Peer-reviewed version available at *Sustainability* **2018**, *10*, 4594; doi:10.3390/su10124594

Article

Determination of the optimal size of photovoltaic systems by using Multi-Criteria Decision Making Methods

Guido C. Guerrero-Liquet [1,*,†], Santiago Oviedo-Casado [2,*,†], J.M. Sánchez-Lozano [3], M. Socorro García-Cascales [1], Javier Prior [2,4] and Antonio Urbina [1]

[1] Department of Electronics, Computers Technology and Projects, Technical University of Cartagena, c/Dr. Fleming, s/n 30202, Cartagena, Murcia, Spain; guidoc.guerrero@edu.upct.es; socorro.garcia@upct.es; antonio.urbina@upct.es

[2] Departamento de Física Aplicada, Universidad Politécnica de Cartagena, 30202 Cartagena, Spain; santiago.oviedo@upct.es; javier.prior@upct.es

[3] Centro Universitario de la Defensa de San Javier. Academia General del Aire. Universidad Politécnica de Cartagena (UPCT), Murcia, Spain; juanmi.sanchez@cud.upct.es

[4] Institute Carlos I for Theoretical and Computational Physics, Universidad de Granada, Granada 18071, Spain; javier.prior@upct.es

* Correspondence: guidoc.guerrero@edu.upct.es & santiago.oviedo@upct.es Tel.: +34-968-326-514

Abstract: The diverse socio-economic and environmental impacts that the set-up of a new photovoltaic installation has must be weighed carefully in order to reach the best possible solution. Among the different photovoltaic systems there are several classification criteria, depending on the technology, application and the size of the modules that define them. The size (installed nominal capacity) stands out as an impartial and critical measure in the decision making process. In this article we use a multi-criteria decision making method to analyse the responses of five experts to a detailed questionnaire in which several different criteria are correlated with various photovoltaic installation sizes. The limitation associated to the low number of experts is addressed with a robustness and sensitivity analysis. With this study we seek first, to apply and demonstrate the feasibility of a methodology which combines technical information with multi-criteria decision making methods, and second, to obtain a clear result oriented that increases the benefits of a forthcoming photovoltaic installation of modules in distributed generation adding up to 1GW total peak power in standard conditions. We observe a consistent result in which smaller photovoltaic modules are the ideal solution that maximises the socio-economic benefits of any installation. If a decision has to be taken about the type of photovoltaic plant to be installed, the conclusion is clear: given a certain size, small, easily scalable installations are the best solution for stake-holders, for the inhabitants, and for the environment.

Keywords: Solar electricity; Photovoltaic Systems; Distributed Generation (DG); Multi-Criteria Decision Making (MCDM); Analytic Network Process (ANP); Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS).

List of acronyms: ANP: Analytic Network Process, CIGRÉ: The International Council of Large Electrical Systems, DEMATEL: Decision making trial and evaluation laboratory, DG: Distributed Generation, ELECTRE: Elimination and Choice Expressing Reality, GW: gigawatt, kWp: kilowatts peak, LCOE: Levelled cost of electricity, MCDM: Multi-Criteria Decision Making, MWp: megawatts peak, PV: Photovoltaic solar energy, PROMETHEE: Preference ranking organization method for enrichment evaluation, TOPSIS: Technique for Order of Preference by Similarity to Ideal Solution, VIKOR: Multi-criteria Optimization and Compromise Solution, w_c: weight of the sub-criteria.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 12 November 2018 doi:10.20944/preprints201811.0267.v1

Peer-reviewed version available at Sustainability 2018, 10, 4594; doi:10.3390/su10124594

1. Introduction

The For many years industrialized countries have increasingly generated electricity in large centralized facilities. The electricity thus generated comes mainly from fossil fuels, nuclear energy, hydroelectric plants and large solar or wind power plants [1]. However, both climate change awareness and the increasing scarcity and raising prices of fossil energy sources are inducing a shift in the way energy is produced globally. Renewable energy sources are experiencing an important increase in the installed power per year.

