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A General Framework for Multi-Criteria Based Feasibility Studies for Solar Energy Projects: Application to a Real-World Solar Farm

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Abstract: The growth of solar energy is projected to slow down during 2023–25 despite the fall in costs due to economic deceleration, reduced incentives, and market barriers including the lack of relevant and flexible energy project planning and decision-making tools. This study proposes a flexible and computationally simple multi-criteria decision analysis (MCDA)-based model that takes technical, financial, environmental, social and legal aspects of all project options as input and outputs a feasibility score for each option, which enables ranking the options and identifying the best alternative. The proposed model is applied to a real-world photovoltaic solar farm planned at a site in England and comprising nine different configurations formed by varying system capacity, energy storage option, mode of stakeholder, and network connections. The results of our study show that in this case the options without battery storage and a greater number of off-taker connections are more favorable than the options with battery storage. The analysis also shows that for the solar farm of the presented case study, 'self-consumption fraction' and 'energy yield', 'net present value', 'life-cycle carbon emission reduction', 'ease of permit acquisition' and 'public approval' are key sub-criteria for 'technical', 'financial', 'environmental', and 'social and legal' criteria, respectively. A sensitivity analysis was conducted to assess the confidence on the obtained solution, and a change in the first preference was noticed when 'environmental' and 'social and legal' aspects are given higher weight over 'technical' and 'financial' aspects. The results obtained are in line with the recommendations by experts, who carried out an independent feasibility analysis considering the same options.

Keywords: solar energy; photovoltaics; multi criteria decision analysis; feasibility; solar farm

Citation: Bandaru, S.H.; Becerra, V.; Khanna, S.; Espargilliere, H.; Torres Sevilla, L.; Radulovic, J.; Hutchinson, D.; Khusainov, R. A General Framework for Multi-Criteria Based Feasibility Studies for Solar Energy Projects: Application to a Real-World Solar Farm. *Energies* **2021**, *14*, 2204. https://doi.org/10.3390/en14082204

Academic Editor: Carlo Renno

Received: 11 March 2021
Accepted: 12 April 2021
Published: 15 April 2021

1. Introduction

Sustainable and clean energy is vital for accelerating economic growth, social inclusion, and environmental protection. The United Nations (UN) has recognised access to clean, sustainable and reliable modern energy as one of the goals for sustainable development in its 2030 envision agenda [1]. Renewable energy sources can help achieve the UN goal and meet the objectives of the Paris climate change agreement [2].

In Europe, for example, generation from renewables surpassed fossil fuels in 2019, as the power generation from fossil fuels dropped by 10% in Europe from 2018 levels. According to [3], the European power market witnessed 1029.1 TWh power generation from renewables, 941.3 TWh from fossil fuels and nuclear powerplants produced 777.0 TWh in 2019. The growth of renewables in the fuel mix is attributed to stable hydro generation and a significant increase in energy from wind farms. Meanwhile, solar power accounts for only 4.1% of the electricity supply in Europe despite a fall in the cost of photovoltaic devices and having a well-developed solar energy market. On the other hand, gas-fired plants witnessed an energy production growth rate of 88% in the last five years, while solar energy generation saw an increase of 40%.

Emrah et al. [4] have studied the barriers to photovoltaic systems diffusion and categorised them into the sociotechnical, management, economic and policy. Along with many complex obstacles, lack of knowledge and adequate energy system planning for solar technologies were identified as reasons for planners not recommending solar energy for new buildings. Although solar energy technology has had a steady growth in the number of patents filed during the last decade and has experienced a reduction of costs [5], there are many market barriers to the deployment of the latest solar energy technologies. Wind and solar technologies account for nearly 90% of the renewable energy investments, which has been consistent over time, and if there is no change in investment trends, solar power technologies will play a prominent role in the energy mix and are estimated [6] to correspond for 60% of new additions to renewable energy worldwide by 2025. Moreover, the international energy agency (IEA) forecasts an 18% share of renewables in the final energy consumption by 2040 at the current growth rate [7]. To cater for this expansion, the importance of holistic feasibility study methods as a part of sustainable energy planning will increase. Therefore, it is vital to explore and adopt robust, flexible, and accessible energy system planning and decision-making support tools focusing on the triple bottom line to aid solar energy adoption through small, medium, and large-scale installations. The triple bottom line framework [8] incorporates social and environmental profits and economic gain to define a project's sustainability.

Energy system planning is an essential part of the decision-making process to deal with the issues associated with sustainable energy development. However, it is often difficult to compare different criteria which may be conflicting, uncertain, and heterogeneous, and assess these for making objective recommendations [9]. There are many decision-support instruments in the scientific literature that can perform an impact assessment of an energy system. In [10], an extensive review is reported of the application of different decision support instruments in sustainable energy planning. The authors have reported that the most widely applied decision support methods are life-cycle assessment (LCA), cost-benefit analysis (CBA) and multi-criteria decision analysis (MCDA). MCDA is the most often used technique in sustainable energy planning while LCA and CBA are often used in the areas of energy policy and management, as well as environment impact analysis. CBA evaluates all criteria by expressing them in monetary terms, however it is often difficult to interpret non-traded goods in monetary terms, making it a less commonly used method. A hybrid framework combining LCA and MCDA has been considered to be an appropriate tool for sustainability evaluation of renewable technologies [11].

1.1. Multi-Criteria Decision Analysis (MCDA) for Sustainable Energy Decision Making

MCDA is a systematic approach to combine heterogeneous, contradictory and uncertain input information and expert/stakeholders opinions to help energy system planners compare and rank the alternatives of a particular project [12]. It should be noted that most feasibility studies involve deciding between alternative project options. MCDA displaces single criteria analysis and promotes explicit, efficient, and rational decisions in energy planning. MCDA is broadly applied to address three types of decisions, i.e., site selection, technology selection and renewable energy policy [8]. Wang et al. [13] have reviewed the MCDA methodology applied in sustainable energy decision-making and reported that the MCDA process comprises the following steps: criteria selection, weighting, evaluation and aggregation. The paper also listed the typical criteria and sub-criteria considered in the literature for energy decision-making analysis. The main criteria in energy decision-making analysis are technical, financial, environmental, and social aspects. There are many evaluation methods used in MCDA, and some studies [14,15] have categorised them as outranking, pairwise comparison and scoring based methods. Fuzzy set theory can be integrated into this categorisation to allow for uncertainty. The most widely applied evaluation techniques in renewable energy planning are multi-objective optimisation, analytical hierarchy process (AHP), preference ranking organisation method for enrichment evaluation (PROMETHEE), elimination and choice translating reality (ELECTRE), multi-attribute utility theory (MAUT), and fuzzy and decision support systems (DSS) [16]. Mardani et al. [12] have reported better performance of hybrid and fuzzy hybrid MCDA methods over standalone MCDA methods in energy management problems. For detailed information, reviews and comparisons of various MCDA methods, references [10,12,13,15–20], can be studied. The above methods involve specific complexities, such as computing scaling constants using an algorithm in the MAUT, identifying the preferred alternative from a set of binary relations in ELECTRE, and using the outranking concept to rank alternatives in PROMETHEE [20,21]. AHP has been extensively used in renewable energy planning and does not involve complicated mathematics. Studies [13] and [20] have listed other frequently used elementary methods such as the weighted sum method (WSM) and weighted product method (WPM). WSM is simple for computation and mostly suitable for single-dimension problems on its own. It is a widely employed technique in energy planning MCDA studies for finding the sustainability index. References [21–26], have used the WSM method in different sustainability assessment areas. This method is flexible and transparent compared to other techniques, which involve complex computations [21].

Recently, a new technique known as the best worst method (BWM), has been proposed to solve MCDA problems. BWM uses a pairwise comparison category and involves upfront identification of best and worst criteria by the decision expert. It has been reported that BWM has better performance than AHP [27], and BWM reduces decision-makers inconsistency during pairwise comparison by significantly reducing the number of pairwise comparisons [28]. Mi et al. [29] have reviewed the application of standalone and integrated BWM in different areas such as supply chain, manufacturing, automotive, airline, transportation, mining, energy and environment, to note some of them. However, there are very few studies [30,31] in the area of energy generation and storage systems that have used the standalone or hybrid BWM technique, and there is a considerable potential to use the method in MCDA to study the feasibility of solar energy projects, considering its computationally less intensive framework.

1.2. MCDA for Hybrid Energy System Sustainability

Many studies have applied MCDA techniques to hybrid energy systems to assess sustainability, and some have included solar technology as a part of the evaluated energy system. Stein et al. [32] built a decision model using the AHP technique based on hierarchy to rank the electrical power plants using renewable (solar PV, wind, geothermal, biomass) and non-renewable sources by considering the typical four criteria of an energy decision-making analysis. The author uses a nine-point evaluation scale proposed in [33] to compare pairs of criteria. San et al. [34] combined the AHP and the compromise ranking method VIKOR (from the Serbian 'Vlse Kriterijumska Optimizacija Kompromisno Resenje', which means 'Multicriteria Optimization and Compromise Solution') and used it in renewable energy project (wind, solar thermo-electric, hydro and biomass) selection according to the Spanish Government's renewable energy plan. The author stressed the importance of using hybrid methods for an added advantage in terms of assigning weights to the criteria based on relative preference. Ertay et al. [35] have used the MACBETH method (Measuring Attractiveness through a Categorical-Based Evaluation TecHnique) and a fuzzy AHP-based technique to evaluate the renewable energy resources (solar photovoltaic (PV), wind, hydro and geothermal) in Turkey for sustainable development. A similar study was undertaken by the authors of [36] who combined the analytical network process (ANP) and technique for order preference by similarity to ideal solution (TOPSIS) method to investigate the potential of the renewable energy sources (solar PV, biomass, geothermal, hydraulic, wind) in Turkey. The hybrid MCDA method was used because ANP is good at comparing the criteria, and TOPSIS can rank the alternatives. Jun et al. [37] have applied the ELECTRE-II technique to study the macro-site selection for wind/solar PV hybrid energy system. The study results were consistent with the findings reported in the literature, reinforcing the credibility of the methodology. A similar solar farm site selection study was undertaken by [38] using the AHP method and geographic information system (GIS). The study is expected to assist the decision-makers for solar energy site selection as the AHP-integrated Geographic Information System (GIS) model would help determine the correct set of criteria with relative importance, which is essential for such a selection.

Vafaeipour et al. [39] have utilized the step-wise weight assessment ratio analysis (SWARA) method combined with WSM and WPM to address the region priority task for a solar energy project in Iran and identified 25 cities in the country to conduct the MCDA study. Similarly, the authors of [40] adopted the AHP and the ANP approach to present a case study on selecting PV solar power plant investment projects. The research has identified the risks at different stages of the power plant project and evaluated them using the hybrid MCDA technique. Both methods produced different weighting values, and this resulted in inconsistent outcomes. It was reported that ANP had generated results that were closer to the expert's instincts.

1.3. MCDA for Solar Energy Technology Assessment

In the area of solar energy, MCDA has been applied for assessment of the photovoltaic and concentrated solar power (CSP) technologies. One of those studies [41] used the PROMETHEE I and II methods to examine eight alternatives, including different CSP and hybrid energy technologies and observed that pure solar thermal technologies are not competitive when compared with a hybrid solar gas-turbine system. A fuzzy TOPSIS method was proposed by [42] for assessing thermal energy storage in CSP systems. The study was based on the analysis of benefits and costs to find the feasibility of using a molten salt-based heat transfer fluid. The integration of fuzzy set theory to TOPSIS helps represent the criteria weight and alternative ratings by triangular membership functions and is set to capture the uncertainty of the subjective assessments. A similar study [43] on CSP project potential in Namibia was undertaken by combining the MCDM technique AHP and levelised cost of electricity (LCOE) analysis from a techno-economic perspective. The authors used the traditional hierarchy approach with seven criteria, including technical, infrastructure, environmental, socio-economic, funding, deliverability, and terrain characteristics, along with 29 sub-criteria to score for performance. Socorro et al. [44] have evaluated manufacturing technology for solar PV cells using the fuzzy TOPSIS method with input from three experts to find the best technology. The study produced results through homogenous aggregation and eliminated the discrepancies in opinions among the experts. Cucchiella et al. [45] have proposed an MCDA model for solar PV systems by considering financial, environmental and energy indicators for the AHP process. The model is useful to compare projects that may use alternative energy technologies located in different locations. The authors conducted a case study on monocrystalline silicon (c-Si) PV facilities in Italy and concluded that selecting appropriate criteria/indicators and computing the criteria weights is a critical phase of the decision-making process. Azzopardi et al. [46] have presented the MCDA outranking technique ELECTRE III for ranking PV technologies using different types of solar cell. The assessment was based on three criteria (technical, economic, and environmental) and used the Simos method to calculate criteria weights. The paper focused on a comprehensive decision-making framework for supporting decision making related to PV system investments that will be vital in the future with emerging PV technologies and criteria such as environmental and social aspects becoming significant for sustainability reasons. Table 1 presents the key performance indicators discussed so far in the literature.

