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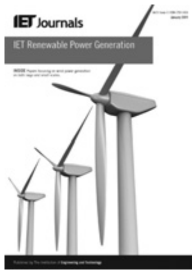

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Decision support system for ranking photovoltaic technologies

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Abstract: The primary photovoltaic (PV) system investment decision-making criteria are economics. These criteria are focused on system efficiency and cost, which is reasonable in the context of generous financial support schemes. However, when financial support is phased out, the PV market becomes technologically diversified. Environmental concerns and other qualitative issues become significant, whereas efficiency and costs may fail to describe PV systems properly. This study presents the first application of outranking techniques for PV technologies within an overall framework that includes qualitative, economic, technical and environmental criteria. The multi-criteria analysis method, ELECTRE III, identifies optimal investment decisions from a pre-determined set of investment alternatives. A case study based on a grid-connected household PV system in the United Kingdom illustrates the methodology. The results suggest emerging excitronic PV technologies such as organic PV to lead the ranking when compared with inorganic technologies. These results have to be taken in the context of a number of assumptions and estimates as well as free market, no financial support schemes and promising future technology developments. The overall decision-making framework provides comprehensive mathematical evaluations that assist PV owners, policy makers and the business community decide on technology, financial support schemes or business strategies.

1 Introduction

Currently the photovoltaic (PV) micro-generation market, which is the largest PV market, is dominated by five inorganic technologies namely mono-crystalline silicon (mono-Si), multi-crystalline silicon (multi-Si), amorphous silicon (a-Si), copper indium gallium diselenide (CIGS) and cadmium telluride (CdTe). Additionally, emerging excitonic PV technologies, such as organic-based PV (OPV) have the potential to enter this market [1].

The search for affordable PV technologies to penetrate into the market competitively has increased as a result of the current high demand for PV, other renewable energy (RE) technologies attaining grid-parity prices, limited financial support schemes and future grid integration such as in the case of competitive dynamic tariffs in smart grids. Hence, in the future, it will be important to have diverse PV technologies to ensure a sustainable PV energy supply to the market [2].

The assessment of investment decisions on PV technologies is based on the compilation and integration of a series of economic, technical and environmental factors that might favour different technologies. That is, the most desirable PV technology, for a decision maker, is likely to differ from the most technically or economically attractive technology. This complicates the assessment process, particularly when the use of PV technologies is diverse. Consequently, it is of significant importance to extend existing PV technologies assessment techniques to address properly different criteria, such as the location, available PV area, performance ratio (PR), economic value and CO_2 emissions, among others. This can be achieved with multi-criteria analysis (MCA).

The application of MCA can facilitate the comparison of PV technologies by combining the different viewpoints that can be used to assess the technology into a standardised evaluation procedure. The purpose is to support decision makers facing problems that have more than one unique optimal solution, using preferences to differentiate between solutions. Hence, the development of customer decision tools for diverse PV technologies is timely.

The primary purpose of this paper is to elaborate and illustrate the first multi-criteria decision support methodology for the assessment of investments in PV systems in a domestic environment. The methodology is based on the ELECTRE III approach, which is the most robust MCA method identified. The methodology is illustrated with a case study based on different commercially available mature and emerging PV technologies, the perspectives of customers and manufacturers, and quantitative and qualitative criteria. The results highlight the most attractive PV technologies according to the many contrasting criteria and perspectives.

This paper is structured as follows. In Section 2, a review on the use of ELECTRE III and similar ranking methods in

RE applications is given. Then, in Section 3, the ELECTRE III algorithm is described. In Section 4, the design and implementation of the decision support tool is elaborated and the case study is evaluated in Section 5. Finally, in Section 6, the main conclusions on PV technology ranking for micro-generation are presented.

2 Review on the application of ranking methods

Existing approaches to model PV systems are meant to study the feasibility of the projects, and focus on potential energy production indicators. However, it can be challenging to compare the feasibility studies, and the scope of the assessments is limited as it is typically based on the equipment available for the contractor or constrained databases.

This problem falls under one of the major multiple-criteria decision-making (MCDM) problems where the alternatives are explicitly defined and termed as a multiple-criteria evaluation problem. The use of MCA methods, such as ELECTRE tools, has increased significantly in the past few years, as these methods facilitate selection of the most preferred alternative from a discrete set of options [3–8].

Available MCA literature offers a wide variety of models and approaches [4, 9]. Among others, the multi-attribute utility theory produces 'value functions' to address multiple criteria based on a set of preferences, handles the tradeoffs among multiple objectives and identifies the most preferred alternative. The analytic hierarchy process (AHP), proposed by Saaty [10] divides the problem into several sub-problems that can be quantitatively compared in pairs, and the weighted sum approach combines all viewpoints based on a weight assigned to each criterion.

The above methods can be used to determine if an investment alternative is better than another based on a set of criteria, as well as to determine the degree of dominance that one investment alternative can have over others. The latter type of MCA approaches called outranking methods, are the tools used in this paper to address the different criteria and alternatives applicable to PV technologies.

Among the outranking methods available in the literature, the ELECTRE III method is the most ideal to address investment decisions in PV systems, as it makes use of both the agreement and discordance concepts and does not hold 'structural properties' in outranking relations, which may turn out to be a difficult task [11]. That is, the ELECTRE III method provides an improved outranking assessment by assessing both the reasons that support and negate the idea that an alternative outranks another, and by allowing the formulation of relations between any investment alternatives. The ELECTRE III method is further explained in Section 3.

The ELECTRE family of outranking method comprises different methods, namely ELECTRE I, ELECTRE II, ELECTRE III, ELECTRE TRI, ELECTRE IV and other ELECTRE evolutions. Among these methods, the ELECTRE III was selected for the assessment of PV systems, as it has been especially developed to assess criteria that can be quantified. The ELECTRE I and ELECTRE TRI methods were developed, respectively, for selection problems and problem assignments. The ELECTRE II is a previous version of ELECTRE III, and the ELECTRE IV method was to assess investment decisions when quantification is not possible, which is not the case for PV systems [12].

