tool was tested by adding actual data from the province of Castellón. The data consists of vector and raster data used in the site selection analysis of photovoltaic power plants. The testing process ensures that the script file and tool communicate smoothly and show the success of the tool development. Both script tools, PVPP site selection, and PVPP impact analysis, were tested and obtained the results.

To test the toolbox, we conducted a study on the province of Castellón in the Valencian community. The main idea was to find 10 suitable sites for establishing photovoltaic power plants. Additionally, the selected sites will be assessed for their impacts on environmental features.

With the support of the Gilytics experts in the field of renewable energy, the main criteria were identified, and the necessary data was collected. The data were grouped into two main categories (Table 5). The exclusion criteria and the evaluation criteria. The exclusion data should be restricted from the suitability analysis while the evaluation data are processed and evaluated for the site selection analysis for PVPP.

The PVPP site selection tool was used first because it was designed to identify suitable sites for photovoltaic power plants. As explained above, the PVPP site selection has five parts. The first part involved setting the input boundary, the distance unit, the cell size, and the coordinate system. Figure 21 shows the information entered in the tool's parameters.

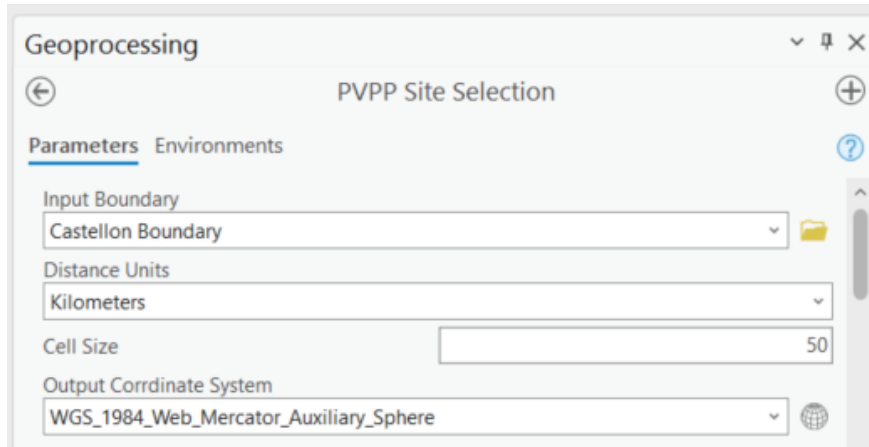


Figure 21: PVPP Site Selection Part 1 Input data.

The second and third parts of the PVPP site selection tool consist of processing the data. Table 5 summarizes all the inputs used on each layer to perform the site selection analysis of photovoltaic power plants in the province of Castellón.

Exclusion criteria for PVPP (Forbidden)	Data Format	Weight (0 - 1)	Buffer 1 (Km)	Buffer 2 (Km)	Buffer 3 (Km)	Rank 0 (0 - 10)	Rank 1 (0 - 10)	Rank 2 (0 - 10)	Rank 3 (0 - 10)
Ecological corridors	Vector	0				0			
High cultural value	Vector	0				0			
Natural park	Vector	0				0			
Natural park and microreserves	Vector	0				0			
Protected Landscape	Vector	0				0			
RAMSAR	Vector	0				0			
ZEPA and ZEC A B zoning	Vector	0				0			
Humid areas	Vector	0				0			
Riverbed	Vector	0				0			
Gas pipeline	Vector	0	0.01				0		
Oil pipeline	Vector	0	0.01				0		
Risks	Vector	0				0			
Livestock roads	Vector	0				0			
<b>Evaluation Criteria</b>									
Evaluation Criteria	Data Format	Weight (0 - 1)	Buffer 1 (Km)	Buffer 2 (Km)	Buffer 3 (Km)	Rank 0 (0 - 10)	Rank 1 (0 - 10)	Rank 2 (0 - 10)	Rank 3 (0 - 10)
<b>Protected areas</b>									
Area delimited by territorial planning	Vector	0.05				2			
Landscape interest	Vector	0.05				2			
Municipal places	Vector	0.05				2			
Natural reserve without planning	Vector	0.05				2			
Strategic forest floor of PATFOR	Vector	0.04				2			
ZEPA and ZEC CD zoning	Vector	0.04				1			
<b>Communication network</b>									

Highways	Vector	0.03	0.025	0.5	1		0	8	7
Minor Roads	Vector	0.03	0.025	0.5	1		1	9	7
Railway (Ring 2)	Vector	0.03	0.02	0.1			0	9	
Roads (Ring 2)	Vector	0.03	0.025	0.5	0.1		0	9	7
Solar project roads	Vector	0.03	0.025	0.1	0.2		5	9	7
<b>Lithology</b>									
Clay	Vector	0.01					4		
Urban soil	Vector	0.01	0.5				10	8	
<b>Global Horizontal Irradiation</b>									
GHI	Raster	0.05							
<b>Risks</b>									
Flooding danger 1 4 PATRICOVA	Vector	0.04					1		
Flooding danger 5 7 PATRICOVA	Vector	0.04					5		
<b>Photovoltaic Power</b>									
1 280.14 - 1 381.03	vector	0.04					5		
1 381.03 - 1 481.92	vector	0.04					5		
1 481.92 - 1 560.38	vector	0.04					6		
1 560.38 - 1 616.43	vector	0.04					8		
1 616.43 - 1 666.87	vector	0.04					10		
1 666.87 - 1 728.53	vector	0.04					10		
PVOUT	Raster	0.04							
<b>Energy</b>									
Electrical lines (2meters)	Vector	0.02	0.02	0.5	1		0	5	5
<b>Terrain</b>									
DEM	Raster	0.04							
Slope	Raster	0.04							
<b>Orientation</b>									
Orientation	Raster	0.04							
<b>Reclassification values</b>									
Features	Format	Weight	Start	End	New				
GHI	Raster	0.05	1271.071	1561.54	5				
			1561.55	1651.52	8				
			1651.53	1723.98	10				
DEM	Raster	0.04	-21	344.6	10				
			344.61	710.2	9				
			710.201	1075.8	8				
			1075.801	1441.4	5				
			1441.101	1807	3				
Slope	Raster	0.04	0.001	5.9	10				
			5.901	12.752	8				
			12.753	20.166	6				
			20.167	29.063	4				
			29.064	75.623	2				

Orientation	Raster	0.04	0	1	4
			1.1	4.9	5
			5	6	6
			6.1	9.9	5
			10	10	4
			10.1	11	5
<b>Linear scaling values</b>					
PVOUT	Raster	0.04	<b>Lowest Value</b>	<b>Highest value</b>	
			3.625	4.64	

Table 5: Input Data with parameters used in the PVPP site selection tool.