The International Council of Large Electrical Systems (CIGRÉ) defines as Distributed Generation (DG) those generation units with a maximum capacity ranging from a few kW to a hundred MW, which are usually connected to the distribution network and which are not centrally designed [2]. Also, DG can be defined as the generation of energy by small-scale units that are installed in the distribution systems where the energy is consumed by the end users [3]. The main objective of the distribution network is to provide a reliable and efficient service for consumers while ensuring that voltage levels and quality of supply are within normal parameters [4]. Traditionally, this objective is achieved through the reinforcement of existing lines and substations or through the installation of new DG systems [5, 6]. If the DG includes renewable sources it will contribute to a cleaner electricity mix [7].

Photovoltaic solar energy (PV) connected to the grid can be expanded as a modular DG. This would save initial investments in smaller systems that can be later upgraded to larger ones, and make their installation by the end-user quite practical [8]. In addition, the modular nature of photovoltaic technologies allows cost per unit of installed power capacity and power conversion efficiency almost independent of the size of the installation. Therefore, photovoltaic distributed energy is of great interest for decentralised energy production. The distributed photovoltaic systems have a significant impact on price [9, 10]. If the total cost of the system is considered the distributed rooftop solar PV system is in principle more expensive than large-scale solar PV plants, but has followed a similar price reduction trajectory --especially in the cost of the photovoltaic modules-- and is nowadays competitive with (or cheaper than) retail electricity prices in many locations (considered as levelled cost of electricity, LCOE) [11]. Contrary to most conventional energy sources, photovoltaic technology has a wide range of applications in a wide range of sizes. For this reason, the size parameters of the DG have to be carefully determined to improve the performance and overall efficiency of the PV. Therefore, the proper size of a distributed power installation is crucial factor for reliability and to meet consumer demand.

Most of the studies aiming to determine the optimal size of photovoltaic installations have focused on small-scale facilities, namely those ranging from solar roofs in the consumer or end user [12]. However, some recent studies emphasize that large solar power plants or large-scale installations are the most recommended, as they guarantee supply needs are covered and they reduce greenhouse gas emissions considerably [13]. In our study, the modules composing the optimum installation are required to add up to 1 GW. We aim to correlate several different economic, technical, and environmental criteria to obtain the ideal module size of a photovoltaic DG installation for each possible application.

It is clear that adequately classifying the size is a crucial aspect when determining the optimal modules of a distributed generation photovoltaic installation [14]. In this article, we have divided these facilities into an small and medium-sized plants category (composed of less than 1 MW of power units, and between 1 and 5 MW respectively), corresponding to those usually installed in homes and buildings [15][1].

With regard to the classification of DG units by order of installed power, scientific research currently uses many definitions including [1]: a few kilowatts up to 50 MW (Electric Power Research Institute), between 5 and 25 MW (Gas Research Institute), or less than 50-100 MW

1 A second category, including larger sizes (> 5MW) but still adding up to 1 GW is presented in the Appendix A. Both the methodology and the results obtained for this large category are the same as for the main, small and medium sized category.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 12 November 2018 doi:10.20944/preprints201811.0267.v1

Peer-reviewed version available at Sustainability 2018, 10, 4594; doi:10.3390/su10124594

(CIGRÉ). The categorisation by installed power is typically divided between: Individual Systems or Power Plants [16]: individual systems are those with a power unit size (or generation capacity) of the order of kW and power plants are photovoltaic installations that have a power unit around MW and large-scale photovoltaic systems or small-scale photovoltaic systems [17]: Large-scale photovoltaic systems are considered to be solar plants greater than 500 kW and small-scale photovoltaic systems are considered to be solar installations greater than 3 kW and less than 500 kW. Here, we will employ the classification proposed by [18] in 2012 and which is summarised in Table1.

Size	Categories	Power
Small and medium distributed generation	Micro-distributed generation	~ 1 W <5 kW
	Small distributed generation	5 kW <5 MW
Large distributed generation	Medium distributed generation	5 MW <50 MW
	Large distributed generation	50 MW <300 MW

Table 1. Different ratings of distributed generation (Source: Viral and Khatod, 2012). The small and medium constitutes the main focus of this article while the results for the large category are presented in Supplementary Information (S.I.) A.