Other outranking methods available in the literature, such as SMART and PROMETHEE can offer similar advantages when simultaneously dealing with qualitative and quantitative criteria. Nevertheless, the ELECTRE III model is preferred as (i) it can manage the uncertainty and ambiguity that is found in predictions and estimations, (ii) it has the same robustness as SMART methods [13] and (iii) it offers superior features of virtually having non-compensatory treatment of the problem and proportional thresholds for imprecise data [14]. Non-compensatory treatment will not allow poor performance in a number of criteria to be compensated for by high performance in the other criteria and hence will reflect in the aggregated performance of an alternative.

The ELECTRE family of outranking methods is widely used in literature. Some examples include: the assessment of engineered infrastructure investments [14–23], the extension of existing planning tools to assess municipal solid waste management based on outranking approaches for MCDM and multi-attribute rating techniques [18, 24–30], personalised ranking of British Universities [31], investment stock selection [32], sustainable demolition waste management strategy [33], energy systems selection [34], thin-film (TF) PV technology processes [35], urban storm water drainage [27] and housing evaluation [36]. These studies illustrate the potential of outranking methods, particularly ELECTRE tools, to assess and provide insights of complex problems, such as PV systems that are viewed with the different conflicting objectives of the stakeholders. This paper presents the first application of outranking techniques for the ranking of PV technologies. The ranking is performed using the ELECTRE III technique, as it has proven to be the ideal tool for this application.

3 ELECTRE III method

The ELECTRE III method is part of the ELECTRE, ELimination Et Choix Traduisant la REalité (elimination and choice expressing reality), outranking decision making family, which is part of the multi-criteria decision analysis methods that originated in Europe in the mid-1960s. Roy and his colleagues at SEMA consultancy firm developed the ELECTRE method as a weighted sum-based tool to solve concrete multiple criteria real-world problems concerning new activities for firms [37]. At first, the ELECTRE method was proposed to find the best alternatives from a given set of actions. The method was later further developed for ranking and sorting applications [38].

Similar to other outranking methods, the ELECTRE III method is based on 'partial comparability'. That is, the comparison of two alternatives is made with four binary relations: indifference (I), heavy preference (P), light preference (Q) and non-comparability (R). In addition, the method uses the criterion thresholds of preference (p), beneath which an investment alternative outranks another; indifference (q), beneath which none of the investment alternatives outranks the other; and veto (v), above which a previously defined outranking relationship is vetoed. These pseudo-criteria are used to allow the method to handle imprecise, indeterminate and uncertain criteria that is typical for complex human decision processes. Ultimately, the method identifies the most desirable investment decisions from a pre-determined set of investment alternatives that are ranked and sorted based on their attributes in a discrete search space.

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The ELECTRE III method consists of two main phases, namely construction and exploitation of the outranking relations. The construction of the outranking relations is performed by comparing alternatives in pairs to discover which alternative is quantitatively better. Each of these pair wise comparisons produces an outranking relation. The exploitation of the outranking relations is performed by constructing two pre-rankings with opposite procedures in ascending and descending order. The combination of these two pre-rankings gives the final ranking.

3.1 Construction of the outranking relations

At this phase of the ELECTRE III method, a credibility matrix is formulated. The credibility matrix expresses the preference of one set of investment criteria over the other. That is, the likeliness of each investment alternative to outrank another. The credibility matrix is built with the concordance and discordance indices, which are described below.

3.1.1 Concordance index: The concordance index (C) is a function of the value of an investment alternative under different weighted criteria, and the indifference (q) and preference (p) thresholds, as expressed by (1). This index indicates the truthfulness of the assertion 'alternative A outranks alternative B'. If $C = 1$, the assertion is true and, if $C = 0$, the assertion is false [31, 35].

$$C(A, B) = \frac{1}{W}\sum_{i=1}^{n} w_i c_i(A, B) \tag{1}$$

where (see (2))

and

$$W = \sum_{i=1}^{n} w_i$$

where A and B are the two different investment alternatives, w and W are, respectively, the weight assigned to each criterion and the sum of the weights, c is an outranking assessment based on a single criterion, z is the performance of the alternative with respect to the criterion and the subscript i represents the different criteria. Therefore the three possible concordance relations between two investment alternatives A and B are:

1. Indifference ($A\ I$ B): $z_i(B)–z_i(A) \leq q_i$, is an agreement on the statement 'A outranks B'.
2. Weakly preferred ($A\ Q\ B$): $q_i < z_i(B)–z_i(A) < p_i$, is a weak agreement on the statement 'A outranks B'.
3. Strictly preferred ($A\ P\ B$): $z_i(B)–z_i(A) \geq p_i$, is a disagreement on the statement 'A outranks B'.

3.1.2 Discordance index: The optional discordance index (D) is used as a cautious measure to refuse the assertion 'A outranks B', which was previously assessed with the concordance index. This statement is vetoed if the discrepancy of performances between the alternative A and B is higher than the veto threshold (v) on a given criterion (i), as expressed by (3) [31, 35]

$$D_i(A, B) = \begin{cases} 0 & \text{if } z_i(B) - z_i(A) \leq p_i \\ \dfrac{z_i(A) - [z_i(A) + p_i]}{v_i - p_i} & \text{if } p_i \leq z_i(B) - z_i(A) \leq v_i \\ 1 & \text{if } z_i(B) - z_i(A) \geq v_i \end{cases} \tag{3}$$

Therefore the three possible discordance relations between two investment alternatives A and B are

1. Indifference ($A\ I\ B$): $z_i(B)–z_i(A) \leq p_i$, is an agreement on the statement 'A outranks B'.
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3. Strictly preferred ($A\ P\ B$): $z_i(B)–z_i(A) \geq v_i$, is a disagreement on the statement 'A outranks B'.

3.1.3 Credibility matrix: The credibility matrix (S) indicates if the outranking hypothesis is true or false. The matrix is constructed with the concordance and discordance indices as expressed by (4). The degree of credibility of the hypothesis is equal to the concordance index if the concordance index is equal or greater than the discordance index for all criteria. Otherwise, the credibility of the hypothesis is doubtful, and the degree of credibility is reduced to a function of the concordance index and related discordance indices [31, 35] (see (4))

where $J(A, B)$ is the set of criteria for which $D_i(A, B) > C(A, B)$.