Figure 22 shows the information used to fill in parameters in the fourth and fifth parts of the tool. The fourth part involves setting up the name and the path of the suitability raster layer. The fifth part involves setting parameters related to the specification of the site itself, including the size, area, and shape.

The screenshot displays the 'Cost Surface' and 'Allocate Optimal Sites' sections of the tool. The 'Cost Surface' section includes a checked 'Do Suitability Analysis' box, an 'Output Suitability Map' field with the value 'Suitability\_Map', and a folder icon. The 'Allocate Optimal Sites' section includes a checked 'Find Optimal Sites' box and several input fields: 'Number of sites' (10), 'Total Area' (100), 'Site Minimum Area' (10), 'Site Maximum area' (10), 'Area Units' (Square Kilometers), 'Minimum distance between regions' (500), 'Maximum distance between regions' (empty), 'Distance Units' (Meters), 'Site shape type' (Square), 'Site Orientation Angle' (0), 'Shape/Cost Value tradeoff (%)' (50), and 'Evaluation Method' (Greatest core area). At the bottom, there is an 'Output Sites' field with the value 'Suitable\_Sites' and a folder icon, and a 'Run' button.

Figure 22: Cost Surface and allocate optimal sites input parameters.

Figure 24 represents the results obtained after running the toolbox in the ArcGIS Pro software. The suitability map and the potential sites allocated are both shown in the

map. The PVPP site selection tool took 1 hour and 14 minutes (Figure 23). The advantage of the tool developed in ArcGIS Pro is that it automatically finds the optimal sites.

**Started:** 09 January 2024 at 16:16:17  
**Completed:** 09 January 2024 at 17:30:54  
**Elapsed Time:** 1 Hour 14 Minutes 37 Seconds

Figure 23: PVPP Site selection execution time.

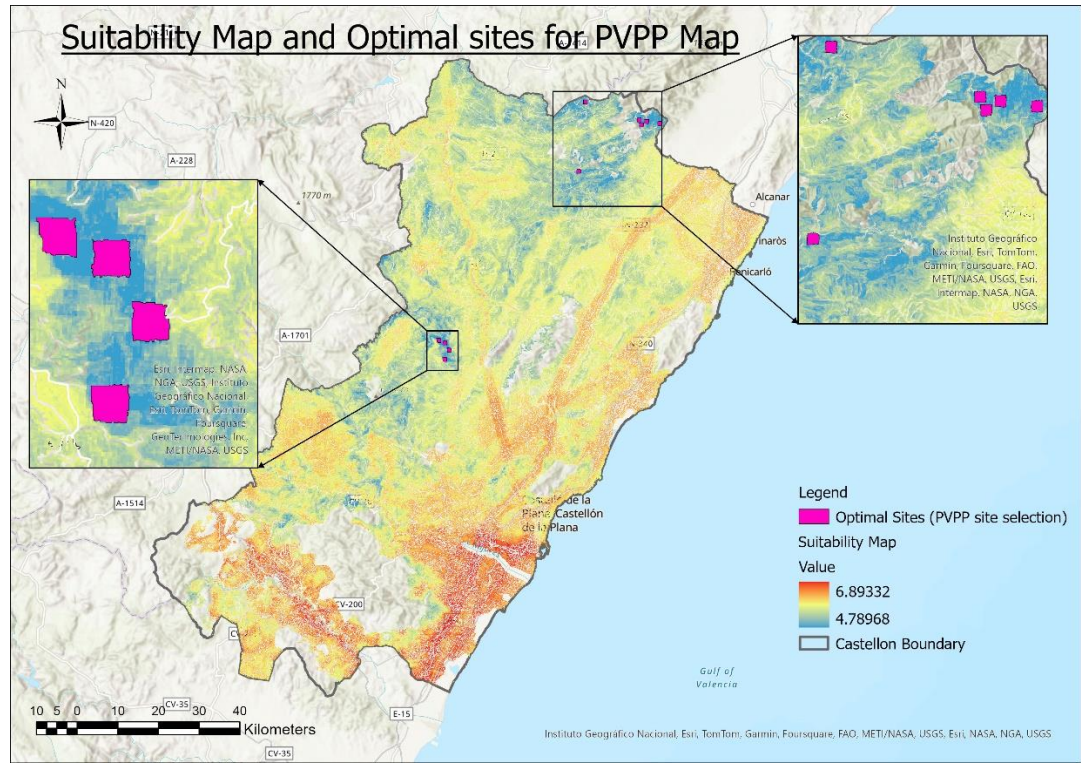


Figure 24: PVPP Site selection execution result.

Secondly, the PVPP impact analysis was computed; it used the results from the PVPP site selection tool to assess the potential environmental and socio-economic impacts of the proposed PVPP sites. This analysis provided valuable insights into the potential benefits and drawbacks of each site, allowing for a more precise comparison of the sites. Figure 25 shows the result of the PVPP impact analysis tool.

Table 6 summarizes the data used in the PVPP impact analysis tool. With the help of the Gilytics team of experts, each layer was given a cost on a scale of 1 to 10.