Table 1. Performance indicators from the literature involving solar energy.

Ref	Purpose of Study	MCDA Method	Key Performance Indicators
[41]	Preliminary assessment of concentrated solar power technologies	PROMETHEE I and II	Solar capacity factor, Levelised cost of electricity, Environmental risk
[42]	Compare different heat transfer fluids for concentrated solar power systems	fuzzy TOPSIS	Land use, Investment and operation and maintenance costs, Thermal storage costs, Technology maturity
[43]	Assess the feasibility of concentrated solar power project in Namibia	AHP	Water use, Availability, Landscape impact, Local community impact, Ecological impact
[44]	Find the best photovoltaic cell	TOPSIS	Efficiency, Pay-back time, Greenhouse emissions
[45]	Sustainability of PV projects in different locations	AHP	Net present value, Energy pay-back time, Discounted pay-back time
[46]	Rank the PV technologies	ELECTRE III	Solar fraction, Aesthetic, Module flexibility
[32]	Rank the electric energy production technologies	AHP	Capacity factor, Fuel cost, Loss of life expectancy, Public acceptance
[34]	Selection of renewable electric generation alternative	AHP-VIKOR	Avoided Tons of CO2, Useful life
[35]	Evaluation of renewable energy alternatives	AHP-MACBETH	Reliability, Need of waste disposal, Political acceptance, Compatibility with national energy policy
[47]	Selection of portfolio of solar energy project experiments for funding	MAUT	System size, Solar cell type
[36]	Selection of renewable energy source for a country	ANP-TOPSIS	Accident fatalities, Soil acidification
[37]	Site selection for wind/solar hybrid power station	ELECTRE II	Public attitude, Transmission line length, Electricity demand
[38]	Solar farm site selection	AHP	Slope, Location of system
[39]	Identification of regions for solar power plant construction	SWARA-WASPAS (Weighted Aggregated Sum Product Assessment)	Transmission grid accessibility, Energy independence, Social acceptability
[40]	Selection of PV power project for investment	AHP-ANP	Connection to the grid, Costs associated with agreements, Local body approval, obtaining licenses, Inverter selection, Availability of incentives
[48]	Evaluation of best location for PV solar power plant	AHP-TOPSIS	Cultural heritage, land slope, characteristics, and orientation
[49]	PV site suitability evaluation	Fuzzy Logic Ordered Weight Averaging (FLOWA)	Sand/dust risk, land accessibility
[50]	Impact of different financial support policies for PV	ELECTRE III	Internal rate of return, cost for support

The methods and applications discussed above have involved solving complex mathematics, and often they are computationally intensive, making them inaccessible for many organisations involved in solar energy projects. Moreover, most of the studies do not elaborate on all the criteria that are essential for a (pre-)feasibility study of solar energy projects. Although there are many MCDA software packages [20] with different features, it may be essential for many organisations to have access to a robust and computationally simple methodology that has been specifically tailored to analyse solar energy projects. Accordingly, as a part of the Interreg 2 Seas SOLARISE project, a methodology based on a weighted sum scoring that considers relevant indicators is proposed to enable decision-makers to perform a comprehensive evaluation and comparison at the feasibility stage of the options being considered. The SOLARISE project aims to showcase future technologies via living labs, installing storage capacity and boosting the adoption of solar energy in historical buildings, public buildings, public land, and low-income households.

This work elaborates and illustrates the application of MCDA in assessing the feasibility of solar energy projects. This study adds to the broader literature on solar energy system planning and project decision making by highlighting the use of MCDA to support decision making at the feasibility stage. The key contributions of this study are:

1. Identifying the relevant performance indicators of a solar energy project and proposing a scoring framework for key criteria.
2. A new robust and flexible MCDA methodology for feasibility analysis of solar energy projects is proposed.

The proposed MCDA methodology for feasibility analysis of solar projects is demonstrated using a real-world solar farm as a case study, illustrating its utility for the assessment, comparison and raking of different project options. For instance, the case study compares options for a solar farm with different system capacity, with and without energy storage, etc.

This paper is organised as follows: Section 2 explains the proposed MCDA methodology, describes the different criteria, sub-criteria and scoring keys for various indicators. Section 3 presents the inputs considered for applying the proposed model to a real word solar farm that is planned at a site in England. Sections 4 and 5 describes the application, results and discussion of the MCDA model and sensitivity analysis. Finally, Section 6 concludes the study with a summary and further research options.

2. Methodology

To effectively assess the feasibility of a given project option, a suitable approach is to use a decision matrix. This evaluation type helps to inform the feasibility study by weighing and scoring the various elements that are relevant to the project and organisation. The key aspects that need to be considered in most solar projects can be grouped into 'technical', 'financial, 'environmental', and 'social and legal' criteria.

The use of a weight (w_i) ranging from 0 to 5 for each *ith* main criterion is proposed, where the weight of 0 indicates that a criterion is not relevant to the project being analysed, and a weight of 5 indicates its very high importance. Table 2 illustrates the meaning of the weights that can be assigned to each main criterion. The score (S_i) of each *ith* criterion is calculated as the average of the scores (S_{ij}) of corresponding non-irrelevant sub-criteria. Table 3 indicates the meaning of the input scores (S_{ij}) that need to be assigned to each *jth* sub-criterion of *ith* main criterion. Table 4 lists the main criteria to be used and the method for calculating the total percentage score.

Table 2. Key for weighting the main criteria.

Weight	Meaning
5	Very high importance
4	High importance
3	Medium importance
2	Low importance
1	Very low importance
0	Irrelevant/Not applicable

Table 3. Key for input scores associated with sub-criteria.

Score	Meaning
10	Outstanding satisfaction of sub-criterion
9	Excellent
8	Very good
7	Good
6	Above satisfactory
5	Satisfactory
4	Below satisfactory
3	Poor
2	Very poor
1	Sub-criterion not satisfied at all
0	Irrelevant/Not applicable

Table 4. Main criteria, weights, and calculation of the weighted and total scores.

Criteria	Weight (0–5)	Non-Irrelevant Sub-Criteria	Input Score	Averaged Score	Weighted Score
C_1	w_1	$C_{1,1}$ $C_{1,2}$ $\vdots$ $C_{1,a}$	$S_{1,1}$ $S_{1,2}$ $\vdots$ $S_{1,a}$	$S_1 = \frac{\sum_{j=1}^{a} S_{1,j}}{a}$	$w_1 \times S_1$
C_2	w_2	$C_{2,1}$ $C_{2,2}$ $\vdots$ $C_{2,b}$	$S_{2,1}$ $S_{2,2}$ $\vdots$ $S_{2,b}$	$S_2 = \frac{\sum_{j=1}^{b} S_{2,j}}{b}$	$w_2 \times S_2$
C_3	w_3	$C_{3,1}$ $C_{3,2}$ $\vdots$ $C_{3,c}$	$S_{3,1}$ $S_{3,2}$ $\vdots$ $S_{3,c}$	$S_3 = \frac{\sum_{j=1}^{c} S_{3,j}}{c}$	$w_3 \times S_3$
C_m	w_m	$C_{m,1}$ $C_{m,2}$ $\vdots$ $C_{m,n}$	$S_{m,1}$ $S_{m,2}$ $\vdots$ $S_{m,n}$	$S_m = \frac{\sum_{j=1}^{n} S_{m,j}}{n}$	$w_m \times S_m$
Total score (percentage)	–			–	$\frac{\sum_{i=1}^{m} w_i\, S_i}{\sum_{i=1}^{m} w_i} \times 10$

It is necessary to define a "pass" percentage score for the project option being evaluated to be considered feasible. Moreover, it is also necessary to define a passing score for all sub-criteria in the range 0–10 and define each sub-criterion as "essential" or "not essential". If an essential sub-criterion does not achieve the defined pass score, the project option being considered is deemed as unfeasible. On the other hand, if a non-essential sub-criterion does not achieve a passing score, this does not cause the option to be unfeasible. For example, suppose the affordability of the project's initial cost does not achieve a passing score (meaning that the organisation cannot afford that project option), and this sub-criterion has been defined as 'essential'. In that case, that project option is deemed to be unfeasible.

It must be noted that when different options are being compared for the same project, it is crucial to consider that the percentage score that is obtained using Table 4 can be used to make meaningful comparisons between options when the set of non-irrelevant sub-criteria (i.e., those whose score is 1 or greater) is the same. Figure 1 illustrates the proposed approach stepwise. The main criteria which apply to most solar energy projects are described in subsequent sub-sections. Note that this list is not exhaustive. It should be emphasised that although a list of criteria and sub-criteria is proposed in the next few sub-sections, the user of this methodology has the choice to use or ignore specific criteria and sub-criteria from the set presented here simply by selecting appropriate weights and scores, as is explained above. It is also possible for users to modify individual sub-criteria to satisfy their requirements and practices, or even to add new sub-criteria, as appropriate.

2.1. Technical Aspects

Technical aspects are divided into three groups, with each group, in turn, is divided into different sub-criteria.

2.1.1. Energy Production and Self-Consumption

These refer to aspects related to the energy generation, self-consumption and export that is of relevance to the feasibility study. These aspects can include:

- Estimated energy yield: this is an estimation of the amount of energy to be produced by the solar plant. Typically, a software package is employed to provide the estimated yield after losses with different levels of sophistication, depending on the purpose of the estimate. Although this value has well known financial implications, considering the energy yield as a sub-criterion is useful when comparing different options (for

instance, different panel technologies and different areas). The score can be assigned depending on how the energy yield compares with other options being considered.
- Self-consumption fraction: this is the percentage of energy that is locally consumed (as opposed to energy exported to the main grid) with respect to the total energy yield after losses. The amount of energy consumed through power purchase agreements can also be counted towards self-consumption, as this is energy that is not being exported to the main grid. High scores can be assigned to options with higher self-consumption percentage. This sub-criterion is not relevant for installations that are principally intended to export energy to the main grid.

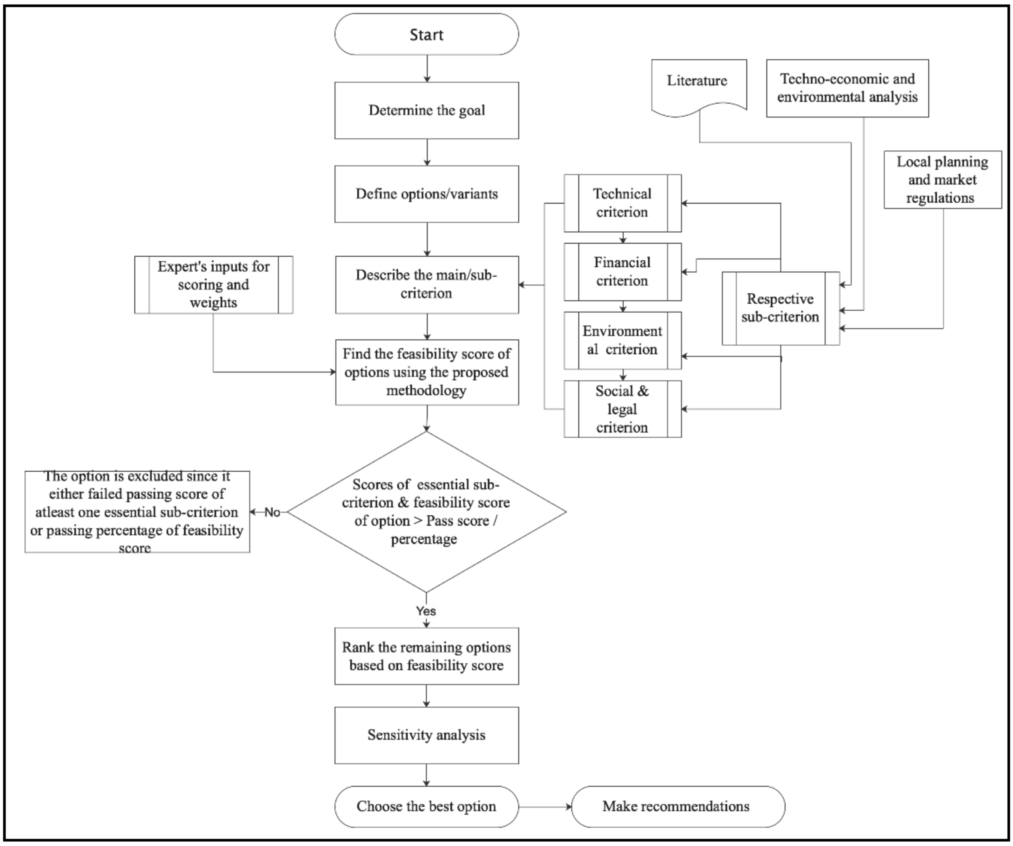

Figure 1. Methodological approach.