To analyse the relative influence of in principle unrelated, independent, or incomparable criteria, powerful optimization techniques and expert advisory panels are needed [19, 20]. Here we employ a committee composed of five experts with heterogeneous background[2], who select a total of 14 criteria, which are then analysed employing Multi-criteria Decision Making Methods (MCDM) [21, 23], in search for the best size alternative fulfilling the decision criteria. To overcome the limitation of the low number of experts caused mainly by the length of the questionnaires, we perform a sensitivity analysis implemented in Matlab/Octave software, to assert the robustness of the method and the optimal scale chosen between the different alternatives. Thus in this article a MCDM supported by robustness analysis is for the first time used to the problem of size in photovoltaic installations, revealing that, contrary to the common paradigm, installations composed by smaller, easily scalable modules maximise the socio-economic and environmental benefits of photovoltaic energy.

This article is organized as follows: in Section 2, the methodology (i.e. the specific MCDM) employed to analyse the experts' responses and correlations among the criteria is described in detail. Section 3 is dedicated to present the results obtained from applying the MCDM to optimize the size of photovoltaic solar installations and the result of the sensitivity analysis. Finally Section 5 presents the conclusions.

2. Materials and Methods

A MCDM is a methodology for making complex problem decisions in a systematic and structured way [24], with the objective to provide an effective framework for the classification and selection of one or more options from a set of alternatives [25]. Practical problems are often characterized by several contradictory criteria, and there may be no solution that meets all the criteria simultaneously. The solution has to be a compromise, according to the preferences of the decision maker [26].

The best-known methods based on multi-criteria decision include the following: AHP, ANP, ELECTRE, PROMETHEE, TOPSIS, VIKOR and DEMATEL [27]. MCDM has been substantially applied in the energy fields, such as site selection, or project and equipment evaluation [28, 32]. In order to achieve our objective, we combine two widely-used multi-criteria decision methods: The

2

The panel is composed by academics working in renewable energy technology (from Technical University of Cartagena), two experts with experience in photovoltaic system installations working in private companies, and finally and end user of a small PV system.

ANP (Analytical Network Process) developed by Saaty [33] and the TOPSIS (Technique for Preference by Similarity to Ideal Solution) developed by Hwang and Yoon [22]. The evaluation procedure of this study consists of the following phases, shown here in Figure 1.

The first step is to identify the multiple criteria that are considered in the decision-making process. Then, the experts determine the relative influence among the different criteria by evaluating the degree of interdependence. After constructing the dependence network, the relative weights of the different criteria are calculated with ANP. Finally, TOPSIS is used to provide a ranking of the alternatives [34].

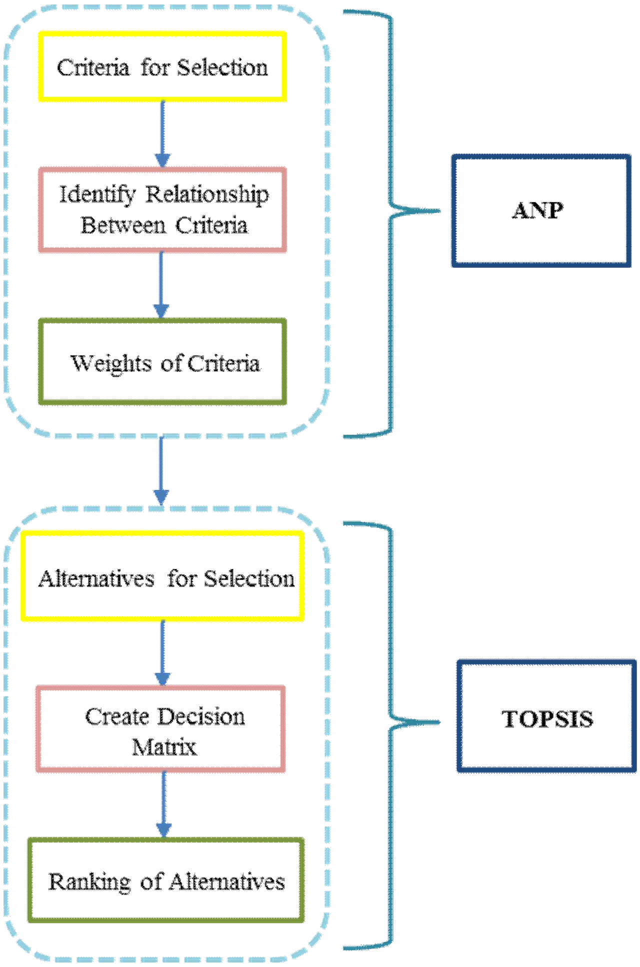


Figure 1. Schematic representation of the different phases of a combined ANP-TOPSIS methodology.