1st Priority	Cost/Sq.m	3rd Priority	Cost/Sq.m
Ecological corridors	10	Flooding danger 1 4 PATRICOVA	6
High cultural value	10	Flooding danger 5 7 PATRICOVA	6
Natural Park	10	DEM	6
Natural Park and microreserves	10	Slope	6
Protected Landscape	10		
RAMSAR	10	<b>4th Priority</b>	<b>Cost/Sq.m</b>
ZEPA and ZEC A B zoning	10		

Humid areas	10
Riverbed	10
Railway	10
Roads	10
Gas pipeline	10
Oil pipeline	10
Risks	10
Urban soil	10

Highways	4
Minor Roads	4
Solar project roads	4

2nd Priority	Cost/Sq.m
Area delimited by territorial planning	8
Landscape interest	8
Municipal places	8
Natural reserve without planning	8
Strategic forest floor of PATFOR	8
ZEPA and ZEC CD zoning	8
Clay	8

Table 6: PVPP impact analysis Input data

Figure 23 shows the outcomes from the PVPP impact analysis tool. After computing the environmental cost of each layer, their costs were summed together to obtain the total cost of each site. Site 5 shows that it has the minimum cost compared to other sites, such as Site 3 and Site 7; this indicates that Site 5 is the most environmentally friendly site with regard to implementing a PVPP.



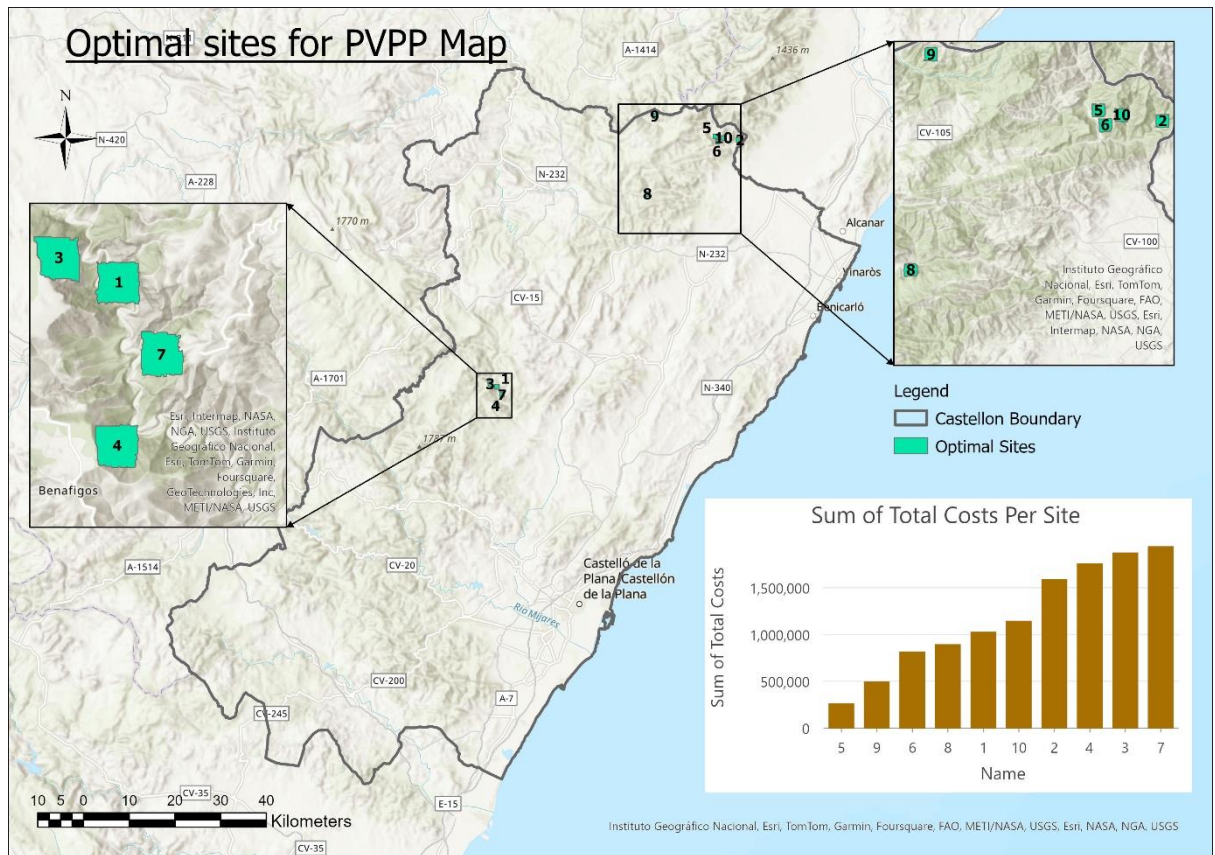


Figure 25: The PVPP impact analysis output result.

### Toolbox Validation

The validation process was done after testing the two developed tools. The validation process involves comparing the results of the geoprocessing tool in ArcGIS Pro to the Pathfinder application. Pathfinder is a cloud-based application used in planning and designing route infrastructure, including roads, railways, electricity lines, and pipelines, as well as identifying optimal sites for solar, wind, and other location-based facilities.

In this study, the first test of the tools developed was performed by finding the optimal sites for photovoltaic power plants in the province of Castellón using the developed PVPP site selection tool. The same study analysis was performed in the Pathfinder application; Figure 26 represents the results. The results were compared, and three factors were analysed, as discussed below.

1: Given the same constraints (input data) from Table 5, do the developed tool and the Pathfinder application produce a similar suitability map?