2.1.2. Site Aspects

These refer to aspects related to the site of the installation that is of relevance when assessing feasibility. The site analysis that is performed when considering the feasibility of solar studies typically include:

- Features of land/roof area: this sub-criterion is intended to capture how easy it would be to mount the solar equipment. A high score should be given for a standard installation where no additional work is needed, and the score can be lowered appropriately where there are features of the land or roof that would require additional work to prepare the surface where the panels are to be installed. The scoring key is described in Table 5.

Table 5. Scoring key for features of land/roof area.

Features	Score Out of 10
Significant additional work needed	2
Moderate additional work needed	5
No additional work needed	10

- Ease of connection to grid or local heat network: this integration can be technically easy or difficult depending on the site. A high score should be given when the connection to the grid or local heat network is straightforward, with very little or no additional work, equipment and materials required, and a lower score can be given when significant additional work, equipment and materials are needed to establish a connection to the electricity grid or local heat network. If the installation is intended to be off-grid or not connected to a local heat network, then the sub-criterion's score can be set to 0, meaning that the sub-criteria is irrelevant. The scoring key is shown in Table 6.

Table 6. Scoring key for ease of connection to grid or local heat network.

Ease of Connection	Score Out of 10
Significant additional work needed	2
Moderate additional work needed	5
No additional work needed	10

- Presence of obtrusive objects causing shade: the presence of shade can adversely affect solar energy systems' output. This sub-criterion is intended to capture the effect of such shade, with a high score being given when no shading is likely to affect the installation, and a lower score given if significant shade is expected to affect the installation. Table 7 is generated by considering the information in references [51,52].

Table 7. Scoring key for shading.

Shading (%)	Score Out of 10
81–100	1
61–80	4
41–60	6
21–40	8
0–20	10

2.1.3. Technology Suitability

- PV Panel efficiency: the solar panel module efficiency varies depending on the type of panel and its material. If the panel is monocrystalline, it is guaranteed to have better efficiency than a polycrystalline panel since the silicon semiconductor's purity is higher. A thin-film panel is flexible and thin, allowing it to be shaped and mounted over roof tiles. Nevertheless, its efficiency is significantly lower than the monocrystalline and polycrystalline panels. Table 8 suggests scores for different levels of solar panel efficiency.

Table 8. Solar panel module efficiency and recommended scores.

Solar Panel Module Efficiency (%)	Score Out of 10
0–5%	1
6–10%	4
11–15%	6
16–20%	8
>20%	10

- PV Panel degradation: a PV module's performance will degrade gradually due to several external factors, including environment and solar cell technology, and its ability to produce electricity for the same amount of solar irradiation will reduce over time. The panel's thermal stresses lead to malfunction, and light-induced degradation due to ultraviolet (UV) exposure deteriorates the material, leading to cracks that can be infiltrated with water vapor and other contaminants. Another type of degradation occurs when polishing the panel surfaces as they become dirty, which can slowly deteriorate the anti-reflective coating. These factors would cause the panel to perform worse and produce a power output of approximately 90% after 12 years and 80% after 25 years (which is the average panel life). Table 9 suggests scores for different levels of degraded panel efficiency after 25 years.

Table 9. Panel efficiency degradation after 25 years and recommended scoring.

Photovoltaic (PV) Panel Efficiency after 25 Years Compared to the Initial Value (%)	Score Out of 10
0–50%	1
51–70%	6
71–80%	8
80–90%	9
>90%	10

- Solar PV panel manufacturer's warranty: the warranty for solar panels ranges between 5 and 25 years, depending on the manufacturer. This is important as solar panels' failure during the project's life will represent extra expenditure in replacing the failed panels unless a valid manufacturer warranty is in place. In some cases, it is possible to pay an additional amount to obtain an extended warranty period. Table 10 suggests scores for different levels of solar panel manufacturer warranty. If the solar panels have a shorter warranty than the project's expected life, it is vital to account for the cost of likely solar panel replacements during the project's lifetime.

Table 10. Solar PV panel warranty and recommended scores.

Solar Panel Warranty (Years)	Score Out of 10
5–10	3
10–15	5
15–20	7
20–25	10

- Battery efficiency: batteries store chemically the electrical energy produced by solar panels to be used at a later time. This is convenient as it allows the use of any excess generation when needed, such as when the sun is not shining. Batteries are most often used in off-grid solar installations, but they are increasingly being used in on-grid installations as they promote self-consumption. Batteries incur energy losses during their operation, and their round-trip efficiency is defined as the ratio of energy output from the device to the energy input. For instance, a lead-acid-based battery's efficiency is close to 80%, while most new lithium-based batteries can be as high as 98%, but is generally in the 92–95% range. The efficiency of a battery can be found in the manufacturer's specifications. Table 11 gives suggested scores for different ranges of battery efficiency.

Table 11. Battery round trip efficiency and key for scoring.

Battery Round Trip Efficiency (%)	Score Out of 10
50–70	2
71–80	4
81–90	6
91–95	9
96–100	10

- Battery energy density: battery energy density is the amount of energy stored in the battery per unit of volume. It is very relevant to the space available for the installation of the battery system. If the battery is large and has a low energy density, it will be less desirable, especially when the installation area is limited. A small and high energy-dense battery system will cost more, nevertheless. A typical lead-acid battery has an energy density range of 60–110 kWh/m^3, while a typical lithium-ion battery has an energy density range of 250–693 kWh/m^3. Energy density can generally be found in the manufacturer specifications. Table 12 suggests scores for different levels of battery energy density.

Table 12. Battery energy density and key for scoring.

Battery Energy Density (kWh/m^3)	Score Out of 10
0–100	1
101–250	3
250–400	6
401–500	9
>500	10

- Battery cycle life: battery cycle life is the number of charge-discharge cycles a battery is expected to withstand before failing. Life can be affected by many parameters, such as the rate of charge-discharge, humidity, and temperature. Most specification sheets show the cycle of life for ambient temperature (25 °C). Battery charge and discharge rate are how fast the battery takes in energy and releases it. The depth of discharge (DOD) is the recommended capacity that the battery can be discharged. Going below the minimum DOD specified for a battery could damage it or reduce its life. For instance, lead-acid batteries typically have a cycle life in the range of 100–2000, while lithium-ion batteries typically have a life cycle range of 250–10,000. Table 13 suggests scores for different levels of battery cycle life.

Table 13. Battery energy density and key for scoring.

Battery Cycle Life (Cycles)	Score
100–500	1
501–2500	2
2500–5000	5
5001–7500	7
7500–9000	9
>9000	10

- Maintenance requirements of batteries: the maintenance requirement of batteries depends on the type of battery. It is usually measured in the days or months between maintenance procedures. Table 14 shows the maintenance requirements for different types of battery and recommended scores.

Table 14. Maintenance requirements for different batteries and recommended scores.

Battery Type	Maintenance Requirement	Score
NiCd	30–60 days	3
NiMh	60–90 days	4
Lead-acid	3–6 months	6
Li-Ion	Not required	10
Li-Ion polymer	Not required	10

- Efficiency of inverters: inverters are generally used for converting direct current (DC) electricity produced by the solar panels into alternating current (AC) electricity, thus enabling an interface to the local AC grid, sometimes through a transformer. The inverters are usually connected either in a string or central configurations. While the former is appropriate for large-scale power plants, the latter demands comparatively less specialized maintenance skills and can facilitate individual string Maximum Power Point Tracking (MPPT) [53]. An inverter's efficiency indicates how much DC (direct current) power is converted to AC (alternating current) power after some loss in power due to heat. Also, some stand-by-power is required for keeping the inverter in powered mode. High-quality and low-quality sine wave inverters are generally rated at 90–95% and 75–85% efficiencies, respectively [54]. As in many installations, all the power generated by PV panels must be processed by inverters. Their efficiency has an impact on the actual energy yield of the installation. Table 15 suggests scores for different levels of inverter efficiency.

Table 15. Inverter efficiency and recommended scores.

Inverter Efficiency (%)	Score Out of 10
85–87.5%	3
87.5–90%	6
90–95%	9
>95%	10

- Manufacturer warranty of inverters: manufacturers' warranties of inverters range between 5 and 25 years. It is important as inverter failure during the project's life will represent extra expenditure in replacing the failed inverter unless a valid manufacturer warranty is in place. In some cases, it is possible to pay an additional amount to obtain an extended warranty period. Table 16 suggests scores for different levels of inverter manufacturer warranty. If the inverters have a shorter warranty than the project's expected life, it is important to account for the cost of likely inverter replacements during the project's lifetime.

Table 16. Inverter manufacturer warranty and recommended scores.

Inverter Warranty (Years)	Score Out of 10
0–5	1
5–10	3
10–15	5
15–20	7
20–25	10

- Efficiency of solar collectors: solar thermal applications use solar collectors, which is a generic term used to refer to various systems that collect solar thermal energy. These could be, for instance, flat plate collectors, evacuated tube collectors, solar bowls, and parabolic trough collectors. The efficiency of solar collectors depends on the technology used. It is difficult to give guidelines for scoring due to the significant differences between collectors types, but the scoring described in Table 3 can be used to rank technological options that exhibit different efficiencies.
- Efficiency of the thermodynamic cycle in solar thermal systems: solar thermal applications typically involve a thermodynamic cycle. The thermodynamic cycle's efficiency depends on the technology used and may involve different components, such as solar receivers, fluid transport through pipes, heat exchangers, heat pumps, and heat storage. The thermodynamic cycle may involve the input of energy of different types, including thermal energy and electrical energy. For example, some solar thermal systems, in addition to having thermal energy as an input, may use pumps and ventilation devices that require electrical energy. The variability of thermodynamic cycles is high, and it is not easy to discuss specific cases. In every case, a boundary needs to be defined to define the system where the thermodynamic cycle's efficiency is to be calculated. Efficiency is defined as the energy that leaves the system's boundary over a period of time to the energy that enters the system's boundary over the same period. Specific measures of efficiency exist for cooling systems, including the coefficient of performance (CoP), which relates the usable cooling energy (or the cooling effect) to the electrical energy (or heat) consumed by the system; as well as the overall system efficiency (OSE), which relates the specific cooling effect (per unit of area) to the incident total radiation intensity.

2.2. Financial Aspects

The financing of a large-scale solar energy project is possible when the solar plant is highly likely to generate sufficient income to cover for debt obligations and all costs of operation and maintenance and generate an acceptable return for the equity invested [55]. In commercial organisations, the decision to progress with a power project's development depends heavily on the project's commercial viability, as determined in a detailed financial assessment. The investment return requirements are lower for public organisations than for commercial organisations. Moreover, in some cases, a negative return on investment can be acceptable if the project's principal aim is different from generating profits (for example, in the case of demonstration projects) and the organisation is willing to bear the cost. Financial analysis will generally consider development, construction, and operational and maintenance costs, along with expected revenues. The predicted energy yield of the solar plant, which is normally estimated through technical considerations, is used to estimate revenues. For the sake of brevity, the examples below refer to solar PV systems.