The ANP-TOPSIS combination eliminates many of the ANP procedures as redundant. Calculations and comparisons by additional pairs are avoided in classifying the alternatives [35], hence allowing a solution to be obtained in a shorter time. The ANP-TOPSIS combination has been used in other areas (see S.I. A); but in the field of photovoltaic solar energy it is used for the first time in this study. The reason may be that the ANP methodology has only recently been introduced into the scope of multi-criteria methodology [36].

The ANP is a generalization of the Analytical Hierarchical Process (AHP) methodology in which hierarchies are replaced by networks to capture the results of dependency and feedback within and among elements [21]. Many traditional MCDM are based on the assumption of independence. However, most situations do not meet the independence condition [25]. Therefore, ANP is divided into two parts. The first consists of a hierarchy of control or the network of criteria and sub-criteria that controls the interactions. The second is a network of influences between elements and groups [37]. The ANP combines all the possible results in the estimation of the

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 12 November 2018 doi:10.20944/preprints201811.0267.v1

Peer-reviewed version available at Sustainability 2018, 10, 4594; doi:10.3390/su10124594

relative influence of the different criteria from which the general priorities derive [28]. Here, the ANP is used to obtain the relative weight of each of the criteria for the proposed model.

The TOPSIS method is a decision model for the classification of preferences by similarity to the ideal solution. The basic principle of the method is the search for an alternative that minimises the distance with the positive ideal solution [38]. In TOPSIS, the weight of each of the criteria is known a priori (hence ANP). However, in many real situations clear data are inadequate to model real-life situations, since human judgement is vague and cannot be estimated with exact numerical values. This method allows searching for the better alternatives for each criterion exposed in a simple mathematical form, with the relative importance weights incorporated in the comparison procedures [25]. Here, TOPSIS is used to obtain the values of the alternatives. The ANP-TOPSIS methodology proposed is thus composed by the ten steps presented in Figure 2.