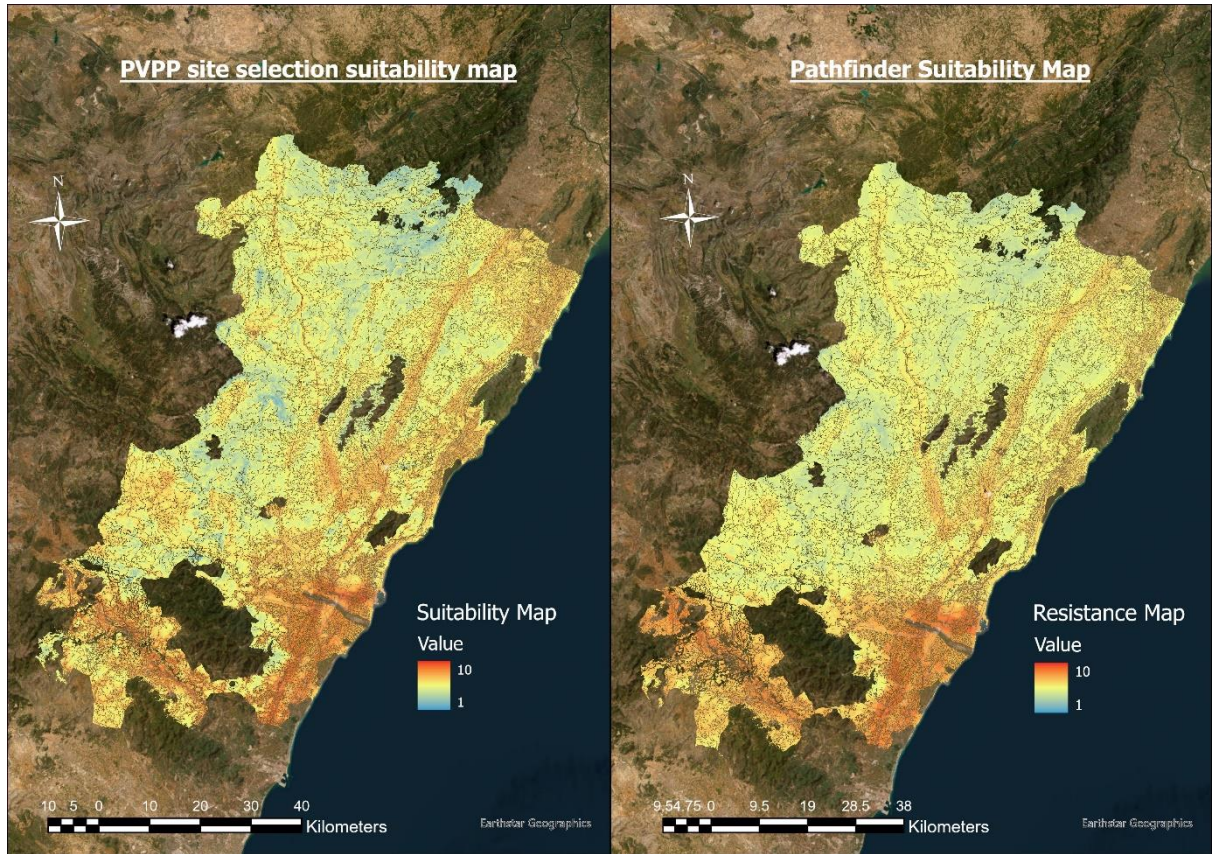


Figure 26: Comparison of PVPP Site selection and Pathfinder suitability map result.

Figure 26 represents two maps: one generated by the developed PVPP site selection tool and the other by the Pathfinder application. The comparison of these maps revealed differences in the suitability map established for photovoltaic power plants in Castellon province. The two maps were symbolized with the same color ramp, and the resulting values were adjusted to a common scale from 1 to 10. 1 represents regions with less suitable areas, while 10 represents highly suitable areas. Both maps show a high similarity in the suitability ranking for PVPP sites in most regions of Castellon province.

However, there were notable variations in certain areas; some areas of the left (PVPP site selection) map show more of an emphasis on a red symbology color - which indicates less suitable areas - compared to the right (Pathfinder) map. Additionally, the map on the right shows a more highly suitable region, indicated by a yellow to light blue color. Hence, this implies that the Pathfinder application may not always produce identical results to the developed PVPP site selection tool.

2: Given the same suitability map, do they identify similar areas as optimal?