Capital costs: the capital costs of a typical solar PV power plant include the following, where Figure 2 indicates the proportion of the total capital costs:

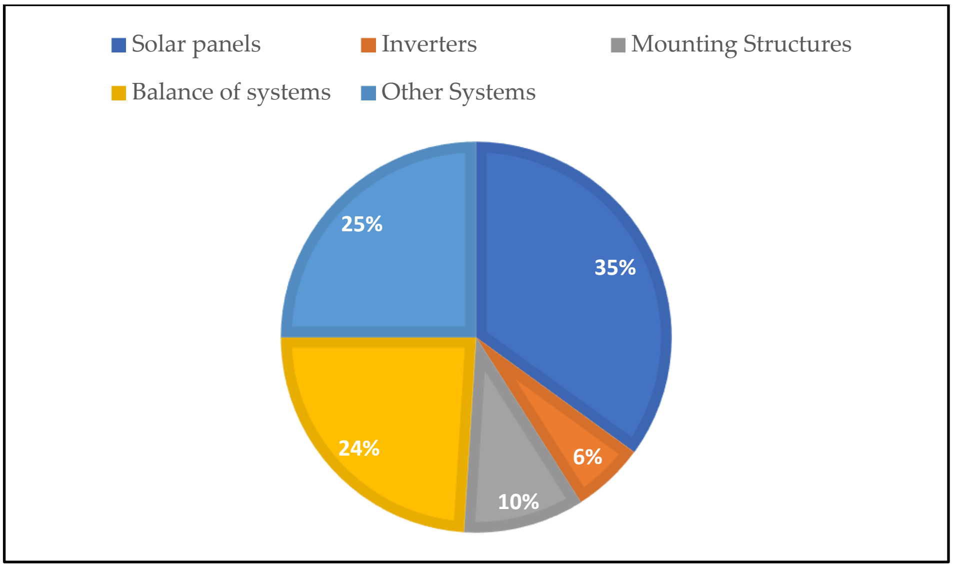

Figure 2. Share of capital costs.

"Balance of systems" include cabling, junction boxes, transformers, switchgear, and batteries. Other costs include installation, approvals, land registry and planning, grid connection, engineering and technical analysis, and financial and legal services. Other costs could also include the cost of land if it is going to be purchased and other infrastructures, such as roads and drainage. To give some ideas on costs, the average costs of a 0–4 kW installation in the UK during 2017–2018 was £1840 (€2094) per installed kW, while the mean value goes down to £1053 (€1198) for larger 10–50 kW installations [56]. Due to large ground-mounted plants' economies of scale, their installation cost is significantly less than rooftop systems. A typical 10MW solar plant's capital cost is in the region of £800,000 (€910,000) per MW installed [57]. Prices of solar installations for all sizes have consistently been decreasing for several years.

Grid connection costs can form a large part of a project's capital expenditure (CAPEX), to the extent of making the project financially infeasible in some cases and can vary significantly from project to project. As the grid's capacity to take an additional generation in some areas becomes scarce, the influence of grid connection issues on decision making in large solar farms projects has increased. Grid connection costs can be largely dependent on the point of connection as additional costs are incurred when upgrades must be made at the substation to accommodate the solar plant's incoming energy. Ultimately, the distribution network operator (DNO) must be contacted to provide the connection fees.

For large-scale solar farms, grid connection costs can range from £100,000/MW to £1,700,000/MW [58]. For smaller solar installations, grid connections are usually below £400/kW [59]. It is worth noting that smaller projects (typically <50 kW) can often be connected to internal distribution boards (such as in commercial or public buildings) instead of being connected to a substation, and therefore incur no grid connection cost.

Operation and maintenance costs: simple technology and less maintenance need are the reasons for comparatively low operational and maintenance (O&M) costs for solar PV energy. The average O&M costs in the developed European market are currently around £4200/MW (€4778/MW) per annum [53]. Generally, operational expenditure comprises insurance, administration, professional fees, land rental and labour. It may also be necessary to replace equipment items, such as batteries, inverters or even panels, during the project's life. Typically, solar farms are constructed in rural areas where the land is not very expensive. In the UK, solar developers pay the landowner a rent in the order of £1000 (€1140) per acre per annum. Also in the UK, the land rental cost can be estimated to be £10,000 (€11,400) per MW per annum [57].

Revenues and electricity tariffs: accurate energy yield predictions are fundamental in large-scale projects since it clearly drives the cash flow model's revenue line. In cases where financing is required, an independent and suitably qualified solar energy consultant must calculate annual energy yield and define the uncertainty associated with the calculations to understand the implications on project viability clearly. Solar power plants typically make revenue through tariffs for generation and occasionally via clean energy and tax credits and other incentives available for developers. Such incentives' permanency should be assessed carefully, as they are often modified or eliminated by the government. Tariffs and incentives vary from country to country. At present, most new utility-scale power plants installed in the UK provide electricity directly to the consumer based on the terms set out in long-term power purchase agreements (PPAs) [53].

Debt servicing and capital repayment: solar energy projects are often financed through a combination of equity and debt (loans). A typical equity/loan ratio in large solar projects is 30/70. Loans require periodic payments, which depend on the interest rate and the amount of capital borrowed. The lender will need to see convincing cash flow predictions that clearly show that the project is highly likely to generate sufficient revenues to cover all ongoing costs and interest and investment repayments over the project's life.

Taxes: as the solar installation will generate revenues and potential profits, any incurred taxes will also need to be covered by the revenues over the project's life. The taxes to be paid will depend on local and national legislation, and the legal entity that owns and operates the solar plant. There may also be local taxes to be paid.

Financial modelling: a financial model is useful for investigating the project's feasibility by considering the cashflows and estimating key parameters needed for the project's financial assessment. Such a model is an important element for decision making and is essential in preparing the project for financing. The model should also demonstrate that the project can generate cash essential to cover the interest repayment and principal on a debt for a certain time. Below, we present definitions of key financial parameters that can be important in solar energy projects.

Net present value (NPV): the net present value (NPV) is the difference between the present value of the investment's future net cash flows and its initial cost. It can be expressed as follows [60]:

$$\text{NPV} = -C_0 + \sum_{i=1}^{N} \frac{C_i}{\left(1 + \frac{r}{100}\right)^i} \tag{1}$$

where C_0 is the initial cost, C_i is the net cash inflow in period i, r is the discount or interest rate over one period (in percentage form), and N is the number of periods. One period can be one year, one month, etc. depending on the case. The net cash inflows consider all income streams for each future period and all expenses for each future period. An investment can be considered prudent if it seems to generate value for the project developers or owners in the presence of time value of money. It implies that the NPV is usually expected to be positive unless a positive NPV is not a priority given other considerations (for example, when the project's principal aim is not to generate a profit).

Internal rate of return (IRR): the IRR is the discount rate that equates the initial cost to all future net cash inflows' present value. The IRR satisfies the following equation [61]:

$$C_0 = \sum_{i=1}^{N} \frac{C_i}{\left(1 + \frac{\mathrm{IRR}}{100}\right)^i} \tag{2}$$

IRR can be calculated considering cash flows and with or without the financing. While the former leads to Equity IRR, the later is called Project IRR. The Equity IRR and Project IRR are the same when the project is completely financed by equity, and in the case of finance by debt, there is no equity IRR [53]. The equity IRR is expected to be more than 10% and significantly more in high-risk markets.

Payback period (PP): the payback period is the amount of time needed for a project to get back its initial cost out of the cash income that it generates. Assuming that time is measured in years and that the annual net cash inflow C_i is the same each year throughout the project, the following formula can be used to compute the payback period [62]:

$$\mathrm{PP} = \frac{C_0}{C_i} = \frac{\text{Initial cost}}{\text{Annual net cash inflow}} \tag{3}$$

Acceptable values of the payback period depend on organisational factors. Payback periods are often within the range of 10 to 20 years.

Cash flow available for debt service (CFADS): The cash flow available for debt service (CFADS) is calculated using Equation (4) for a given period (typically one year) and is a precise measure of available cash for debt service. Non-cash items like depreciation are not part of the CFADS [63].

$$\mathrm{CFADS} = \text{Revenue} – \text{OPEX} – \text{Working capital adjustment} – \text{Interest} - \text{Tax} \tag{4}$$

Debt service coverage ratio (DSCR): DSCR is a measure of a project's ability to meet the current debt obligations. It is determined as CFADS divided by the amount of projected debt service (capital plus interest) over a particular time duration (typically one year) [64]. Generally, private banks expect a DSCR value of 1.15–1.35 to ensure cash flows required for repayment of loans [53]. A negative cash flow will give DSCR less than one. The following equation computes DSCR:

$$\mathrm{DSCR} = \frac{\text{CFADS}}{\text{Scheduled debt service}} \tag{5}$$

Loan life coverage ratio (LLCR): LLCR gives information about the project's credit quality from a lender's perspective. It is a measure of the ability to meet the debt obligations over the entire project life and calculated using Equation (6). The LLCR ratio usually ranges from 1.25 times for highly geared infrastructure investment (such as solar farms) to 2.5 times or higher in investments with more insecure income [65]. The equation for finding LLCR is:

$$\mathrm{LLCR} = \frac{\text{Net present value of CFADS}}{\text{Remaining amount of debt owed}} \tag{6}$$

Levelised cost of electricity (LCOE): "discounted lifetime cost for ownership and use of a power generation asset" given in the units of currency per kilowatt-hour (cost of generation), for example, USD/kWh or EUR/kWh or per megawatt-hour [66,67]. It is the minimum electricity selling price for an energy generating plant to break even and is generally computed for 20 to 40 years [68]. LCOE considers lifetime costs, including initial investment, operations and maintenance, cost of fuel, and capital cost, and it can be used to compare different power generating assets. There is a specialised variant of LCOE for cooling systems known as the levelised cost of cooling [69]. Moreover, a specialised variant of LCOE has been defined for heating systems, known as the levelised cost of heat [70].

2.3. Environmental Aspects

The possible environmental impacts of solar power include land use and biodiversity loss, water use, dangerous materials in production, landscape and visual impacts, and global warming emissions.

Habitat loss: the solar power installations should be sited sensitively to avoid impacts on wildlife and land of high ecological interest. The potential issues associated with the plant are dependent on the required area of land, solar resource intensity, design and technology and presence of biodiversity at the location [71]. For example, a utility-scale PV system requires 3.5–10 acres per MW, while a concentrating solar thermal plant (CSP) needs 4–16.5 acres per MW [72]. Habitat loss is possible, leading to a decline in the species' population and may become a reason for the extinction. This can be managed by deploying more small-scale installations on homes or commercial buildings, setting large-scale installations in former landfills, and restoring the field at the end of the development period.

Ground concurrency: it is not desirable to displace potentially productive agricultural land because of a solar installation. Although policy measures restrict agricultural land use in some countries, an alternative to such restrictions is implementing low-impact solar development through solar centric design or vegetation-centric design or co-location design depending on the project goal. These options will enable leaving the current vegetation or replacing them with low-intensity vegetation that can support habitats. Proper planning and development of vegetation co-location at the time of site preparation will reduce the total installed cost by approximate 3–8% per watt [73].

Water use: the use of water depends on the location and solar energy technologies considered as part of the power project. For example, solar PV technology does not use water for power generation except for cleaning or maintenance and construction of the plant. On the other hand, CSP may require 600 to 650 gallons of water per MWh of electricity generation [72]. The use of water should be compared to that of local communities, and any impact on local water supplies should be understood and mitigated.

Life-cycle environmental impact of solar energy systems: solar energy systems actively contribute to climate change mitigation and sustainable development. However, their large-scale implementation has possible negative environmental consequences [74,75]. There are many ways of measuring environmental impact, and each organisation may have their preferences. Perhaps the most straightforward measure is to consider the global warming emissions associated with solar installation.

It is a known fact that solar energy does not produce global warming emissions during power generation. However, emissions are associated with the materials used to manufacture the energy systems, shipping, construction, fixing, maintenance, and decommissioning. Harmful materials are used in the cleanup and cleansing of the semiconductor surface in the PV cell production process. The life-cycle emissions for solar PV systems and concentrating solar power are estimated to be 32–81 g and 36 to 90 g of carbon dioxide equivalent per kWh, respectively.

Conventional silicon cells are less toxic than thin-film cells [72]. Tools, such as the Solar Scorecard, can compare PV cells' environmental impact from different manufacturers [76]. A 2012 research studied the production of different battery technologies and reported that lithium-ion batteries are less toxic than nickel-cadmium batteries and about half as harmful as lead-acid batteries per MJ of capacity. The least dangerous are nickel-metal hydride and sodium-sulphur batteries. However, the lithium-ion and nickel-metal-hydride battery technologies cause most greenhouse gas emissions due to high energy consumption for production [77].