3.2 Exploitation of the outranking relations

At this phase of the ELECTRE III method, the credibility matrix is used to rank the investment alternatives. This is done by arranging the alternatives in descending and ascending order based on two distillation procedures, and combining both pre-orders to build the final ranking.

3.2.1 Distillation procedures: The distillation procedures are two processes performed to pre-order the investment alternatives in descending and ascending order. That is, a descending distillation is performed to order the alternatives from the best-rated alternative to worst, and an ascending distillation is performed to order the alternatives from the worst-rated alternative to the best. The result of

$$c_i(A, B) = \begin{cases} 1 & \text{if } z_i(B) - z_i(A) \leq q_i \\ \dfrac{p_i\big(z_i(A)\big) + z_i(A) - z_i(b)}{p_i\big(z_i(A)\big) - q_i\big(z_i(A)\big)} & \text{if } q_i \leq z_i(B) - z_i(A) \leq q_i \\ 0 & \text{if } z_i(B) - z_i(A) \geq p_i \end{cases} \tag{2}$$

$$S(A, B) = \begin{cases} C(A, B) & \text{if } D_i(A, B) \leq C(A, B)\forall i \\ C(A, B) \displaystyle\prod_{i \in J(A,B)} \frac{(1 - D_i(A, B))}{(1 - C(A, B))} & \text{otherwise} \end{cases} \tag{4}$$

the distillation procedures are two rankings that do not necessarily agree.

The distillation processes rely on the credibility matrix (***S***) to sort the investment alternatives. It is assumed that an investment alternative A outranks another alternative B only if the credibility of the statement 'A outranks B' is above a threshold (λ_2) and considerably above the degree of credibility of the opposite statement 'B outranks A'. This is expressed by (5) [31, 35] (see (5))

where λ_0 is the highest credibility value in the credibility matrix, λ_1 is a cut-off level used to accept credibility values near λ_0, λ_2 is the main credibility index just below λ_1, G is the set of investment alternatives, $s(\lambda_0)$ is a discrimination threshold and α and β are, respectively, 0.3 and 0.15 as recommended by Collette and Siarry [38].

The descending distillation identifies several best solutions based on strict rules expressed by (5). Within this sub-set of solutions, the best investment alternatives are identified and extracted from the sub-set by relaxing the cut-off level (λ_1). That is, the value of λ_1 is reduced to make the statement 'A outranks B' easier to accept. The procedure is repeated while gradually relaxing the selection rules and decreasing the size of the sub-sets by extracting the best alternatives. The procedure finishes when only one alternative is leftover or a set of alternatives cannot be disconnected.

The extraction procedure for the descending distillation is performed based on scores assigned to each investment alternative. Whenever A outranks B, the score of alternative A is increased in one unit (strength) and the score of alternative B is decreased by one unit (weakness). The final score of each investment alternative is the sum of the strengths and weaknesses. In the descending distillation, the investment alternative with the highest ranked score is removed from the credibility matrix. This process is repeated until all investment alternatives have been ranked. In cases where two or more alternatives possess identical scores, the process is repeated within the subset until an alternative obtains a higher score and it is ranked, or the highest credibility value (λ_0) becomes zero and the alternatives are declared indifferent.

The ascending distillation procedure uses similar pre-ranking and extraction rules as those used for the descending distillation procedure. The only difference is that, in the ascending distillation, the worst rated investment alternatives are selected first.

3.2.2 Final ranking: The final ranking is formulated with the results of the two pre-orders. The resulting ranking matrix considers the following four possible cases:

1. A ***P*** $+B$: The investment alternative A is better than B. This occurs when A is ranked over B in both distillations, or A is higher than B in one distillation, and has identical ranking in the other distillation.
2. A ***R*** B: The alternative A is incomparable to B. This happens when A is ranked over B in one distillation and B is ranked over A in the other distillation.
3. A ***I*** B: The alternative A is indifferent to B. That is A has the same ranking as B in both distillations.
4. A ***P–*** B: The alternative A is worse than B. This occurs when A is ranked below B in both distillations or A is ranked below B in one distillation and has the same ranking in the other distillation.

The final ranking is achieved by adding the number of ***P+***. In the case when several alternatives possess the same score, the alternatives within the subset are compared with identify which ones are preferred, indifferent or incomparable to other alternatives within the subset. The ranking of the other alternatives is not affected by the presence of any subset of alternatives.

4 Design and implementation of the decision support tool

The following section will define the development of the outranking technique, as a decision support tool, for the assessment of PV systems alternatives. The definition of different evaluation criteria is described and their perspectives for different decision makers are implemented using a weighting technique. The defined criteria for the PV systems alternatives are calculated upfront.

4.1 Evaluation criteria

The investment decisions in PV micro-generation projects are compared with different economic, technical and environmental criteria to obtain a reasonable overall assessment. The most relevant parameters for PV systems within these criteria were chosen as shown in Table 1.

The criteria can be classified as quantitative and qualitative. The quantitative criteria, namely PV contribution ($C1$), defined as the solar fraction (SF) net kg-eq CO_2 (Net_{CO_2}) ($C3$) and net present value (NPV) ($C5$), are calculated with an optimised time series simulation that considers distinct PV technology parameters such as PV module efficiency, PV module efficiency degradation limit, system PR and CO_2 content during manufacturing.