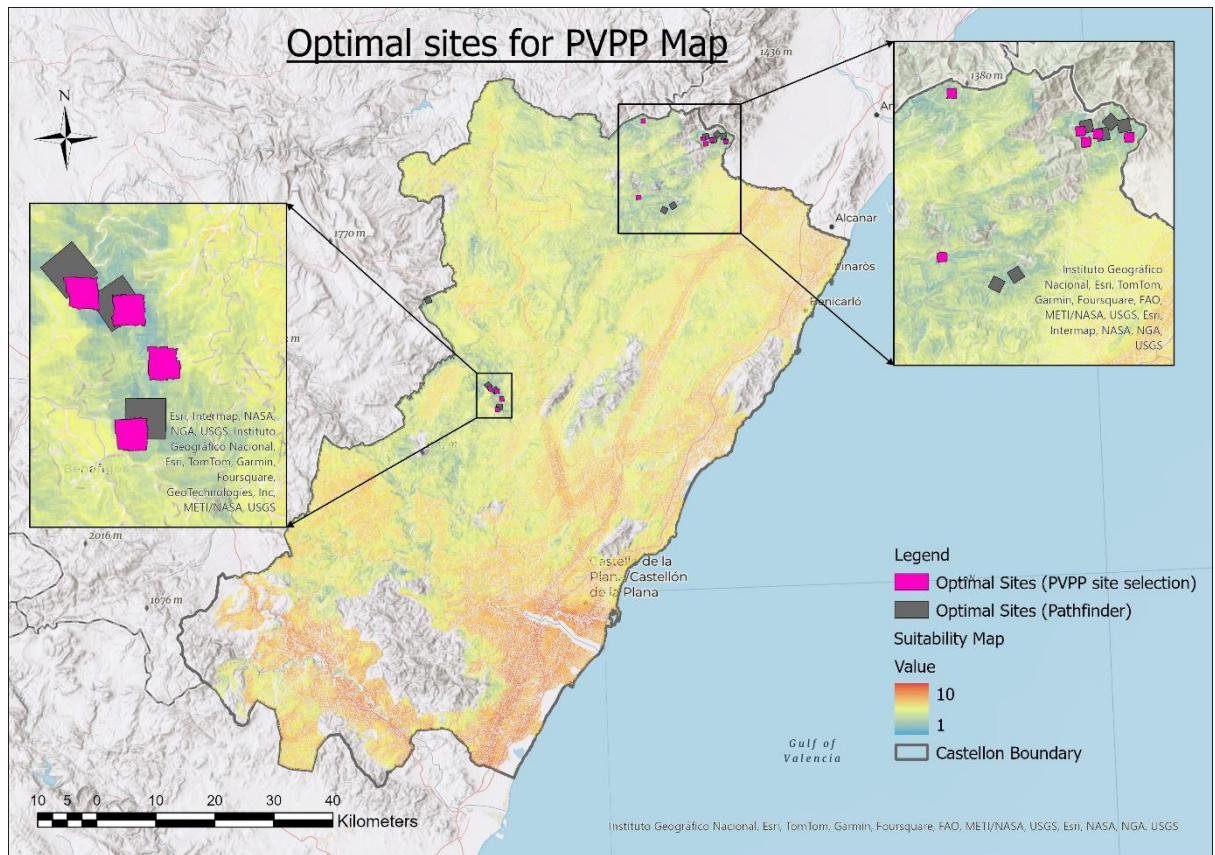


Figure 27: Comparison of PVPP Site Selection and Pathfinder of optimal site output.

The second analysis of the developed tool is to find the optimal sites. A similar tool is also available in the Pathfinder application. Therefore, both tools were given the same input data, which is the suitability raster layer of the previous analysis. The results (Figure 27) show an overlap of the sites in some regions. In particular, 6 sites of the developed PVPP site selection tool intersect with 6 sites identified by the Pathfinder application as optimal locations for PVPP development. This indicates that the developed tool (the PVPP site selection tool) is eligible to be used for identifying optimal sites for PVPP development, as it aligns with the results from an established tool like Pathfinder.

### 3: What are the drawbacks and advances of each solution?

PVPP site selection drawbacks are: it takes too long to process the input data because it runs on local memory, while the Pathfinder is built on strong computational power, thus processing data very quickly. Secondly, the resulting geometries of potential sites for the PVPP site selection tool are not computed precisely as in the Pathfinder results. Conversely, the PVPP site selection tool provides more options for setting the site's appearance. It includes the site orientation angle, the distance between the sites, and the evaluation methods. Additionally, the interface of the PVPP site selection tool integrates all the steps/processes of finding the optimal site, making it user-friendly and efficient for users.

## Chapter 5: Conclusion

The growth of renewable energy is a priority to reduce dependency on fossil fuels and address emerging climate change concerns. Stakeholders in this industry are encouraged to find possible solutions to advance and act on the urgency of transitioning to sustainable energy sources, including wind, solar, and hydroelectric power. GIS and MCDM tools are frequently used to find optimal locations for photovoltaic power plants due to their capability to evaluate various spatial data criteria simultaneously.

The study identified a gap in existing research that combined the available methods for site selection and impact analysis into a single and convenient application. Additionally, the existing tools on the market fail to consider all the relevant information and required functionality to carry out a reliable site selection process in a guided and unified manner. To address this challenge, this study was conducted to develop a user-friendly toolbox within the ArcGIS Pro environment for site selection and environmental and social impact analysis for photovoltaic power plants.

In response to the first research question, a literature review method was conducted. The review involved analyzing existing research on using GIS and MCDM methods for selecting sites for photovoltaic power plants. The results showed that not all stages of MCDM use GIS-based methods. Only the normalization and alternative evaluation stages use methods that can be integrated with GIS tools. The methods used in the normalization phase include reclassification, fuzzy membership functions, linear scaling, and expert scoring. The methods used in the alternative evaluation phase include weighted overlay, weighted sum, and fuzzy overlay. This information was used in the development of the toolbox.

To address the second question, the study used a design-and-creation method to develop a toolbox that can be integrated into the ArcGIS environment. The necessary steps identified include developing script files, creating a custom toolbox, adding the script files to the geoprocessing script tools, customizing the script tool's properties and parameters, modifying the script to accept the input from the tool, and testing the tool. Two script tools were created and integrated into the toolbox -- [PVPP site selection and PVPP impact analysis](#) -- for finding optimal sites and analyzing the social and environmental impacts of photovoltaic power plants, respectively.

One of the major limitations of this study was the lack of validation for PVPP impact analysis. This could be attributed to the fact that there are no existing tools for impact assessment. Various institutions and businesses typically develop these tools internally, and they are a part of their intellectual property. There is not much public information available regarding specific methodologies or specialized GIS products on the market; they are simply tools that different organizations create for their own use.

Future work from this study could involve conducting field studies to validate the effectiveness of this tool in different geographical locations, which would further enhance its credibility and applicability. Additionally, there are other important factors for photovoltaic site selection that can be integrated into the toolbox, such as the calculation of the levelized and carbon footprint costs for photovoltaic power plant projects.

## References

ArcGIS Pro Documentation, 2024. *Create a script tool*. [Online]

Available at: [https://pro.arcgis.com/en/pro-](https://pro.arcgis.com/en/pro-app/3.1/help/analysis/geoprocessing/basics/create-a-python-script-tool.htm)

[app/3.1/help/analysis/geoprocessing/basics/create-a-python-script-tool.htm](https://pro.arcgis.com/en/pro-app/3.1/help/analysis/geoprocessing/basics/create-a-python-script-tool.htm)

[Accessed 22 January 2024].