A possible (but not free) source of information on environmental impact [78] is the Ecoinvent database [79] which provides life-cycle inventory information for many products and processes, including many standard components of solar energy systems. This database has been used in many studies to assess the environmental impact of solar energy systems [80]. The life-cycle impact can be obtained as:

$$\begin{gathered}\text{Life cycle environmental impact of solar energy system} = \\ \text{Expected energy yield (kWh/year)} \times \text{Life-cycle duration (years)} \times \text{Life-cycle} \\ \text{emissions for photovoltaic systems (gCO}_2\text{/kWh)}\end{gathered} \tag{7}$$

Landscape and visual impacts: large solar farms tend to have more visibility when they are not suitably sited and screened within the communities they are expected to serve. They can have different impacts on the character and designation of the landscapes. The potential risks can be avoided by having a detailed site layout and design, the project's scale, and considering plantations to reduce visual impact due to glint and glare. It might be better to limit the scale of the project enough to meet the immediate stakeholders' demands to avoid a comprehensive environmental impact assessment.

Reduction in carbon emissions: the reduction in carbon emissions because of the substitution of fossil fuel generation with a solar energy installation positively impacts the environment. A simple initial calculation of solar panels' carbon savings involves assuming that all solar electricity directly replaces electricity produced by large power stations. A common way of calculating this is by using the 'average grid carbon intensity, which is the average amount of CO_2 emitted for each kWh of electricity produced for the power grid, estimated at 445 g CO_2 in the UK, 2013. Please note that this average figure may vary from country to country. A more conservative approach assumes that solar power replaces electricity produced by efficient gas power plants commonly used as a rapid response supply to ensure grid balance. It is estimated that these efficient gas plants in the UK currently emit 392 g CO_2/kWh [81]. The reduction in carbon emissions can be computed using the following equation:

$$\begin{gathered}\text{Life-cycle carbon emission reduction} = \text{Average grid carbon intensity} \times \\ \text{Expected energy yield (kWh/year)} \times \text{Lifetime of the system}\end{gathered} \tag{8}$$

2.4. Social and Legal Aspects

Ease of permit acquisition: permits and licensing can be a lengthy process requiring approvals from organisations at the local, national, and central level. Depending on the characteristics of the project and the local or national legislation, some (or all) of the following may be necessary [53]:

1. Land lease accord.
2. Site access license.
3. Planning consent.
4. Environmental certificate.
5. Grid connection contract; and
6. Operator licence.

Impacts on cultural heritage: the impacts on cultural heritage can be identified by proper site layout, and design and any impacts on archaeological value due to ground excavation and cultural heritage should be mitigated by avoiding the areas of concern. Anyone proposing works to a listed or protected building must follow the policies set out by national planning regulations and planning permission will likely be required. It is very important to conserve the heritage assets, and more weight must be assigned to the sub-criteria dealing with impacts on cultural heritage due to the current project development. Many historical buildings have large roof slopes that can be sites for generating energy through solar panels or slates. Such roofs are often highly visible and, therefore, contribute to the character of the building. Solar panels may be accommodated easily on the buildings with shallow-pitched roofs, which may be mostly hidden from view, or internal roof slopes that cannot be seen from ground level.

Community engagement: community engagement is an integral part of large-scale power project development involving sharing information with and creating awareness in local communities. It is important to develop and sustain a constructive relationship with the local community enabling active participation to detect and mitigate any potential negative impacts on the local community [53].

Energy independence: when an organisation, community or household can produce enough of its energy to meet its demands, then it is referred to as being energy independent. Energy independence can be desirable as it isolates the organisation, community or household from price fluctuations, quality of supply issues, and it can bring clear financial advantages. Even if the organisation, community or household is not fully energy independent, just increasing the degree of independence from external energy suppliers can be a desirable consequence of a solar energy project.

Ease of agreement between stakeholders: in community projects in particular, it is often difficult in the initial stages to agree on key aspects of the project due to the different opinions, priorities, and dislikes that the different stakeholders can have.

Table 17 summarises all the aforementioned criteria/sub-criteria key for a solar energy project's feasibility study.

Table 17. Performance indicators of the solar energy system.

Technical		Financial	Environmental	Social and Legal
Site Aspects	**Technology Suitability**			
• Estimated energy yield • Self-consumption fraction • Features of land/roof area • Ease of connection to grid or local heat network • Presence of obtrusive objects causing shades	• PV Panel efficiency • PV Panel degradation • Solar PV panel manufacturer's warranty • Battery efficiency • Battery energy density • Battery cycle life • Maintenance requirements of batteries • Efficiency of inverters • Manufacturer warranty of inverters • Efficiency of solar collectors • Efficiency of a thermodynamic cycle in solar thermal systems	• Capital costs • Operation and Maintenance costs • Revenues and electricity tariffs • Debt servicing and capital repayment • Taxes • Financial modelling • Net Present Value • Internal rate of return • Payback Period • Cash Flow Available for Debt Service • Debt Service Coverage Ratio • Loan Life Coverage Ratio • Levelised Cost of Electricity	• Habitat loss • Ground concurrency • Water use • Life cycle environmental impact of solar energy systems • Landscape and visual impacts • Reduction in carbon emissions	• Ease of permit acquisition • Impacts on cultural heritage • Community engagement • Energy independence • Ease of agreement between stakeholders

3. Case Study

The study uses the data from a real solar farm planned in England. Due to confidentiality and commercial sensitivity, the solar farm's exact location and other geographical details are not disclosed or have been purposefully modified in this study. Two different specifications, as listed in Table 18, were initially proposed by considering the planning constraints.

Table 18. Specifications.

Specification	Details
A	6.4 MW_p PV system String Inverter Configuration
B	2.5 MW_p PV system String Inverter Configuration

A wide range of options for each of the above specifications was suggested based on electricity sales and integration. These options are described in the following sub-section and summarized in Table 19.

Table 19. All nine options from two specifications.

Specification	Option	Electricity Sales				Technical			Connection	
		S1	S2	S3	S4	Battery Storage	Load balancing	Designated PV array	Grid connection and Private wire	Sleeving
A	A1	✓							✓	
	A2	✓	✓	✓				✓	✓	
	A3	✓	✓	✓		✓		✓	✓	
	A4	✓	✓	✓			✓		✓	
	A5				✓					✓
B	B1				✓					✓
	B2	✓							✓	
	B3	✓		✓				✓	✓	
	B4	✓		✓		✓		✓	✓	

3.1. Description of Options

The following sub-section describes the key considerations about installed capacity, planning permission, electricity sales, integration of storage and distribution network for each option in the feasibility study. A 6.4 MW_p, solar PV system is proposed in options A1 through A5 as the expected highest allowable capacity based on the site features. A 2.5 MW_p, solar PV system is proposed in options B1 through B4 based on the vital considerations over receiving planning consent from the local authority. Some of them are:

- Solar PV development will need to be of an appropriate scale for its location, have no significant environmental impact, and a development scale that meets its user's needs.
- Limit the system capacity to the scale of solar PV farms already approved by the local authorities to increase the likelihood of approval and avoid the likelihood of a full environmental impact assessment.

Stakeholder 1 (S1, large institution), Stakeholder 2 (S2, large hospital complex) stakeholder 3 (S3, large leisure complex), and stakeholder 4 (S4, public buildings) have been identified for the purchase of electricity generated by the solar farm based on the distance to the site and annual electricity demand. While S1 to S3 are expected to use private wire for electricity transfer, S4 will have electricity sleeving through a distribution network. The anonymous organisation and future owner of the solar farm will be able to generate more revenue if all the stakeholders are connected to the site and import electricity from the solar farm site, thus reducing energy export to the grid. However, it may not always be possible to connect more stakeholders to the site due to issues associated with obtaining power purchase agreement, technical complexities and securing permissions, to name some of the factors. Thus, option A1 considers a scenario where the majority of energy generation is exported to the grid due to limited stakeholder connections. Additionally, a sleeving setup is suggested in option A5 and B1. Sleeving is a way of selling electricity from a generator to a user via an intermediary licensed energy supplier/utility. For this purpose, the consumer and generator must be connected to the distribution network. Sleeving guarantees the generator with a stable income source from the off-taker through an agreed energy price during the supply contract period. The consumer also will gain from a fixed energy price linked to indexation and renewable certificate entitlements.

It is essential to isolate the stakeholders electrically when multiple stakeholders are connected to the solar farm site to avoid potential system failure. The isolation can be done either using a simple solution like a designated solar PV array or an expensive approach using a power electronics device for load balancing. In the first case, each stakeholder is assigned a separate solar PV array with its own switchboard on the solar farm site. However, this approach would export energy to the grid during periods of low demand. Instead, the exported energy could have been utilised by one of the other stakeholders, increasing potential generator revenue. For the second case, all the stakeholders are connected to the same PV system, and a power electronics device is installed between the switchboards on the solar farm site. This approach will enable energy sharing between the stakeholders without connecting them electrically, and could minimise the energy export to the grid depending on on-site demands. The total solar PV system capacities proposed in specification 1 and specification 2 can be divided across three stakeholders based on their estimated peak capacity, as shown in Table 20.

Table 20. Solar PV capacity split by consumers' electricity sales via energy provider.

Stakeholder	Option A2, A3	Option B3, B4
S1	1.0 MWp array	0.5 MWp array
S2	3.4 MWp array	Not sufficient generation
S3	2.0 MWp array	2.0 MWp array

All nine variations require a connection to the distribution network. Moreover, each stakeholder requires a separate private wire for connection from the solar farm site, excluding options A5 and B1. Options A3 and B4 include integrating a 0.5 MW/1.0 MWh grid-scale lithium-ion battery storage system that is likely to be packaged in a shipping container. Many factors, such as safety, connection point, access, security, noise, flood risk, landscape and visual impact, and existing planning conditions, were considered for analysing these two options. Due to its demand profile and closeness to the solar farm site, S3 is a better PPA counterparty for the energy storage option.

3.2. Modelling

The solar PV generation modelling was carried out for the anonymous future owner of the solar farm by expert analysts using commercial PV software and feeding the required input information, such as site location, meteorological data, inverter and module details with corresponding array arrangement and module framework. The modelling software used does not have a list of standard transformers in its database for selection, and hence transformer losses were modelled by assuming 0.1% of iron losses and around 1% due to I^2R losses. The software does not adequately incorporate complex site characteristics into energy generation analysis. However, using a different solar energy estimation software, it was observed that the difference in energy between a flat site and a site with a 5 degree south facing slope is only of the order of 1%, and hence this small difference is neglected because solar irradiance has a margin of around ±5%. The following sections describe the key inputs considered for the energy assessment, financial and environmental analysis.

3.2.1. Technical

The specifications of the solar panel and battery storage system are described in Table 21, while the annual electricity demand of four potential stakeholders is illustrated in Table 22. The parameters mentioned in Table 21 are fetched by the commercial PV software from its library of components from different manufacturers. These values can vary depending upon the location and manufacturer, similar to the studies [82–84].

Table 21. Specifications of solar panel and battery storage.

Description	Details
Solar Panel	
Module rating (Wp)	400
Module type	Monocrystalline
Module direct current (DC) nameplate (MWp)	6.39
Intrarow spacing (m)	4
Orientation	Due South
Panel Tilt	20°
Inverter	String configuration; 40 kWp
Average annual insolation at 20 deg	1321 kWh/m^2
Battery	
Rated power	500 kW
Rated capacity	1000 kWh
c-rate	0.5
Efficiency	94%
Depth of discharge	80%
State of charge (minimum)	100 kWh
State of charge (maximum)	900 kWh
Available discharge energy	800 kWh
Time to full discharge	1.6 h
Maximum half-hourly discharge rate	250 kWh
Degradation	1.2%
Maximum number of cycles	7000
Lifetime	20 years

Table 22. Electricity demand details of all the stakeholders.