Table 1 Different chosen criteria for evaluation and their meaning

technical	$C1$	PV (contribution Solar fraction)	PV to local load contribution (ratio)
	$C2$	module design	indication of flexibility
environmental	$C3$	net kg-eq CO_2	net CO_2-eq (surplus/deficit)
	$C4$	aesthetic	indication of the level of aestheticity possible
economic	$C5$	net present value	net present value of the PV system
	$C6$	maturity	indication of the maturity of the module technology

$$\left.\begin{array}{c} A \text{ outranks } B \quad \text{if } S(A,B) > \lambda_2 \quad \text{and} \quad S(A,B) - S(B,A) > s(\lambda_0) \\ \lambda_2 = \max\limits_{S(A,B)\le\lambda} S(A,B) \qquad \forall\{A,B\} \in G \\ \lambda_1 = \lambda_0 - s(\lambda_0) \\ \lambda_1 = \max\limits_{A,B\in G} S(A,B) \\ s(\lambda_0) = \propto + \beta\,\lambda_0 \end{array}\right\} \tag{5}$$

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The PV contribution ($C1$), defined as the solar fraction (SF), is the fraction of load met directly by a PV system given in (6)

$$\mathrm{SF} = 1 - \sum_{t=1}^{8760} \frac{E_{\mathrm{in}}(t)}{E_{\mathrm{LOAD}}(t)} \tag{6}$$

where E_{in} is the grid imported energy and E_{LOAD} is the household electrical energy demand, both on hourly basis.

The equation second part of (6) is also known as the 'loss of load probability', 'deficit of energy' or 'loss of power probability'. The SF is also known as 'autonomy' or 'load coverage rate'. These terms are usually used for stand-alone systems. However, this term also quantifies reliability in grid-connected PV systems with respect to a thorough techno-economic analysis. A negative factor implies imported energy is stored for later use, whereas a positive factor implies the fraction that the PV system contributes directly to the local load.

As expressed by (7), the net kg-eq CO_2 ($C3$) is composed of two terms. The first term is the initial CO_2-equivalent emissions for system components, such as balance of system (BOS), energy storage and PV modules. The second term is all the yearly CO_2-equivalent emission flows (EF) throughout the system lifetime, which includes any CO_2-equivalent emissions for system component replacements, the CO_2-equivalent emissions mitigated from energy produced or saved that is generated, and grid CO_2-equivalent of the consumed energy. A negative value implies a positive contribution in CO_2 mitigation, whereas a positive value implies a net CO_2-equivalent from the holistic electrical energy system within the household that is non-zero CO_2 housing.

$$\mathrm{Net}_{CO_2} = I_0 - \sum_{y=1}^{T} \mathrm{EF}_y \tag{7}$$

The NPV ($C5$) is also composed of two terms, as expressed in (8). The first term is the initial investment referring to BOS component and PV modules costs. The second term comprises all discounted cash flows (CF) throughout the system lifetime, which includes an increase of investment because of any replacements, benefits from not importing electricity and any revenue from selling electricity into the grid. A positive value implies a surplus within the complete electrical energy system lifetime of a household

$$\mathrm{NPV} = -I_0 - \sum_{y=1}^{T} \frac{\mathrm{CF}_y}{(1+r)^y} \tag{8}$$

The qualitative criteria comprise the module design ($C2$), aesthetics ($C4$) and maturity ($C6$). The performance of an investment alternative under each qualitative criterion is modelled with a number from one to three; the higher the number, the better the alternative. These values reflect the technology status for three PV technologies, namely crystalline modules, TF and emerging technology. The module design represents the flexibility of the PV module within the design of a building integrated PV (BIPV) system and ease of its installation. The aesthetics criterion reflects the possible visual impact of the modules. In BIPV systems, the frameless modules have lower visual impacts than bolt-on solutions. The maturity of the PV technology indicates the need for more research and development investments to improve the technology. Hence, mature technologies tend to be preferred, as their characteristics and installation procedures are better known.

It is important to note that the six criteria chosen for this study tend to be specific for a given PV project in a particular location. As such, the criteria have implicit geographical and social implications. Therefore unless the criteria can be modelled in a completely generic manner, the study will implicitly include social and geographical criteria.

4.2 Weights and threshold values

The importance of any given criterion is not the same for all stakeholders. The importance that a stakeholder gives to different criteria can be modelled with weights allocated to each criterion. In this study, three different sets of weights were used to represent the political, customer and contractor perspectives.

The criteria thresholds and weights considered in this study are listed in Table 2. The quantitative thresholds were selected based on recommendations found in existing literature [15, 39], whereas the qualitative thresholds were set as 1 for the indifference threshold and 1.5 for preference threshold based on the modelled qualitative criterion numbered from one to three; the higher the number, the better the alternative.

The weight of each criterion is expected to vary for different stakeholders. These weights were calculated using the Simos method with updates [21, 40–42]. An example of the application of the Simos method to estimate the weights for the political perspective is shown in Table 3.

The different sets of weights represent the political perspective, and the viewpoints of the consumers and contractors. The political perspective is the baseline scenario in which there is a balance between all categories. That is, all weights are equal. The perspectives of the consumers and contractors were taken from an outranking study for battery technologies for electric vehicles [43]. Accordingly, the viewpoint of customers and contractors is more focused on technical and economic criteria.

The customer perspective gives more importance to economic benefits. Therefore the NPV has the highest weight. Customers usually do not take into account the PV contribution, whether there is a net export or import. Hence, this parameter is of less importance than in the political perspective. The flexibility of a technology may have a high importance to consumers, as it can make a difference in adaptation. The maturity of the technology also has a high weight, as customers value the reliability of the PV technology.

Table 2 Weights and threshold values

Criteria	*C1*	*C2*	*C3*	*C4*	*C5*	*C6*
indifference (*q*)	15%	1	15%	1	15%	1
preference (*p*)	30%	1.5	30%	1.5	30%	1.5
veto (*v*)	90%	n/a	90%	n/a	90%	n/a
political importance (weight)	0.259	0.074	0.259	0.074	0.259	0.074
customer importance (weight)	0.238	0.095	0.19	0.048	0.29	0.143
contractor importance (weight)	0.271	0.104	0.208	0.042	0.271	0.104

Table 3 Calculating criteria weight using the Simos method

Ranking r^a	Criteria	No. of criteria in rank	Weight, W	Average weight	Relative weight	Total
1	*C2 C4 C6*	3	1, 2, 3	(1 + 2 + 3)/3 = 2	7.41	22.22
2	–	–	(4)	–	–	–
3	–	–	(5)	–	–	–
4	*C1 C3 C5*	3	6, 7, 8	(6 + 7 + 8)/3 = 7	25.93	77.78
5	–	–	(9)	–	–	–
6	–	–	(10)	–	–	–
		6	27^b			100

[a]From worst to best
[b]Sum of weight excluding parenthesis

The manufacturer perspective gives the highest importance to both technical and economic criteria. Consequently, the weights for these criteria are higher than the political perspective.