ArcGIS Pro Documentation, 2024. *Fuzzy Membership (Spatial Analyst)*. [Online]

Available at: [https://pro.arcgis.com/en/pro-app/latest/tool-reference/spatial-](https://pro.arcgis.com/en/pro-app/latest/tool-reference/spatial-analyst/fuzzy-membership.htm)

[analyst/fuzzy-membership.htm](https://pro.arcgis.com/en/pro-app/latest/tool-reference/spatial-analyst/fuzzy-membership.htm)

[Accessed 15 January 2024].

ArcGIS Pro Documentation, 2024. *How Fuzzy Overlay works*. [Online]

Available at: [https://pro.arcgis.com/en/pro-app/latest/tool-reference/spatial-](https://pro.arcgis.com/en/pro-app/latest/tool-reference/spatial-analyst/how-fuzzy-overlay-works.htm)

[analyst/how-fuzzy-overlay-works.htm](https://pro.arcgis.com/en/pro-app/latest/tool-reference/spatial-analyst/how-fuzzy-overlay-works.htm)

[Accessed 21 January 2024].

ArcGIS Pro Documentation, 2024. *How Rescale by Function works*. [Online]

Available at: [https://pro.arcgis.com/en/pro-app/latest/tool-reference/spatial-](https://pro.arcgis.com/en/pro-app/latest/tool-reference/spatial-analyst/how-rescale-by-function-works.htm)

[analyst/how-rescale-by-function-works.htm](https://pro.arcgis.com/en/pro-app/latest/tool-reference/spatial-analyst/how-rescale-by-function-works.htm)

[Accessed 10 February 2024].

ArcGIS Pro Documentation, 2024. *How Weighted Overlay works*. [Online]

Available at: [https://pro.arcgis.com/en/pro-app/latest/tool-reference/spatial-](https://pro.arcgis.com/en/pro-app/latest/tool-reference/spatial-analyst/how-weighted-overlay-works.htm)

[analyst/how-weighted-overlay-works.htm](https://pro.arcgis.com/en/pro-app/latest/tool-reference/spatial-analyst/how-weighted-overlay-works.htm)

[Accessed 21 January 2024].

ArcGIS Pro Documentation, 2024. *Locate Regions (Spatial Analyst)*. [Online]

Available at: [https://pro.arcgis.com/en/pro-app/latest/tool-reference/spatial-](https://pro.arcgis.com/en/pro-app/latest/tool-reference/spatial-analyst/locate-regions.htm)

[analyst/locate-regions.htm](https://pro.arcgis.com/en/pro-app/latest/tool-reference/spatial-analyst/locate-regions.htm)

[Accessed 21 January 2024].

ArcGIS Pro Documentation, 2024. *Reclassify (Spatial Analyst)*. [Online]

Available at: <https://pro.arcgis.com/en/pro-app/latest/tool-reference/spatial-analyst/reclassify.htm>

[Accessed 15 January 2024].

ArcGIS Pro Documentation, 2024. *Weighted Sum (Image Analyst)*. [Online]

Available at: <https://pro.arcgis.com/en/pro-app/latest/tool-reference/image-analyst/weighted-sum.htm>

[Accessed 21 January 2024].

ArcGIS Pro Documentation, 2024. *What is Geoprocessing?*. [Online]

Available at: <https://pro.arcgis.com/en/pro-app/3.1/help/analysis/geoprocessing/basics/what-is-geoprocessing-.htm>

[Accessed 22 January 2024].

energypedia, 2018. *Solar Irradiation*. [Online]

Available at: [https://energypedia.info/wiki/SPIS\\_Toolbox\\_-\\_Solar\\_Irradiation](https://energypedia.info/wiki/SPIS_Toolbox_-_Solar_Irradiation)

[Accessed 7 February 2024].

ESRI, 2022. *Sentinel-2 Land Cover Explorer App*. [Online]

Available at: <https://livingatlas.arcgis.com/landcoverexplorer/#mapCenter=-154.873%2C19.477%2C11&mode=step&timeExtent=2017%2C2022&year=2022>

[Accessed 26 January 2024].

Eurostat, 2023. *Population density by NUTS 3 region*. [Online]

Available at:

<https://data.europa.eu/data/datasets/gngfvpqmfu5n6akvxqkpw?locale=en>

[Accessed 25 January 2024].

Gilytics AG, 2023. *Proposal of Key metrics / KPIs*, s.l.: Gilytics AG.

Gilytics AG, 2024. *Speed-up energy and transportation routing and siting through collaborative design*. [Online]

Available at: <https://www.gilytics.com/#h-solution>

[Accessed 21 January 2024].

IEA, 2020. *World solar PV electricity production by region, 2005-2019*. [Online]

Available at: <https://www.iea.org/data-and-statistics/charts/world-solar-pv-electricity-production-by-region-2005-2019>

[Accessed 26 January 2024].

Singh, A., Williams, J. & Barba, J., 2020. *Site Selection Decision Support Tool Using Geographic Information Systems and Multi-Expert Analytic Hierarchy Process*. Charlottesville, VA, USA, IEEE, pp. 1-6.

Smoot, G., 2023. *What Is the Carbon Footprint of Renewable Energy? A Life-Cycle Assessment*. [Online]

Available at: <https://impactful.ninja/the-carbon-footprint-of-renewable-energy/>

WNA, 2022. *Carbon Dioxide Emissions From Electricity*. [Online]

Available at: <https://www.world-nuclear.org/information-library/energy-and-the-environment/carbon-dioxide-emissions-from-electricity.aspx>

[Accessed 04 07 2023].

Agyekum, E. B., Amjad, F., Shah, L., & Velkin, V. I. (2021). Optimizing photovoltaic power plant site selection using analytical hierarchy process and density-based clustering–Policy implications for transmission network expansion, Ghana. *Sustainable Energy Technologies and Assessments*, 47, 101521.

Ahmetović, H., Nukić, E., Hivziefendić, J., Šarić, M., & Ponjavić, M. (2022). *PV system site selection using PVGIS and Fuzzy AHP*. 1–6.