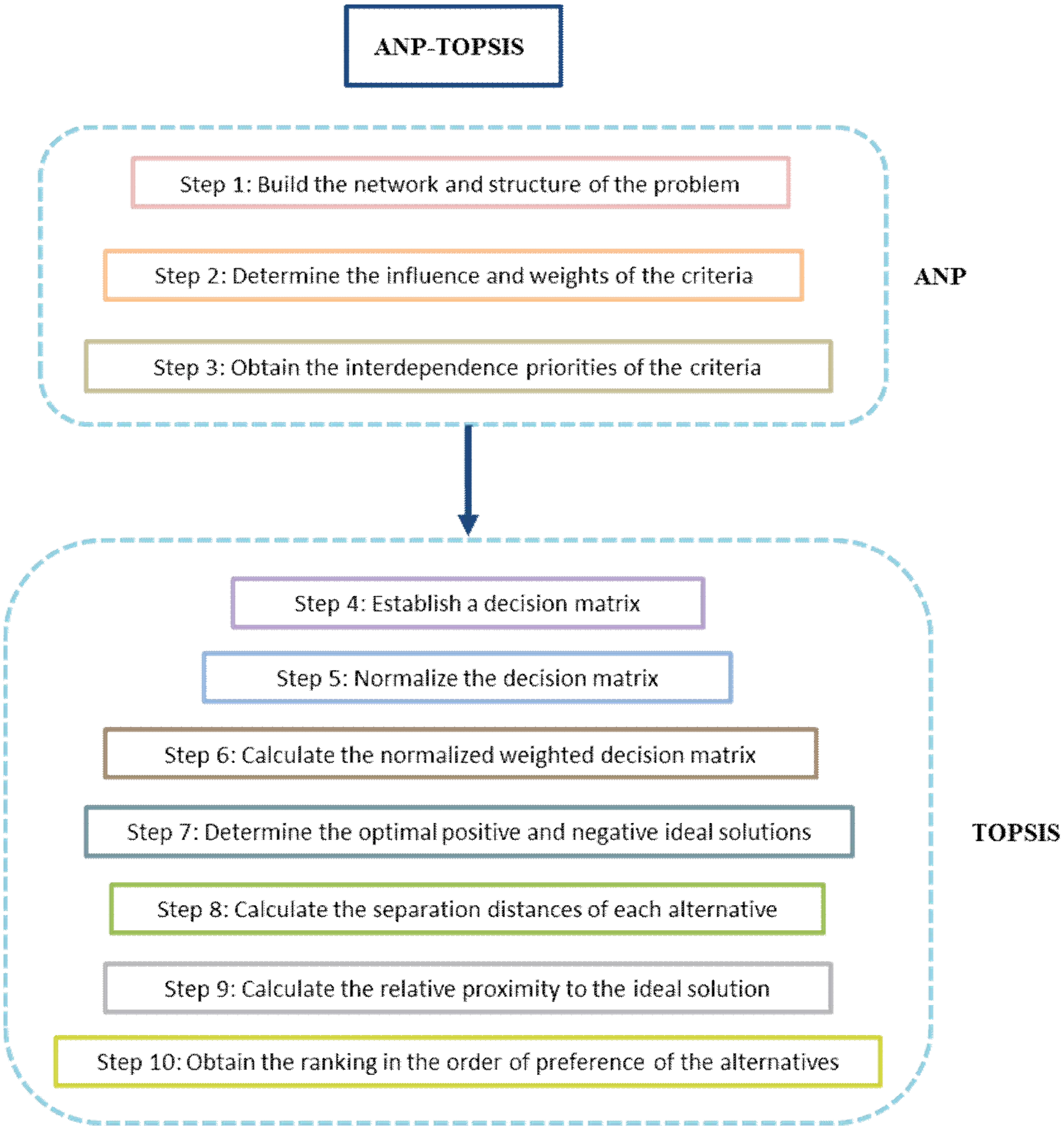


Figure 2. The ten different steps of ANP-TOPSIS as implemented through this article.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 12 November 2018 doi:10.20944/preprints201811.0267.v1
Peer-reviewed version available at Sustainability 2018, 10, 4594; doi:10.3390/su10124594

3. Results

We use ANP-TOPSIS to tackle the question of size of photovoltaic installations, according to the classification shown in the previous section (Table 1): small / medium and large scale (shown in the S.I. A) of photovoltaic systems for distributed generation. For this analysis a team composed of 5 experts belonging to the photovoltaic energy sector and representing areas such as: installer engineers, academics, researchers and users where interviewed using a detailed questionnaire. Three question sessions were held for each expert per case. In the first session, the criteria and sub-criteria were selected, and the relative influence of each of the sub-criteria to one another was answered by the experts, leading to the matrix of interaction domination (step 1 of ANP-TOPSIS in Figure 2), composed of 1's and 0's depending on whether a sub-criteria is influenced by another, or not.

The second session questioned both the importance and influence of the criteria among themselves, asking whether a criterion is inconsequential (1) or extremely important (9) to another (step 2 of ANP-TOPSIS in Figure 2). The geometric mean of each of the resultant matrices leads to the importance priorities among criteria and sub-criteria (step 3 of ANP-TOPSIS in Figure 2), which when multiplied by the interaction domination matrix gives us the relative weights of each of the sub-criteria, which will be used to evaluate the alternatives. In this step, consistency measures are calculated to assert the uniformity of each expert.

In the last session the experts value the qualitative criteria for each alternative (step 4 of ANP-TOPSIS in Figure 2), which is then normalised (step 5) and weighted (step 6), i.e. each alternative, composed by 14 values corresponding to each of the sub-criterion, is multiplied by the corresponding weight calculated in the previous steps.

Finally, to decide the alternatives ranking, the ideal positive and negative values (step 7) are calculated from the best possible positive/negative weighted alternatives, then the geometric distance of each of the alternatives to the ideals are calculated (step 8) and with it the relative proximity to the ideal solution (step 9). Finally, a ranking of alternatives according to the relative proximity to the ideal is established (step 10). The following subsections present the system components (criteria, factors and alternatives), results and the comparative analysis.