4.3 Performance of alternative scenarios

The case study is based on a grid-connected PV system installed on a typical four Bed household with gas and electricity services located in Manchester, UK. It is assumed that there are no financial support schemes available, the operational lifetime of the systems is 30 years, the PV panels are installed with an optimal tilt in an available area of 25 m^2, and the project can be designed with the different PV technologies presented in Table 4.

As shown in the table, each alternative involves an investment in a mature or emerging PV technology, which is represented by the underlying assumed or estimated parameters. The system level technical parameters that are assumed comprise the PR which is a measure of the quality of a PV system, module efficiency (η_{PV}), module efficiency degradation limit (δ_{PV}) and module lifetime (L_{PV}).

The performance of crystalline PV modules that is mono-Si and multi-Si, in A1 and A2, is usually guaranteed to be at least 80% of their original efficiency after 25 years of operation. In addition, some manufacturers may guaranty the efficiency degradation on the fifth and tenth years of operation. These guarantees are one of the advantages of mature inorganic PV technologies, particularly a-Si technologies.

Emerging PV technologies, such as OPV, are novel technological concepts and hence do not have a proven track record. Current emerging organic-based PV technologies suffer from disintegration over time and have only exhibited low lifetimes. Stability remains their main challenge, as materials are susceptible to degradation in the presence of oxygen and water [44–46]. Hence lifetime of OPV is most often defined as the time until their efficiency reaches 50% of its original or maximum value [47]. It can be argued that this low efficiency may bring system performance down, however, OPV technologies may be replaced every 3–5 years for successful applications [48]. This is economically feasible because of the low cost of OPV, even considering their short operational lifetime. Moreover, OPV systems can be an economically attractive option in domestic applications [49]. In this case, replacement of PV modules about their lifetime is necessary since a higher system lifetime is exhibited.

The PR represents system losses caused by shadowing effects, inverter inefficiencies, soiling effect, among others. The PR is the main index for characterising the system performance under specific conditions. It is directly proportional to the system yield, which is a fundamental parameter for PV generation, as it is pivotal for cash flow calculations, and related energy output indices. Hence, it is ideal to use annual yield figures differentiated according to module technologies installed within any PV analysis. However, these figures are based on field monitored performance data, and because of the time required for data gathering and lack of PV alternatives in the old days, there are only few studies. In fact, the only UK based study, providing directly comparable data on PV module technologies performance under UK and Mediterranean climate conditions, is the PV-Compare project [50].

Table 4 Possible PV technology alternatives for PV micro-generation

Alternative	Technology	Assumed and Estimated Parameters						
		Technical				Environmental		Economic
		PR	η_{PV}	δ_{PV}	L_{PV}	MJ/m^3	kg-eq CO_2	£/m^2
A1	mono-Si	0.85	22%	80%	30	6034	241	660
A2	multi-Si	0.82	17%	80%	30	3870	155	510
A3	a-Si	0.94	9%	80%	30	1110	44	248
A4	CIGS	1	11%	80%	30	2965	118	366
A5	CdTe	0.66*	11%	80%	30	1828	73	366
A6	emerging PV (a)	1	5%	50%	5	—	30	50
A7	emerging PV (b)	1	(b)	50%	(b)	—	30	(b)
A8	emerging PV (c)	1	(c)	50%	(c)	—	30	(c)
A9	emerging PV (d)	1	(d)	50%	(d)	—	30	(d)

*This was one of the first PR calculated on demonstration modules. PR for CdTe may have improved significantly
(a) Refer to emerging organic PV (OPV) with no technology development during the whole system lifetime
(b)–(d) refer to OPV reference, optimistic and pessimistic technology anticipated developments respectively in efficiency (η_{PV}), lifetime (L_{PV}) and price in £/m^2

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Table 5 PV performance results in PV-Compare project

Technology	Product	Mediterranean (Mallorca - Spain) Annual radiation 1700 kwh/m^2		United Kingdom (Begbroke - Oxford) Annual radiation 1022 kWh/m^2	
		kWh/kWp	PR	kWh/kWp	PR
Amorphous (3-j)	Unisolar US64	1380.4	0.81	858.6	0.84
Amorphous (2-j)	ASE 30 DG-UT	1655.3	0.97	991.8	0.97
Amorphous (2-j)	Solarex Millennia	1515.5	0.89	926.6	0.91
Amorphous (1 -j)	Intersolar Phoenix	887.4	0.52	557.3	0.55
Monocrystalline	BP 850	1389.2	0.82	871.8	0.85
Multicrystalline	Evergreen	1283.3	0.75	824.8	0.81
Multicrystalline	Astropower	1352.9	0.80	821.8	0.80
Multicrystalline	Solarex MS X	1368.0	0.80	842.0	0.82
Multicrystalline	ASE 300DGUT	1340.4	0.79	875.1	0.86
CIS	Siemens ST40	1553.3	0.91	1025.3	1.00
CdTe	BP Apolio	958.5	0.56	673.7	0.66
Assumed PR					
Amorphous			0.80		0.82
Monocrystalline			0.82		0.85
Multicrystalline			0.79		0.82
CIS			0.91		1.00
CdTe			0.56		0.66

3-j, 2-j, 1-j refers to triple, double and single junction, respectively

The PV-Compare project evaluates eleven systems comprising different commercial PV systems that were tested under two climate conditions. This project offers an informative tool for retailers, systems designers, architects, energy advisors and product developers. The expected annual energy yield for each technology was determined. Although the results from the project may differ from current performances because of technology progress, the outdoor performance of PV systems under different technology and climatic conditions is yet to be understood.