Stakeholder	Half Hourly Electricity Demand (MWh)	Key Features
S1 (large institution)	1994	• Annual profile: demand higher during winter months • Week profile: demand higher during weekdays • Day profile: Demand higher during the day and tapering off in the evening • Other: Demand lower during holidays • Peak demands: 561 kW
S2 (large hospital complex)	22,201	• Annual profile: demand is highest between January-March • Week profile: demand higher during weekdays • Day profile: demand higher during the day and tapering off in the evening • Other: Demand lower during holidays • Peak demand: 5.5 MW
S3 (large leisure complex)	5417	• Annual profile: demand higher during winter months • Day profile: higher demand during the day • Other: higher demand during significant events • Peak demand: 2.1 MW
S4 (public buildings)	8801	• Annual profile: Some seasonal variation • Day profile: Demand higher during the day

3.2.2. Financial

Table 23 summarizes the assumptions considered during the financial analysis. Some of these assumptions are specific to geographical location and can vary by some margin, similar to the reference [82]. The UK's base inflation rate was 2.1 at the point of this analysis and was adjusted conservatively. The degradation rate of crystalline panels in England was found to be in the range of 0.7% to 0.9% per year [85]. The PPA prices have been estimated based on the document [86] produced by Department for Business, Energy and Industrial Strategy (BEIS), UK. The PPA price assumptions in this paper are conservative, reasonable and fall within the BEIS projections until 2035 which should improve the confidence in profitable and slightly profitable options. The development costs include feasibility and site assessment works, seeking consents, and any potential planning contingency works. Purchase and construction of generation equipment, site works, and grid connection costs and management and legal fees constitute the construction costs. Finally, the operating and major maintenance costs will occur after the PV system's construction and will cover maintenance, general costs, business rates and insurance. Options A3 and B4 also include costs (Capital = £425,980, Operating = £8520 and Electricity purchase = £10,045) of a battery storage system embedded in the final costs reported in Table 24.

Table 23. Inputs for financial modelling.

Assumptions	Value
Inflation	2.2%
Electricity price inflation	3.25%
Availability of plant	95%
Degradation of panels	0.7% per year
Public Works Loan Board finance rate	2.5%
Discount rate	6.0%
Power purchase agreement—Off taker	£85/MWh
Power purchase agreement—Sleeving	£50/MWh
Power purchase agreement—Sold to grid	£50/MWh

Table 24. Assumed costs for each option in the study.

Specification	Option	Development Costs (£)	Construction Costs (£)	Operating Costs (£)	Major Maintenance (£) (Year 10 and 20)
A	A1	295,750	4,594,000	107,000	320,000
	A2	295,750	4,345,000	107,000	320,000
	A3	295,750	4,770,980	125,565	320,000
	A4	295,750	4,620,000	107,000	320,000
	A5	295,750	4,402,000	107,000	320,000
B	B1	178,750	1,652,000	52,000	125,000
	B2	178,750	1,791,000	52,000	125,000
	B3	178,750	1,901,000	52,000	125,000
	B4	178,750	2,326,980	70,565	125,000

The purpose of financial analysis is to distinguish the nine variations based on the three key financial metrics. Each variation came with a proposed capacity, share of energy exported to the grid and sold directly to a stakeholder and consequently, the generated revenue over the project's lifetime.

4. Results and Discussion

This section describes and discusses the results of applying the proposed MCDA model to the case study described in Section 3. The sub-criteria relevant to the case study for which data are available is considered in the analysis. The objective, main-criteria, sub-criteria and the available options for analysis are shown in Figure 3. Tables 25–28 provide the key technical, environmental, financial, and social parameters values and information required for assigning scores to all the sub-criteria. Relevant additional information is provided as a part of footnotes under each table. The scores are given using the information from the above tables and the framework discussed in Section 2, Tables 2–4. The results are presented in Tables 29–32.

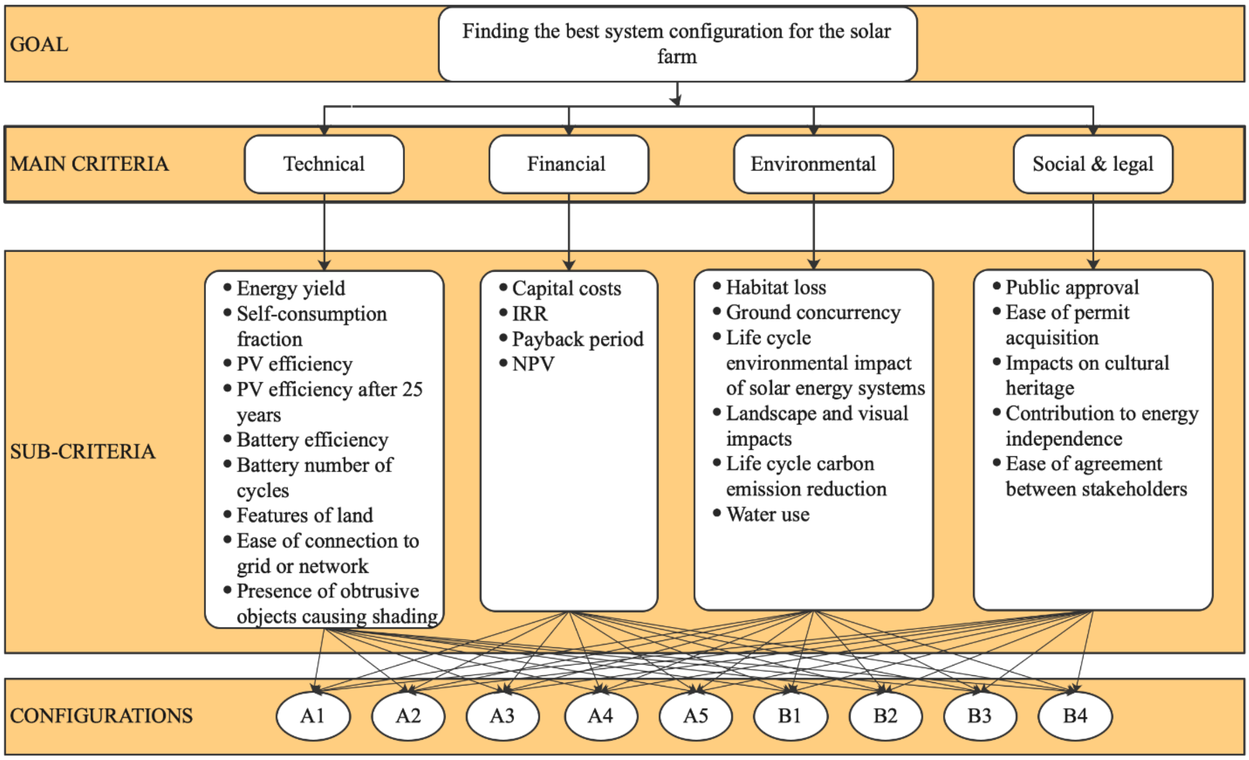

Figure 3. Relation between different levels of process.

Table 25. Values of different technical sub-criteria considered in the case study.

<table>
<tr><th rowspan="2">Sub-Criteria</th><th colspan="9">Options</th></tr>
<tr><th>A1</th><th>A2</th><th>A3</th><th>A4</th><th>A5</th><th>B1</th><th>B2</th><th>B3</th><th>B4</th></tr>
<tr><td>Energy yield (MWh/year)</td><td colspan="5">← 6867 →</td><td colspan="4">← 2683 →</td></tr>
<tr><td>PV panel efficiency (%)</td><td colspan="9">← 19.4 →</td></tr>
<tr><td>PV panel efficiency after 25 years compared to the initial value (%)</td><td colspan="9">← 80 →</td></tr>
<tr><td>Battery efficiency (%)</td><td>-</td><td>-</td><td>94</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>94</td></tr>
<tr><td>Battery number of cycles</td><td>-</td><td>-</td><td>7000</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>7000</td></tr>
<tr><td>Features of land</td><td colspan="9">← ✶ →</td></tr>
<tr><td>Ease of connection to grid or network</td><td colspan="9">← ✶ →</td></tr>
<tr><td>Presence of obtrusive objects causing shading</td><td colspan="9">← ✶ →</td></tr>
<tr><td>Self-consumption fraction (%)</td><td>15</td><td>82</td><td>83</td><td>90</td><td>53</td><td>88</td><td>33</td><td>72</td><td>74</td></tr>
</table>

✶ The site has tall trees on the east boundary, south facing slope (up to 5°), a pathway for pedestrians to the south of the site and terrain irregularities in the middle of the land. There are chances of inter-panel shading due to the slope if sufficient distance between panels is not maintained. Mineral deposits were located on the eastern side of the site, and as a result, a ground survey would be needed to analyse the impacts of the mineral deposits on the installation of support structures. Options A1 to A5 require a large land area, and it is difficult to avoid the terrain irregularities in the middle. However, the system's capacity is small in options B1 to B4, and it is possible to avoid the terrain irregularities in the middle of the site for panel mounting.

Table 26. Values of financial sub-criteria for all the options in the case study.

Sub-criteria	Options								
	A1	**A2**	**A3**	**A4**	**A5**	**B1**	**B2**	**B3**	**B4**
Capital costs (£ million)	4.9	4.6	5.1	4.9	4.7	1.8	2	2.1	2.6
Internal rate of return (IRR) (%)	3.8	9.3	8.4	9.1	2.8	1.8	4.1	6.4	4.9
Payback period ■ (years)	17.5	11	11.5	11	19	21	17	13.5	15.5
Net present value (NPV) @6% ❖ (£ million)	−1.1	1.7	1.3	1.7	−1.4	−0.7	−0.4	0.1	−0.3

■ Payback period is the period needed for recovering the investment costs. In the present study, options A2 and A4 have the lowest payback period of 11 years, while option B1 has the highest payback period of 21 years. Since the expected useful life of some of the components used in the system is less than 20 years, any option with a payback period greater than the life of assets is not recommended. The shorter the payback period, the less risky it is to the solar farm owner. This metric is also useful to decide on the period of any power purchase agreements. Although the payback period gives an idea about how long it takes to recover the initial investment, it does not give information about the return on investment. For example, when comparing options A5 and B1, it is possible to select A5 over B1 solely on the payback period. However, the NPV of option B1 is better than the NPV of option A5, which supports the notion that the payback alone is not sufficient to make a decision. In fact, the proposed methodology aggregates the scores for different sub-criteria when calculating the score for the financial criteria. ❖ A positive NPV is generally recommended for getting returns on an investment aimed at making profits. When comparing multiple options with positive NPVs, the one with the highest NPV can be more profitable. In the current study, the options A2, A3, A4, B3 and B4 have positive NPV, which means these configurations will generate future net cash flows whose present value is worth more than the initial cost. On the other hand, options A1, A5, B1 and B2 have negative NPVs, meaning that these options might create loss based on the projected cash flows and should not be usually considered further, although this may not be true for all the situations and depends on company policy, subsidy policy for energy projects [87], and project purpose. It is important to note that all the inputs to an NPV analysis are uncertain, and a static NPV ignores the volatility of future cash flows [88].

Table 27. Values of environmental sub-criteria for all the options in the case study.

Sub-Criteria	Options								
	A1	**A2**	**A3**	**A4**	**A5**	**B1**	**B2**	**B3**	**B4**
Habitat loss	←				✶				→
Ground concurrency	←				❖				→
Life cycle environmental impact of solar energy systems (tonnes CO_2 eq.)	←		4394.9		→	←		1717.1	→
Landscape and visual impacts	←				⊙				→
Life cycle (20 years) carbon emission reduction (tonnes CO_2)	←		53,837.3		→	←		21,034.7	→
Water Use	←				⟑				→

⊙ The site selected for the solar energy system is shielded from view with trees and shrubbery, and no negative impact on local amenity is expected. The location of the battery in large containers might add to negative visual amenity. ❖ The site is currently not allocated as agricultural land, even though it is utilised for agricultural reasons leaving scope for the local planning authority to deem it as an undetermined quality of agricultural land. ✶ The development is sited to avoid ecological impacts and increase biodiversity quality by following best practices from across the world. No significant habitat loss is expected due to the construction of the project. ⟑ The project does not require water for operation except during construction and maintenance (for cleaning the panels).

Table 28. Values of social and legal sub-criteria for all the options in the case study.