This section may be divided by subheadings. It should provide a concise and precise description of the experimental results, their interpretation as well as the experimental conclusions that can be drawn.

3.1 Criteria and factors to consider for the optimal size in PV

First, four large main groups of criteria have been established. They are the general criteria that determine the optimum size of the photovoltaic system: technical, economic, environmental and social criteria. Fourteen sub-criteria are selected from almost 70 determining factors that affect the optimal size of a distributed generation photovoltaic system (Table 2) that recent studies show [39] [40, 42], according to the criterion to which it belongs. These sub-criteria are divided into quantitative and qualitative according to the characteristics of measurement in each case.

Criteria	Sub-criteria	Measurement Characteristics	Factors that make it up
Technical (CT)	Connection to the Network (CNK)	Qualitative	*Overvoltage, additional transmission lines, Transmission and distribution losses, Intermittency in generation, Connection facilities, Distance to Transformation Substations*
	Geolocation (GEO)	Qualitative	Geographic location, Solar resource available, Site Surface, Performance Ratio, Angle of inclination, Orientation
	Annual Power Loss (APL)	Qualitative	Loss of annual power output due to degradation of the modules
	Functionality of	Qualitative	Technical and operational constraints, System reliability,

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 12 November 2018 doi:10.20944/preprints201811.0267.v1
Peer-reviewed version available at Sustainability 2018, 10, 4594; doi:10.3390/su10124594

	the System (FUS)		System Degradation
Economic (CE)	Economic Costs (EC)	Quantitative	Operating costs, Investment cost, Maintenance Cost, Cost of electricity supplied by the network, Saving transmission
	Economic Barriers (EB)	Qualitative	Barriers to financing, Barriers in hiring
	Incentives and Economic Profitability (IEP)	Qualitative	*Possible Aid and tax relief, Additional income due to possible emission reduction, Internal rate of return (IRR), Net Present Value (NPV),*
Environmental (CM)	Physical Impacts on the Ground (PIG)	Qualitative	*Natural Restrictions in the topography of the land, , Land availability, Environment*
	Environmental viability (EV)	Qualitative	*Environmental impact, Reducing Greenhouse Gas Emissions, Recovery End of Life Photovoltaic Project, Legal restrictions on environmental protection*
Social (CS)	Generated Employment (GE)	Quantitative	Employment generated in the construction phase, Employment Generated in the operation phase, Employment Generated in the dismantling and recycling phase
	Regulatory framework (RE)	Qualitative	Regulatory framework
	Socio-political Perception of the Population (SPP)	Qualitative	*Acceptance of the community and perceived equity, Public perception of information, Socio-political impacts , Poverty alleviation and reduction of inequalities*
	Socio-economic Viability (SV)	Qualitative	Promotion of energy savings and awareness towards environmental problems, Development of local infrastructure, Production of goods and services, Economic development
	Electric Supply Service (ESS)	Qualitative	*Energy utilization , Local dispatch ability, Degree of User Satisfaction, Demand coverage*

Table 2. Parameters determining the small and medium size of a distributed generation photovoltaic system.

With the knowledge the criteria and the factors that compose them, the panel of specialists identifies their mutual influence to build the network and the structure of the problem (Figure 3).

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 12 November 2018 doi:10.20944/preprints201811.0267.v1

Peer-reviewed version available at Sustainability 2018, 10, 4594; doi:10.3390/su10124594