Almasad, A., Pavlak, G., Alquthami, T., & Kumara, S. (2023). Site suitability analysis for implementing solar PV power plants using GIS and fuzzy MCDM based approach. *Solar Energy*, 249, 642–650.

- Aslani, A., & Wong, K.-F. V. (2014). Analysis of renewable energy development to power generation in the United States. *Renewable Energy*, 63, 153–161.
- Ayudiani, V. L., & Akbar, S. (2017). *An extensible tool for spatial clustering*. 1–6.
- Azarpour, A., Mohammadzadeh, O., Rezaei, N., & Zendehboudi, S. (2022). Current status and future prospects of renewable and sustainable energy in North America: Progress and challenges. *Energy Conversion and Management*, 269, 115945.
- Bošnjaković, M., Santa, R., Crnac, Z., & Bošnjaković, T. (2023). *Environmental Impact of Pv Power Systems*.
- Colak, H. E., Memisoglu, T., & Gercek, Y. (2020). Optimal site selection for solar photovoltaic (PV) power plants using GIS and AHP: A case study of Malatya Province, Turkey. *Renewable Energy*, 149, 565–576.
- Cross, N. (1993). A history of design methodology. *Design Methodology and Relationships with Science*, 15–27.
- Custodio, G., Trindade, F., Petrou, K., & Ochoa, L. F. (2019). *An advanced GIS-based tool for the analysis of future distribution networks*. 1–6.
- Demir, A., Dinçer, A. E., & Yılmaz, K. (2023a). A novel method for the site selection of large-scale PV farms by using AHP and GIS: A case study in İzmir, Türkiye. *Solar Energy*, 259, 235–245.
- Demir, A., Dinçer, A. E., & Yılmaz, K. (2023b). A novel method for the site selection of large-scale PV farms by using AHP and GIS: A case study in İzmir, Türkiye. *Solar Energy*, 259, 235–245.
- Dobesova, Z. (2011). *Programming language Python for data processing*. 4866–4869.
- Elboshy, B., Alwetaishi, M., Aly, R. M., & Zalhaf, A. S. (2022). A suitability mapping for the PV solar farms in Egypt based on GIS-AHP to optimize multi-criteria feasibility. *Ain Shams Engineering Journal*, 13(3), 101618.



- Fard, M. B., Moradian, P., Emarati, M., Ebadi, M., Chofreh, A. G., & Klemeš, J. J. (2022). Ground-mounted photovoltaic power station site selection and economic analysis based on a hybrid fuzzy best-worst method and geographic information system: A case study Guilan province. *Renewable and Sustainable Energy Reviews*, 169, 112923.
- Gairaa, K., Guermoui, M., Zaiani, M., Belaid, S., & Benkacali, S. (2023). *Optimal Land Suitability Based on GIS Tools for Solar PV Farms*. 1–4.
- Gao, J., Wang, Y., Huang, N., Wei, L., & Zhang, Z. (2022). Optimal site selection study of wind-photovoltaic-shared energy storage power stations based on GIS and multi-criteria decision making: A two-stage framework. *Renewable Energy*, 201, 1139–1162.
- Genç, M. S., & Karipoğlu, F. (2021). *Wind-solar site selection using a GIS-MCDM-based approach with an application in Kayseri province/Turkey*. 1–4.
- Gómez-Navarro, T., Brazzini, T., Alfonso-Solar, D., & Vargas-Salgado, C. (2021). Analysis of the potential for PV rooftop prosumer production: Technical, economic and environmental assessment for the city of Valencia (Spain). *Renewable Energy*, 174, 372–381.
- Habib, S. M., Suliman, A. E.-R. E., Al Nahry, A. H., & Abd El Rahman, E. N. (2020a). Spatial modeling for the optimum site selection of solar photovoltaics power plant in the northwest coast of Egypt. *Remote Sensing Applications: Society and Environment*, 18, 100313.
- Habib, S. M., Suliman, A. E.-R. E., Al Nahry, A. H., & Abd El Rahman, E. N. (2020b). Spatial modeling for the optimum site selection of solar photovoltaics power plant in the northwest coast of Egypt. *Remote Sensing Applications: Society and Environment*, 18, 100313.

- Hasti, F., Mamkhezri, J., McFerrin, R., & Pezhooli, N. (2023). Optimal solar photovoltaic site selection using geographic information system–based modeling techniques and assessing environmental and economic impacts: The case of Kurdistan. *Solar Energy*, 262, 111807.
- Islam, M. R., Aziz, M. T., Alauddin, M., Kader, Z., & Islam, M. R. (2024). Site suitability assessment for solar power plants in Bangladesh: A GIS-based analytical hierarchy process (AHP) and multi-criteria decision analysis (MCDA) approach. *Renewable Energy*, 220, 119595.
- Karytsas, S., Mendrinou, D., & Karytsas, C. (2020). *Measurement methods of socioeconomic impacts of renewable energy projects*. 410(1), 012087.
- Kocabaldır, C., & Yücel, M. A. (2023a). GIS-based multicriteria decision analysis for spatial planning of solar photovoltaic power plants in Çanakkale province, Turkey. *Renewable Energy*, 212, 455–467.
- Kocabaldır, C., & Yücel, M. A. (2023b). GIS-based multicriteria decision analysis for spatial planning of solar photovoltaic power plants in Çanakkale province, Turkey. *Renewable Energy*, 212, 455–467.
- Marques-Perez, I., Guaita-Pradas, I., Gallego, A., & Segura, B. (2020). Territorial planning for photovoltaic power plants using an outranking approach and GIS. *Journal of Cleaner Production*, 257, 120602.
- Mendoza-Rivera, R. J., García-Pérez, L. E., & Venegas-Martínez, F. (2023). Renewable and non-renewable energy consumption, CO2 emissions, and responsible economic growth with environmental stability in North America. *International Journal of Energy Economics and Policy*, 13(4), 300–311.
- Muñoz, D. S., & García, J. L. D. (2021). GIS-based tool development for flooding impact assessment on electrical sector. *Journal of Cleaner Production*, 320, 128793.