Sub-Criteria	Options								
	A1	**A2**	**A3**	**A4**	**A5**	**B1**	**B2**	**B3**	**B4**
Public approval	←				⊙				→
Ease of permit acquisition	←				✶				→
Impacts on cultural heritage	←				⧫				→
Contribution to energy independence	←				⟑				→
Ease of agreement between stakeholders	←				❖				→

⟑ System capacity of options A1 to A5 offers more energy independence compared to options B1 to B4. However, none of the nine options can completely meet the total demand from all the stakeholders. Options A3 and B4 have battery storage, increasing the value of power sold to the consumers and will have a better match with the local demand required as per the local planning authority. ✶ As a part of early-stage application advice, all the local planning authorities were consulted to understand the potential planning requirements. An appropriate scale project that is near to the electricity serving sites and meeting the demand of the property being served is found to be an important policy criterion. Any battery storage facility development that could impact landscape, noise, and biodiversity is not recommended. Based on some of the previously permitted solar energy projects with similar development landscapes, national park location and planning policies, the following approach seems favourable. A limited system capacity near to 2.5 MW_p that can arguably be appropriate to serve the energy demand and avoid a full environmental impact assessment is found to be better for planning considerations. Moreover, the local planning authority policy interpretation gave the impression that it has not comparatively been a supporter of large-scale solar farm development. Therefore, the system capacities in options B1 to B4 have more chances of obtaining permission from planning authorities. ⧫ The solar farm development is located near several buildings, sheltered from view by trees and shrubbery, and thus well screened. It is not sited in isolation to avoid significant impacts on visual amenity. Options B1 to B4 will have a fair advantage over options A1 to A5 in this aspect. ❖ All the stakeholders discussed in the study were interested in purchasing solar energy from the solar farm via the private wire subjective to the PPA price or synthetic PPA price. The time and resources required increases as the number of stakeholders increase. ⊙ None of the options are expected to face significant public dissent due to wellscreened siting except for options A3 and B4, where battery storage is recommended with potential site locations near public areas. Factors such as fire, explosion, noise, and flooding may raise concerns among the public.

Table 29. Scores of technical sub-criteria for all the options in the case study.

Sub-Criteria	Options																	
	A1		A2		A3		A4		A5		B1		B2		B3		B4	
	E	S	E	S	E	S	E	S	E	S	E	S	E	S	E	S	E	S
Energy yield (MWh)	Y	8	Y	8	Y	8	Y	8	Y	8	Y	6	Y	6	Y	6	Y	6
PV panel efficiency (%)	Y	8	Y	8	Y	8	Y	8	Y	8	Y	8	Y	8	Y	8	Y	8
PV panel efficiency after 25 years compared to the initial value (%)	Y	9	Y	9	Y	9	Y	9	Y	9	Y	9	Y	9	Y	9	Y	9
Battery efficiency (%)	N	0	N	0	Y	9	N	0	N	0	N	0	N	0	N	0	Y	9
Battery number of cycles	N	0	N	0	Y	7	N	0	N	0	N	0	N	0	N	0	Y	7
Features of land	Y	7	Y	7	Y	7	Y	7	Y	7	Y	8	Y	8	Y	8	Y	8
Ease of connection to grid or network	Y	9	Y	9	Y	7	Y	7	Y	8	Y	8	Y	9	Y	8	Y	7
Presence of obtrusive objects causing shading	Y	8	Y	8	Y	8	Y	8	Y	8	Y	9	Y	9	Y	9	Y	9
Self-consumption fraction (%)	Y	5	Y	9	Y	9	Y	10	Y	7	Y	10	Y	6	Y	8	Y	8
TECHNICAL SCORE	**7.71**		**8.29**		**8.11**		**8.14**		**7.86**		**8.29**		**7.86**		**8.00**		**7.89**	

E—Essential? S—Score, Y—Yes, N—No.

Table 30. Scores of financial sub-criteria for all the options in the case study.

Sub-Criteria	Options																	
	A1		A2		A3		A4		A5		B1		B2		B3		B4	
	E	S	E	S	E	S	E	S	E	S	E	S	E	S	E	S	E	S
Capital costs (£ million)	Y	7	Y	7	Y	6	Y	7	Y	7	Y	9	Y	9	Y	9	Y	8
IRR (%)	Y	7	Y	10	Y	9	Y	10	Y	6	Y	5	Y	7	Y	8	Y	7
Payback period (years)	Y	6	Y	9	Y	9	Y	9	Y	6	Y	5	Y	7	Y	8	Y	7
NPV @6% (£ million)	Y	6	Y	9	Y	9	Y	9	Y	5	Y	7	Y	7	Y	8	Y	8
FINANCIAL SCORE	**6.5**		**8.75**		**8.25**		**8.75**		**6.0**		**6.50**		**7.50**		**8.25**		**7.50**	

E—Essential? S—Score, Y—Yes, N—No.

Table 31. Scores of environmental sub-criteria for all the options in the case study.

Sub-Criteria	Options																	
	A1		A2		A3		A4		A5		B1		B2		B3		B4	
	E	S	E	S	E	S	E	S	E	S	E	S	E	S	E	S	E	S
Habitat loss	Y	8	Y	8	Y	8	Y	8	Y	8	Y	9	Y	9	Y	9	Y	9
Ground concurrency	Y	8	Y	8	Y	8	Y	8	Y	8	Y	9	Y	9	Y	9	Y	9
Life cycle environmental impact of solar energy systems	Y	8	Y	8	Y	8	Y	8	Y	8	Y	9	Y	9	Y	9	Y	9
Landscape and visual impacts	Y	8	Y	8	Y	7	Y	8	Y	8	Y	9	Y	9	Y	9	Y	8
Life cycle carbon emission reduction (tonnes CO_2)	Y	9	Y	9	Y	9	Y	9	Y	9	Y	6	Y	6	Y	6	Y	6
Water Use	Y	8	Y	8	Y	8	Y	8	Y	8	Y	9	Y	9	Y	9	Y	9
ENVIRONMENTAL SCORE	**8.20**		**8.20**		**8.00**		**8.20**		**8.20**		**8.50**		**8.50**		**8.50**		**8.30**	

V—Value, E—Essential? S—Score, Y—Yes, N—No.

Table 32. Scores of social and legal sub-criteria for all the options in the case study.

Sub-Criteria	Options																	
	A1		A2		A3		A4		A5		B1		B2		B3		B4	
	E	S	E	S	E	S	E	S	E	S	E	S	E	S	E	S	E	S
Public approval	Y	8	Y	8	Y	7	Y	8	Y	8	Y	9	Y	9	Y	9	Y	7
Ease of permit acquisition	Y	8	Y	8	Y	7	Y	8	Y	8	Y	9	Y	9	Y	9	Y	8
Impacts on cultural heritage	Y	8	Y	8	Y	8	Y	8	Y	8	Y	9	Y	9	Y	9	Y	9
Contribution to energy independence	Y	9	Y	9	Y	9	Y	9	Y	9	Y	8	Y	8	Y	8	Y	8
Ease of agreement between stakeholders	Y	9	Y	8	Y	8	Y	8	Y	7	Y	7	Y	9	Y	8	Y	8
SOCIAL AND LEGAL SCORE	**8.40**		**8.20**		**7.80**		**8.20**		**8.00**		**8.40**		**8.80**		**8.60**		**8.00**	

V—Value, E—Essential? S—Score, Y—Yes, N—No.

The final criteria scores from Tables 29–32 are introduced in Table 33. Weights are assigned to the criteria based on the expert's experience, and it is assumed that all the sub-criteria have equal weight. Note that the interaction between sub-criteria belonging to different criteria is not considered in this study. The final average weighted scores are computed according to the methodology discussed in Table 4.

Table 33. Final feasibility scores of technical, financial, environmental, and social legal aspects criteria.

Criteria	Weight (1 to 5)	Score (1 to 10)									Total Average Weighted Score								
		A1	A2	A3	A4	A5	B1	B2	B3	B4	A1	A2	A3	A4	A5	B1	B2	B3	B4
Technical	4	7.71	8.29	8.11	8.14	7.86	8.29	7.86	8.00	7.89	30.84	33.16	32.44	32.56	31.44	33.16	31.44	32.00	31.56
Financial	5	6.5	8.75	8.25	8.75	6.00	6.50	7.50	8.25	7.50	32.50	43.75	41.25	43.75	30.00	32.50	37.50	41.25	37.50
Environmental	4	8.20	8.20	8.00	8.20	8.20	8.50	8.50	8.50	8.30	32.80	32.80	32.00	32.80	32.80	34.00	34.00	34.00	33.20
Social and legal aspects	4	8.40	8.20	7.80	8.20	8.00	8.40	8.80	8.60	8.00	33.60	32.80	31.20	32.00	32.00	33.60	35.20	34.40	32.00
		Final feasibility Score (%)									**76.32**	**83.83**	**80.52**	**83.48**	**74.26**	**78.39**	**81.26**	**83.32**	**78.98**

There are no substantial technical, commercial, or legal barriers to a power purchase agreement or private wire. One risk is the need to obtain wayleaves for laying private wire wherever required, which could be obstructed by a single landowner. It is, therefore, important to minimize the number of wayleaves that are required. S2 is far from the solar farm site and requires a longer private wire than S1 and S3. It also requires obtaining wayleaves from others. Another challenge is the possibility of system failure when two or more sites are connected to a solar PV system. To overcome system failure, two options were proposed, i.e., designated solar PV array and use of power electronics device. Option A4 considered using a power electronics device while A2, A3 and B3, B4 will use a designated array. Since option A1 has only one stakeholder connection, there are no challenges associated with system failure. Option A3 has additional battery storage connected to S3, and it is planned for installation on the S3 land, and there is a requirement for obtaining wayleave from the S3. A5 and B1 involve sleeving via the distribution network to the customers. In the present case study, export to stakeholders could contribute to a high self-consumption fraction and better business cases compared to exporting to the grid.

Figure 4 displays the total averaged weighted scores of different criteria for each alternative. Alternative A2 and B1 scored highest in the technical aspects criteria, while A5 and B2 have the lowest score. The final technical scores are driven by the sub-criteria 'self-consumption fraction' and 'energy yield'. In the financial category, alternatives A4 and A2 have the highest score, followed by A3, B3, B2, B4, B1 and A1. Alternative A5 has the lowest score for financial criteria. Here, the sub-criterion NPV played an important role in the final financial scores. The scores for environmental criteria are the same for many variants such as B3, B2, B1, and they all occupy first place, followed by A1, A2, A4, A5, B4 in the second-highest position. Alternative A3 has the lowest score in the environmental aspects. The sub-criteria 'life-cycle carbon emission reductions' proved to be critical in limiting the gap between final environmental scores of B-type and A-type configurations.

Finally, alternative B2 scored highest for the social and legal aspects criteria, while A3 had the lowest score for those aspects. High scores in the 'ease of permit acquisition' and 'public approval sub-criteria' are the reasons for the superior score of option B2. These observations are only relevant for the current solar farm study and will generally vary for other solar energy projects. It is essential to highlight that no single alternative dominated all four criteria, stressing the importance of MCDA for solar energy projects.

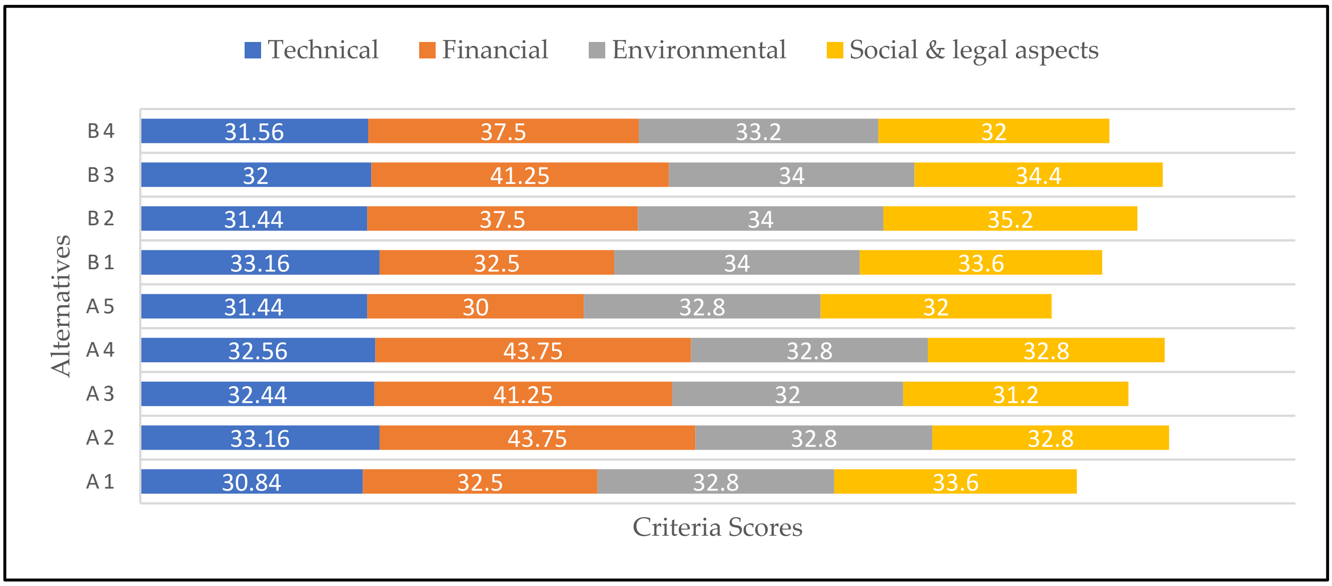

Figure 4. Scores of different criteria for each alternative.