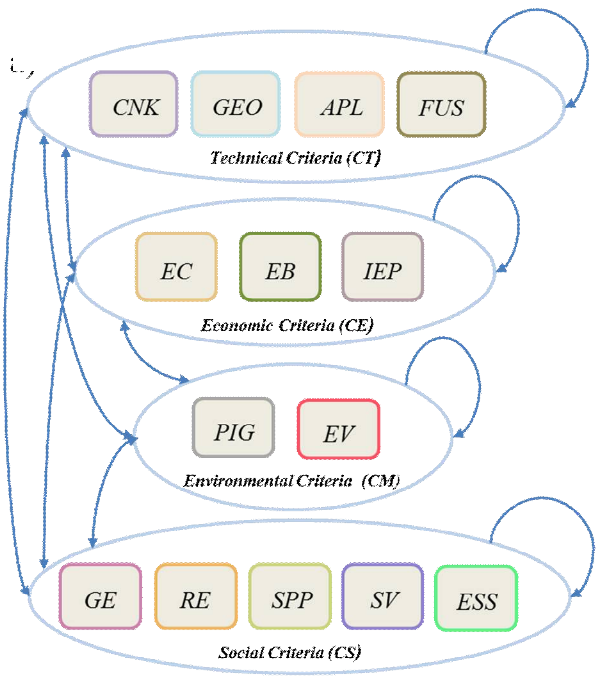


Figure 3. The interrelation among criteria, used for the evaluation of small and medium scale systems. Notice that the arrows indicate that each cluster has relation with criteria within other clusters and within the same cluster. The same relation has been used for large systems (see Supplementary Information).

3.2 Results of the model in small and medium-sized photovoltaic systems

In order to obtain the weight of the sub-criteria (w_c) of the small and medium size of the PV systems with DG, we carried out two questionnaire stages. Steps 2 and 3 of the ANP-TOPSIS are applied. In this stage the consistency of each of the experts is analysed. The result of the weights helps us evaluate the alternatives in the following steps (These results are presented in detail on S.I. B).

To determine the alternatives, we have a size range from 5kWp to 5 MWp according to the small and medium size that we have determined of the photovoltaic systems. The number of systems in each alternative should add up to 1 GWp of installed capacity, and therefore the different size alternatives are comprised by different number of independent systems: the smaller the size of the system, the larger number that have to be installed in that category. The following four groups have been weighted as alternatives:

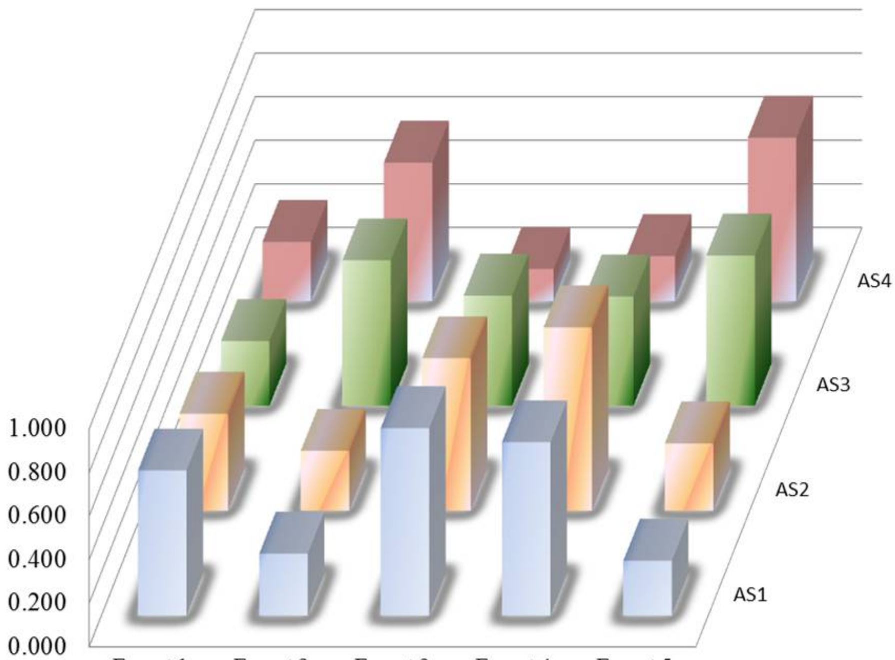
- Alternative 1 (AS1) - 200,000 photovoltaic systems with 5 kWp of power. These facilities would be located in multi-family housing for self-consumption.
- Alternative 2 (AS2) - 2,000 photovoltaic systems with 500 kWp of power. These facilities would be located in the roofs and parking areas of medium-sized companies.
- Alternative 3 (AS3) - 1,000 photovoltaic systems of 1 MWp of power. Installations located on decks and car parks of large companies with an area larger than 5,000 square meters
- Alternative 4 (AS4) - 200 photovoltaic systems with 5 MWp of power. Installations located in industrial areas that contain the necessary surface according to established regulations.