- Noennig, J. R. (2022). The Science of Tooling–Design Framework for Digital Tools in Support of Socio-Spatial City Analysis. *Procedia Computer Science*, 207, 1462–1471.
- Pandey, A., Iqbal, A., Mishra, A. K., & Husain, M. A. (2019). *Economic Feasibility Analysis of Solar PV Generation at REC Ambedkar Nagar*. 1–6.
- Qiu, T., Wang, L., Lu, Y., Zhang, M., Qin, W., Wang, S., & Wang, L. (2022). Potential assessment of photovoltaic power generation in China. *Renewable and Sustainable Energy Reviews*, 154, 111900.
- Rahayani, R. D., & Nair, N.-K. C. (2023). *A Double MCDM-GIS Analysis for Solar Power Plant Site Selections in Disaster-Prone Area: A case study of Hawkes Bay*. 64–69.
- Rediske, G., Siluk, J. C. M., Michels, L., Rigo, P. D., Rosa, C. B., & Cugler, G. (2020). Multi-criteria decision-making model for assessment of large photovoltaic farms in Brazil. *Energy*, 197, 117167.
- Rekik, S., & El Alimi, S. (2023). Land Suitability Mapping For Large-scale Solar PV Farms In Tunisia Using GIS-Based MCDM Approach. *EasyChair*.
- Rekik, S., & El Alimi, S. (2024). A GIS based MCDM modelling approach for evaluating large-scale solar PV installation in Tunisia. *Energy Reports*, 11, 580–596.
- Rios, R., & Duarte, S. (2021). Selection of ideal sites for the development of large-scale solar photovoltaic projects through Analytical Hierarchical Process–Geographic information systems (AHP-GIS) in Peru. *Renewable and Sustainable Energy Reviews*, 149, 111310.
- Saraswat, S., Digalwar, A. K., Yadav, S., & Kumar, G. (2021). MCDM and GIS based modelling technique for assessment of solar and wind farm locations in India. *Renewable Energy*, 169, 865–884.

- Shao, M., Han, Z., Sun, J., Xiao, C., Zhang, S., & Zhao, Y. (2020). A review of multi-criteria decision making applications for renewable energy site selection. *Renewable Energy*, 157, 377–403.
- Singh, A., Williams, J., & Barba, J. (2020). *Site Selection Decision Support Tool Using Geographic Information Systems and Multi-Expert Analytic Hierarchy Process*. 1–6.
- Steffen, B. (2020). Estimating the cost of capital for renewable energy projects. *Energy Economics*, 88, 104783.
- Susanto, J. (2021). Photovoltaic power plant planning and modeling. In *Hybrid Renewable Energy Systems and Microgrids* (pp. 235–258). Elsevier.
- Tempa, U., & Singh, J. G. (2020). *Assessment of solar energy potential using GIS and AHP approach: A case study of Bumthang Valley*. 705–710.
- Tercan, E., Eymen, A., Urfalı, T., & Saracoglu, B. O. (2021). A sustainable framework for spatial planning of photovoltaic solar farms using GIS and multi-criteria assessment approach in Central Anatolia, Turkey. *Land Use Policy*, 102, 105272.
- Tsoutsos, T., Frantzeskaki, N., & Gekas, V. (2005). Environmental impacts from the solar energy technologies. *Energy Policy*, 33(3), 289–296.
- Vargas-Salgado, C., Aparisi-Cerdá, I., Alfonso-Solar, D., & Gómez-Navarro, T. (2022). Can photovoltaic systems be profitable in urban areas? Analysis of regulation scenarios for four cases in Valencia city (Spain). *Solar Energy*, 233, 461–477.
- Verdugo, C., Candela, J. I., Luna, A., & Rodriguez, P. (2017). *Power station for large scale photovoltaic power plants*. 768–773.
- Villacreses, G., Martinez-Gomez, J., Jijon, D., & Cordovez, M. (2022). Geolocation of photovoltaic farms using Geographic Information Systems (GIS) with Multiple-criteria decision-making (MCDM) methods: Case of the Ecuadorian energy regulation. *Energy Reports*, 8, 3526–3548.

- Wang, C.-N., Dang, T.-T., & Bayer, J. (2021). A two-stage multiple criteria decision making for site selection of solar photovoltaic (PV) power plant: A case study in Taiwan. *IEEE Access*, 9, 75509–75525.
- Wang, Y., Tao, S., Chen, X., Huang, F., Xu, X., Liu, X., Liu, Y., & Liu, L. (2022). Method multi-criteria decision-making method for site selection analysis and evaluation of urban integrated energy stations based on geographic information system. *Renewable Energy*, 194, 273–292.
- Zambrano-Asanza, S., Quiros-Tortos, J., & Franco, J. F. (2021a). Optimal site selection for photovoltaic power plants using a GIS-based multi-criteria decision making and spatial overlay with electric load. *Renewable and Sustainable Energy Reviews*, 143, 110853.
- Zambrano-Asanza, S., Quiros-Tortos, J., & Franco, J. F. (2021b). Optimal site selection for photovoltaic power plants using a GIS-based multi-criteria decision making and spatial overlay with electric load. *Renewable and Sustainable Energy Reviews*, 143, 110853.
- Zandbergen, P. A. (2020). *Advanced python scripting for ArcGIS pro*. Esri Press Redlands, CA.
- Zhang, M., Yue, P., & Guo, X. (2014). *GIScript: Towards an interoperable geospatial scripting language for GIS programming*. 1–5.
- Zhang, N., Zheng, J., Song, G., & Zhao, H. (2022). Regional comprehensive environmental impact assessment of renewable energy system in California. *Journal of Cleaner Production*, 376, 134349.





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