Figure 5 presents the feasibility scores of all the options. Option A2 has an overall score of 83.83 and is the best configuration for the solar farm. The second-best option is A4, with a score of 83.48, followed by option B3 in the third position. Options A5 and A1 are the least possible configurations for setting up the solar farm. Although option A4 and option A2 did not dominate all the four criteria, they are the top two recommended options when all the sub-criteria are considered as part of the feasibility study. Option A3, which has a similar configuration to option A2, has been pulled down due to the additional costs from battery storage resulting in a low financial score. The only other option with battery storage, this is option B4, is limited by its off-taker connections and low technical and financial score. The observations indicated that the options with a greater number of stakeholder connections and without battery storage performed better than the options with battery storage. The results obtained using the proposed model are consistent with the recommendations made by the analysts who carried out the feasibility study for the anonymous future owner of the solar farm. In the original feasibility study upon which this work is based, options A4 and A2 were finally selected for further evaluation. However, it is important to note that the analysts' recommendations were based only on the highest financial return, without directly accounting for all the key technical, environmental, and social and legal aspects that have been considered in this work. The analysts took into consideration the planning permission constraints while proposing the system specifications and corresponding options listed in Tables 18 and 19, respectively.

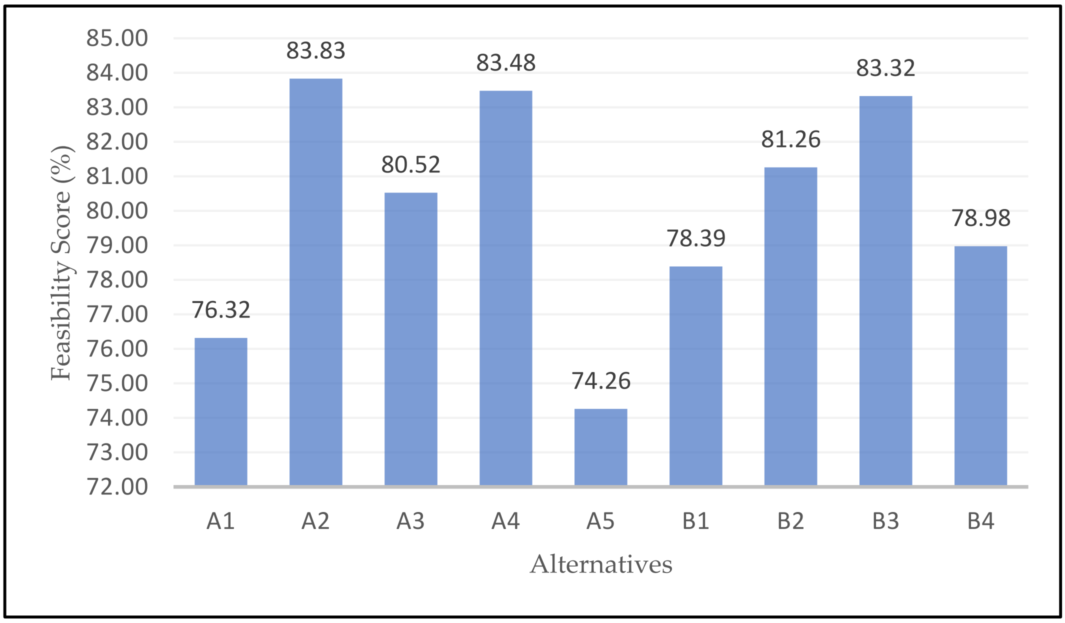

Figure 5. Feasibility scores of all the alternatives in the study.

5. Sensitivity Analysis

It is essential to conduct a post-selection sensitivity analysis to assess the confidence of the results as there may be uncertainty in some of the data, and the assignment of weights and scores is subjective. According to Erhan et al. [89], a sensitivity analysis can address the following questions:

- What is the impact on alternatives ranking if a weight (w_i) is changed to w_i'?
- What is the smallest change in the weights required to change the highest alternative ranking?
- How many experts have selected the same alternative despite different opinions in terms of criteria comparison?

Accordingly, the criteria weights have been changed, as indicated in Table 34, and feasibility scores for all the alternatives are computed to observe potential changes in the ranking order. Table 34 and Figure 6 illustrate the feasibility scores for different weight combinations. It is noted that option A2 is ranked highest in majority of cases except for the weight combination (4,4,5,5) where the environmental and social aspects are considered more important than the technical and financial aspects. In this case, B3 ranked highest followed by A2 and A4, while A5 remained the least attractive variant in all cases. In Table 34, the dark green color gradient indicates a high score, while the red color denotes a relatively low score.

Table 34. Feasibility scores of alternatives for different criteria weight combinations.

Weights (T, F, E, S) *	Feasibility Score (%)								
	A1	**A2**	**A3**	**A4**	**A5**	**B1**	**B2**	**B3**	**B4**
(4,5,4,4)	76.32	83.83	80.52	83.48	74.26	78.39	81.26	83.32	78.98
(5,4,4,4)	77.03	83.56	80.44	83.12	75.35	79.44	81.47	83.18	79.21
(4,4,5,5)	77.69	83.42	80.24	83.09	75.80	79.81	82.19	83.61	79.48
(4,5,3,5)	76.44	83.83	80.41	83.48	74.14	78.33	81.44	83.38	78.80
(5,5,4,3)	75.91	83.88	80.71	83.44	74.18	78.32	80.71	82.97	78.91
(3,5,4,5)	76.72	83.78	80.34	83.51	74.34	78.45	81.81	83.68	79.04

* T—Technical, F—Financial, E—Environmental, S—Social, and legal aspects.

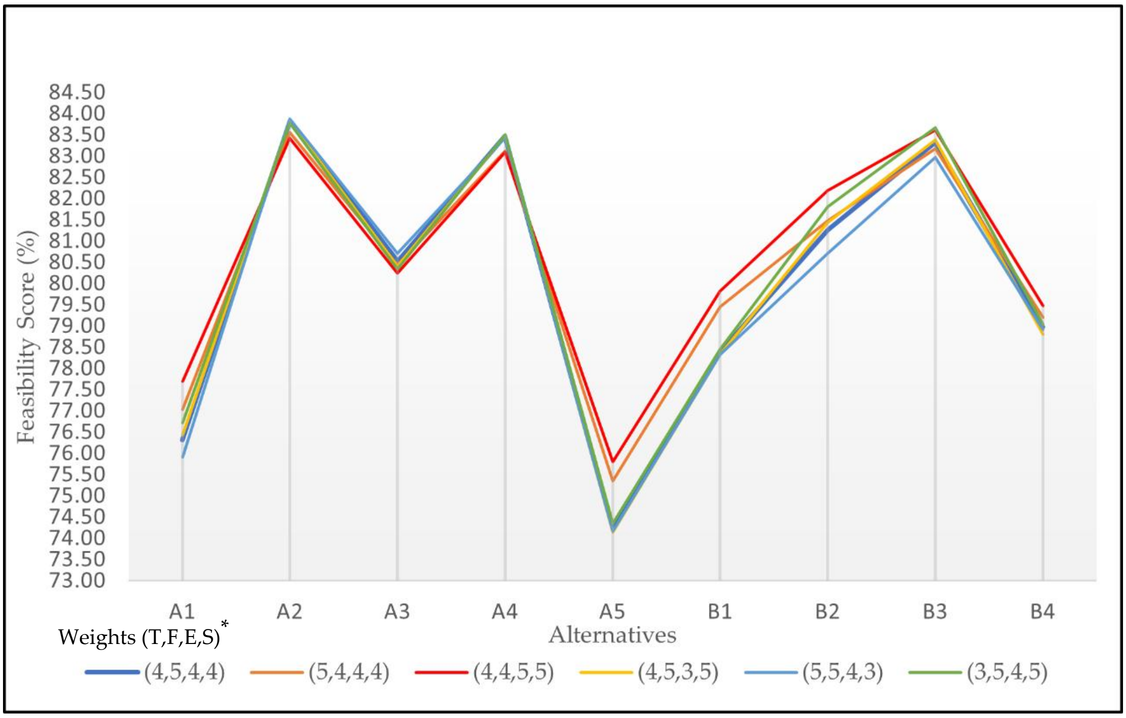

Figure 6. Feasibility scores of alternatives for different weight combinations. * T—Technical, F—Financial, E—Environmental, S—Social and legal aspects.

From this analysis, it clear that the proposed MCDA model produces consistent results for small changes in the weights associated with the main criteria.

6. Conclusions

Solar energy is acknowledged to be key to transition to less carbon-intensive energy power generation, and it has witnessed investments on an unprecedented scale, leading to technological advancements and falling costs of key components. Despite the plummeting costs, solar energy penetration relies on strategic decision making and is subject to energy system planning methods, which may vary from organisation to organisation. MCDA has been widely used for energy system planning and feasibility, as described in Section 1.

The research presented in this study collected information about the key technical, financial, environmental, social and legal aspects that are typically considered as performance indicators when planning a solar energy system. A flexible MCDA model has then been proposed to compute the feasibility score of different configurations for a solar energy project. The proposed model has been applied to a real-world solar farm that is planned at a site in England, and it allowed us to identify the best configuration by considering all four proposed performance criteria and corresponding sub-criteria. The results indicate that option A2, which involves a greater number of off-taker connections and no battery storage, returned the highest feasibility score owing to its superior performance in the technical and financial criteria. However, the sensitivity analysis indicated that the results may change depending on the weights of the main criteria. Compared to other options, A1 and A5 had very low self-consumption fraction, thus reducing their revenues and making them score poorly in the technical and financial criteria, resulting in these two options being ranked lowest. The proposed model identifies that the sub-criteria 'self-consumption fraction' is critical for the feasibility of studied solar farm. This model is not limited to solar energy projects, but can be adapted to projects in other areas, simply by selecting relevant criteria and sub-criteria. In the case of solar energy projects, the model can be used to rank and compare project options at the feasibility stage in rooftop solar PV, solar thermal plants, and solar PV farms, including cases involving the use of energy storage. Moreover, this model has been successfully used by stakeholders of the Interreg 2 Seas

SOLARISE project [90] to conduct a range of the feasibility studies for solar PV installations on historical and public buildings owned by municipalities and contributed to strategic decision making in those cases. Further research will include computing the weights of criteria/sub-criteria based on a survey from experts, while accounting for uncertainty and interaction between the factors at the same hierarchical level. Also, it will be interesting to investigate the behaviour of the feasibility score when the problem's dimensionality is reduced by using machine learning algorithms.

Author Contributions: Conceptualisation, S.H.B., S.K. and V.B.; methodology, S.H.B., S.K. and V.B.; software, S.H.B., S.K., H.E. and L.T.S.; formal analysis, S.H.B., S.K.,V.B., H.E., L.T.S., J.R., D.H. and R.K.; investigation, S.H.B., S.K., V.B. and H.E.; writing—original draft preparation, S.H.B., S.K. and V.B.; writing—review and editing, S.H.B., S.K.,V.B., H.E., J.R., D.H. and R.K.; supervision, V.B. and S.K. All authors have read and agreed to the published version of the manuscript.

Funding: The first author is a DTA3/COFUND MSCA early-stage researcher and has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement No 801604. This research has also received funding from the Interreg 2 Seas programme 2014–2020 co-funded by the European Regional Development Fund under subsidy contract No 2S04-004 (SOLARISE).

Institutional Review Board Statement: Not Applicable.

Informed Consent Statement: Not Applicable.

Data Availability Statement: Not Applicable.

Acknowledgments: The authors would like to thank the anonymous organisation for providing and allowing use of the solar farm details in the present study.

Conflicts of Interest: The authors declare no conflict of interest.

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