For the purposes of this paper, the PV-Compare project results were aggregated to discriminate different PV technologies as shown in Table 5. So far, comparable performance studies on PV systems using emerging PV technologies have not been developed, since these technologies are mainly lab-based. However, companies may state that their organic PV panel may absorb from a wider angle, instigating that such technology performs better than commercial available PV. For this reason, the PR of emerging PV technology, OPV Alternatives 6–9, are taken as the highest recorded value that is similar to the results of CIS technologies in the PV-Compare analysis.

A6, in Table 4, refers to OPV technology with no future technology development and therefore with constant system level technical assumed parameters. A7, A8 and A9 refer to reference (b), optimistic (c) and pessimistic (d) technology developments in organic-based PV technologies with respect to efficiency, lifetime and price. The debate of whether or not emerging OPV technology require same lifetime and efficiency as current mature PV technologies is ongoing [1, 2, 51–54]. The following scenarios were derived from targets in the literature. The developments are depicted within 40 years timescale, thin film historical development and lab-commercial ratio of 60% with respect to efficiency records, and a starting price of £50/m^2 with an 80% progress ratio:

1. Reference (b) – A7 – from 2 years (currently) to 25 years lifetime, from a module efficiency of about 2–5% by 2012 to 10% by 2020 and to about 17% in 30 years, with a modest progress ratio of 90% and considering a shakeout in about 5 years' time to a continuous 80% progress rate.
2. Optimistic (c), – A8 – from 5 years (achievable) to 30 years lifetime, from a module efficiency of about 5–60% of theoretical efficiency record in 40 years (that is around 30%), considering the typical PV progress ratio of 80%; and
3. Pessimistic (d) – A9 – from 1 to 15 years lifetime, from a module efficiency of 1% to about 10% within 30 years, and considering a confidence gain for the next 5 years or so at 110% progress ratio.

The performance of the different investment alternatives under the different criteria considered in this work is shown in Table 6. It is evident that no investment alternative stands out completely from the rest in all criteria, implying need for a MCA.

5 Evaluation of the case study

The ELECTRE III model was applied to the case study. The final ranking of all the different investment alternatives under the three perspectives considered is shown in Fig. 1. Tables 7

Table 6 Performance of alternative scenarios

	$C1^+$	$C2^+$	$C3^-$	$C4^+$	$C5^+$	$C6^+$
A1	0.34	1	(19 439)	1	(14 242)	3
A2	0.32	1	4531	1	(9957)	3
A3	0.29	2	26 186	2	(3763)	2
A4	0.31	2	16 713	2	(6527)	2
A5	0.28	2	32 260	2	(6856)	2
A6	0.22	3	48 725	3	(2123)	1
A7	0.26	3	32 570	3	(967)	1
A8	0.28	3	28 076	3	248	1
A9	0.2	3	49 281	3	(3503)	1

$^+$High values are best alternatives
$^-$Low values are best alternatives

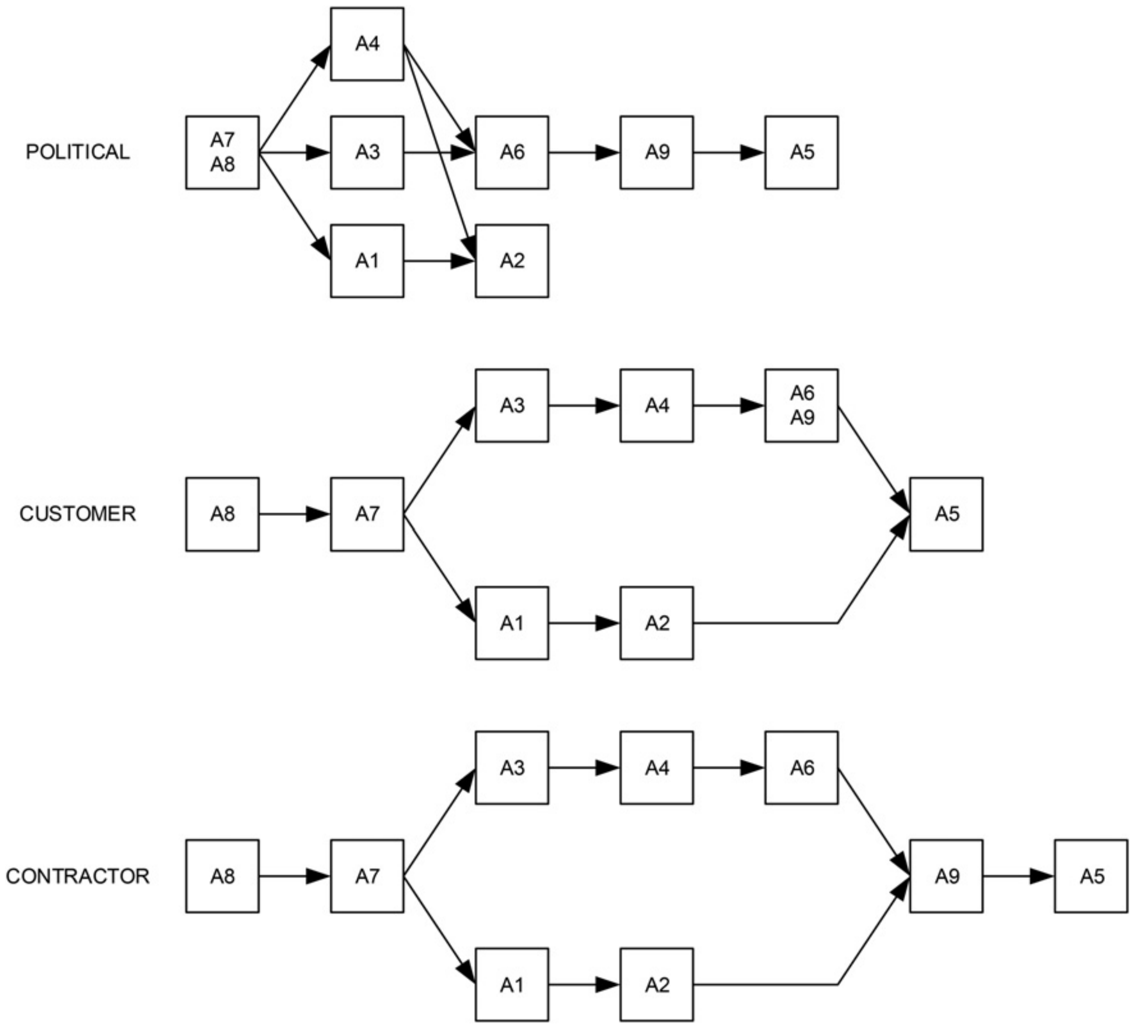

Fig. 1 *Final ranking under three perspectives*

Table 7 Credibility matrix for the political perspective

	A1	A2	A3	A4	A5	A6	A7	A8	A9
A1	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
A2	0.00	1.00	0.00	0.47	0.74	0.00	0.00	0.00	0.00
A3	0.00	0.74	1.00	0.90	1.00	0.99	0.80	0.74	1.00
A4	0.00	0.74	0.74	1.00	1.00	0.74	0.74	0.10	0.74
A5	0.00	0.74	0.74	0.74	1.00	0.74	0.49	0.00	0.74
A6	0.00	0.29	0.48	0.48	0.63	1.00	0.79	0.45	1.00
A7	0.00	0.53	1.00	0.67	1.00	1.00	1.00	1.00	1.00
A8	0.00	0.67	1.00	0.85	1.00	1.00	1.00	1.00	1.00
A9	0.00	0.24	0.48	0.48	0.57	1.00	0.43	0.22	1.00

and 8 present the credibility matrix and the corresponding ranking matrix that represents the political perspective.

The credibility matrix (S), Table 7, indicates if the outranking hypothesis is true or false. The S formula in (4) is the concordance value $C(A, B)$ in (1), if the concordance $C(A, B)$ exceeds the discordance $D(A, B)$ in (3), else the statement $A\ \boldsymbol{S}\ B$ is doubtful and $C(A, B)$ is altered as in (4). Therefore when there is no credibility in the statement $A\ S\ B$ $S(A, B)$ is 0.00.

The ranking matrix, Table 8, is obtained by the combination of the two pre-orders. The four possible cases are $\boldsymbol{P+}$, $\boldsymbol{R}$, $\boldsymbol{I}$ and $\boldsymbol{P-}$ which represent an alternative A is better, incomparable, indifferent or worse to alternative B, respectively. The final ranking is achieved by adding the number of $\boldsymbol{P+}$. In case of a tie such as A7 and A8, the decision between indifferent or incomparable is taken, in this case indifferent.

The top-ranked alternatives are A7 and A8. These alternatives represent emerging OPV technology, with modest and optimistic technology developments over the system lifetime. OPV technology have already, to some extent, been deployed by some pioneering companies as well as exhibited promising cell efficiencies such as Konarka [55], Heliatek [56] and Solarmer [57]. The modest and optimistic technology developments over the system lifetime are based on existing targets as described in Section 4.3. These alternatives gained their high rank mainly because of their quantitative economic benefits. That is, they offer a high NPV because of their low capital

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Table 8 Ranking matrix for the political perspective

	A1	A2	A3	A4	A5	A6	A7	A8	A9
A1	I	P+	R	R	P+	R	P–	P–	P+
A2	P–	I	R	P–	P+	R	P–	P–	P+
A3	R	R	I	R	P+	P	P–	P–	P+
A4	R	P+	R	I	P+	P	P–	P–	P+
A5	P–	P–	P–	P–	I	P–	P–	P–	P–
A6	R	R	P–	P–	P+	I	P–	P–	P+
A7	P+	P+	P+	P+	P+	P+	I	I	P+
A8	P+	P+	P+	P+	P+	P+	I	I	P+
A9	P–	P–	P–	P–	P+	P–	P–	P–	I

investment costs. It should be mentioned that these technologies are not a mature technology as clearly indicated by the economic maturity criteria *C*6, however, it is expected that during frequent replacements of OPV modules new developments in technology will result in rapid technology advancements. Similarly, other emerging polymeric PV technology are also in experimental stages by, for example, Heliatek [56] and Solarmer [57] and therefore it is still unclear which emerging technology will ultimately make a successful development process in accordance to the assumptions and estimates taken.

The next alternatives in the ranking are crystalline silicon (A1 and A2) and thin film technologies [CIGS (A4) and a-Si (A3)] which are incomparable as seen in Fig. 1.

The alternatives that follow in the ranking are emerging technologies with fixed replacements and no technology developments and pessimistic developments (A6 and A9, respectively).

The worst technology according to the ranking is A5 (CdTe), which scored last mainly because of its low PR. Over the last years, PR for this technology has significantly improved. In fact, if a more plausible PR of 0.80 is assumed for all technologies, A5 (CdTe) technologies will rate as high as A4 (CIGS) technologies, as shown in Fig. 2.

It is important to note that the study presented in this work is sensitive to the weights and the criteria thresholds. The sensitivity of the study to weight variations is addressed by considering different perspectives, as discussed above. In order to assess the sensitivity of the study to variations of the criteria thresholds, the preference, indifference and veto thresholds are varied by ±10% and ±20%. The results demonstrate that the top ranks are robust to variations of these values. The results of this study can be seen in Table 9.

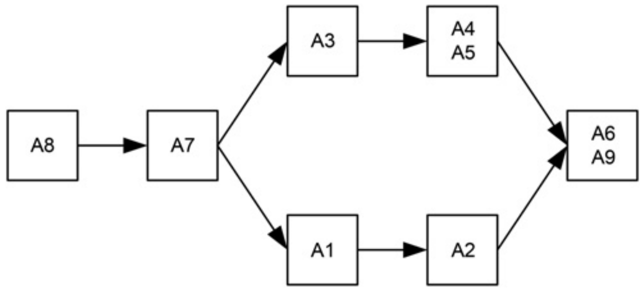

Fig. 2 *Final ranking under all three perspectives with 0.80 PR*

6 Conclusions

The comparison of different technologies is always a difficult task, as it involves a wide range of parameters. With PV technologies increasing in number over three generations, comparative assessment of these technologies is not an exception. This paper highlighted an overall decision-making framework that provides a comprehensive mathematical evaluation that would help PV owners, policy makers and the business community decide on PV technologies, financial support schemes and business strategies.

The primary decision making criteria in PV system investment is economic such as the NPV, return on investment and/or pay-back time. These criteria are focused on the efficiency and cost of the system, which is reasonable in the context of generous financial support schemes. However, when financial support for PV is phased out, the PV market becomes technologically diversified, and environmental concerns and other qualitative issues become significant, whereas efficiency and costs may fail to describe a PV system properly.

This work has focused on PV technologies for application in a domestic environment, with particular focus on future

Table 9 Sensitivity analysis

Sensitivity	Final ranking	Sensitivity	Final ranking
Political: A8 A7 - A1 A3 A4 - A2 A6 - A9 - A5			
−10% (*q*)	stable	−20% (*q*)	stable
+10% (*q*)	A8 - A7 - A1 A3 - A2 A4 - A6 - A9 - A5	+20% (*q*)	A8 - A7 - A1 A3 - A2 A4 - A6 - A9 - A5
−10% (*p*)	A8 A7 - A1 A3 A4 - A2 A6 A5 - A9	−20% (*p*)	A8 A7 - A1 A3 A4 - A2 A6 A5 - A9
+10% (*p*)	A8 - A7 - A1 A3 - A2 A4 - A6 A9 - A5	+20% (*p*)	A8 - A3 A7 - A4 A1 - A6 A2 - A9 - A5
−10% (*v*)	A7 A8 - A1 A3 A4 - A2 A5 - A6 A9	−20% (*v*)	A7 A8 - A1 A3 A4 - A2 A5 - A6 A9
+10% (*v*)	A7 A8 - A1 A3 A4 - A2 A6 A9 - A5	+20% (*v*)	A7 A8 - A3 A4 - A2 - A5 A1 - A6 A9
Customer: A8 - A7 - A1 A3 - A2 A4 - A6 A9 - A5			
−10% (*q*)	stable	−20% (*q*)	A8 A7 - A1 A3 - A2 A4 - A6 A9 - A5
+10% (*q*)	A8 - A7 - A1 A3 - A2 A4 - A6 - A9 - A5	+20% (*q*)	A8 - A7 - A1 A3 - A2 A4 - A6 - A9 - A5
−10% (*p*)	A8 - A7 - A1 A3 - A2 A4 - A6 - A9 - A5	−20% (*p*)	A7 A8 - A1 A3 A4 - A2 A6 - A9 - A5
+10% (*p*)	A8 - A7 - A1 A3 - A2 A4 - A6 - A9 - A5	+20% (*p*)	A8 - A7 - A1 A3 - A2 A4 - A6 - A9 - A5
−10% (*v*)	A8 - A7 - A1 A3 - A2 A4 - A6 A9 A5	−20% (*v*)	A8 - A7 - A1 A3 - A2 A4 - A6 - A9 A5
+10% (*v*)	stable	+20% (*v*)	A8 A7 - A3 A4 - A2 - A1 - A6 A9 - A5
Contractor: A8 - A7 - A1 A3 - A2 A4 - A6 - A9 - A5			
−10% (*q*)	stable	−20% (*q*)	A8 A7 - A1 A3 - A2 A4 - A6 - A9 - A5
+10% (*q*)	stable	+20% (*q*)	stable
−10% (*p*)	A8 A7 - A1 A3 - A2 A4 - A6 - A9 - A5	−20% (*p*)	A8 A7 - A1 A3 A4 - A2 A6 A5 - A9
+10% (*p*)	stable	+20% (*p*)	stable
−10% (*v*)	A8 - A7 - A1 A3 - A2 A4 - A5 A6 A9	−20% (*v*)	A8 - A7 - A1 A3 - A2 A4 - A5 A6 A9
+10% (*v*)	A8 - A7 - A1 A3 - A2 A4 - A6 A9 - A5	+20% (*v*)	A8 A7 - A3 A4 - A2 - A1 A5 - A6 A9

technology developments of emerging PV technologies. In this work, general assumptions were made on these technologies requiring certain common requirements to be met before market integration. It is important to stress that the results and calculations presented in this paper are based on the specific assumptions, and hence the results and discussions must be seen in this context. Nevertheless, the framework developed in this work is robust and it could be easily extended to consider other assumptions.

The economic net-benefit for today's commercial PV technologies is still undermined by the expensive PV module costs. This paper included a number of scenarios having lower costs and more frequent replacements suggested in emerging polymeric PV technologies. The MCA evaluated nine alternative scenarios including future developments forecasts as well as assumptions for emerging PV technologies within a domestic environment, by using the ELECTRE III method for three categories: technical, environmental and economic.

A reduction in cost and the technology developments are required for preferential ranking. In order to achieve this, market growth is necessary, unless there is a sudden and significant change in PV technologies. Hence, financial support is also a key stimulus for emerging PV technologies in a domestic environment.

Currenlty, TF and crystalline (c-Si) PV technologies have a competitive edge in the market, and this study shows certain insuperabilities. In this context, crystalline technologies are more expensive, but also more environmentally friendly than emerging technologies because of their high efficiency levels.

From a technical viewpoint, all technologies can have a PV contribution to load in the region of 20–34% with respect to the system PR, PV module efficiency and PV module efficiency degradation. However, because of uncertainty in future PV support schemes, the issue of PV contribution against exports is a matter for further discussions.

The environmental impact of PV modules is far less than that of other conventional sources of energy. In addition, even though c-Si modules have the highest energy impact among the technologies considered, there is a favourable net benefit of CO_2 emission. The reason is mainly because of high module efficiencies. In fact, the PV generation is higher than the local demand. Hence, in this context c-Si resulted in a significant environmental 'positive' rating, which had an overall gain in ranking amongst other technologies.

On the other hand, the overall net economic benefit for c-Si technology is the lowest since there is not much benefit from exports. Meanwhile for emerging technologies the number of replacements within the system, lifetime will lower the initial investments costs, which is not common so far in the PV industry for a PV module. In fact, OPV are found to lead the ranking from another five inorganic technologies under a free market with no financial support schemes and considering future promising technology developments.

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