The alternatives can be considered as independent systems (all the same size within the alternative) or as groups of systems which add up to the maximum size considered in this alternative, therefore providing a partial mixed solution within each alternative. For example, in alternative 1, a few systems of 5kWp can be grouped and considered as a larger system (limited by

doi:10.20944/preprints201811.0267.v1

Peer-reviewed version available at *Sustainability* **2018**, *10*, 4594; doi:10.3390/su10124594

the maximum of 500kWp which is the minimum for the following alternative). The results of the decision matrix step 4 of Section 2.2 can be seen in S.I. B. The data of the quantitative sub-criteria economic costs (EC) and generated employment (GE) were weighted based on a study published by the International Renewable Energy Agency [42]. The other sub-criteria are qualitative and their value was established from the answers given by the experts in the last stage of questionnaires. Applying the remaining steps of ANP-TOPSIS, we obtain the distance of each of the alternatives to the ideal solution, which permits their classification in preference order, as shown in Figure 4 and Table 3.



	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5
AS1	0.665	0.284	0.859	0.795	0.251
AS2	0.444	0.274	0.699	0.841	0.308
AS3	0.297	0.667	0.505	0.501	0.689
AS4	0.271	0.634	0.147	0.205	0.749

Figure 4. Relative proximity of each of the alternatives composing the size choices in small and medium distributed photovoltaic systems.

3.3 Comparative analysis

The comparison of the results obtained from the alternatives is shown in Table 4, where the ranking of sizes for each of the experts and the trend that finally prevails is presented.

	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5
Ranking	AS1>AS2>AS3>AS4	AS3>AS4>AS1>AS2	AS1>AS2>AS3>A4	AS2>AS1>AS3>AS4	AS4>AS3>AS2>AS1

Table 3. Ranking of alternatives case small and medium-scale as classified by the relative distance calculated from the analysis of each expert.

The most repeated trend is A1 > A2 > A3>A4 (the same result is found in the large installations case, see Supplementary Information), while no other trend is repeated. The deviations produced from this trend can be analysed in terms of sensitivity to human errors, as we will explore in the next section. The predominant alternative is therefore 200,000 small installations of 5kWp for the small and medium size group, selecting thus the smaller size within the available range. These results suggest that for a given output power, smaller size modules optimise distributed generation photovoltaic systems. The same methodology has been applied to evaluate the large size

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 12 November 2018 doi:10.20944/preprints201811.0267.v1

Peer-reviewed version available at Sustainability 2018, 10, 4594; doi:10.3390/su10124594

photovoltaic systems and the result is again that the systems with smaller size in this category are the optimum solution. Details of the parameters' and results are presented in the Supplementary Information for the evaluation of large size systems. To confirm this trend and the robustness of the results, we carried out a sensitivity analysis that is shown and discussed in what follows.

3.4. Sensitivity analysis of the results

The results obtained from the ANP-TOPSIS direct analysis show that results are pretty much consistent for all experts. In this section, we will analyse the robustness of these results against changes and errors both in the evaluation of alternatives and the relative weights assigned to each of the sub-criteria by each of the experts. To do so, we introduce percentage variations on the values provided by the experts in each of the 14 sub-criteria composing the four different alternatives proposed, for both the small-medium and the large solar plant cases (the latter shown in the S.I.). We thus simulate errors that the experts might have committed in assessing the value assigned to each of the sub-criteria in each of the alternatives. In that way, we confirm the strength of the decision and the method used to reach it, and also identify the weak points and the most sensitive sub-criteria whose value might have to be double checked.

Given the structure of the ANP-TOPSIS decision method, percentage variation analysis is the same for both the final relative weights assigned to each of the sub-criteria and to the values provided for each alternative. In the ANP-TOPSIS method, the normalized final weights obtained after correlating the criteria and sub-criteria, are each multiplied by the corresponding normalized value of each sub-criteria in each alternative. This particularly means that any variation produced in either of weights (alternatives) will spread and diffuse to all the weights when normalization procedure is applied. Moreover, correlating the alternatives with the weights means that it does not matter where the error is produced, and the results shown in Figure 5 are valid and equivalent for both variations introduced in the weights and the alternatives.

a)

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 12 November 2018 doi:10.20944/preprints201811.0267.v1

Peer-reviewed version available at Sustainability 2018, 10, 4594; doi:10.3390/su10124594

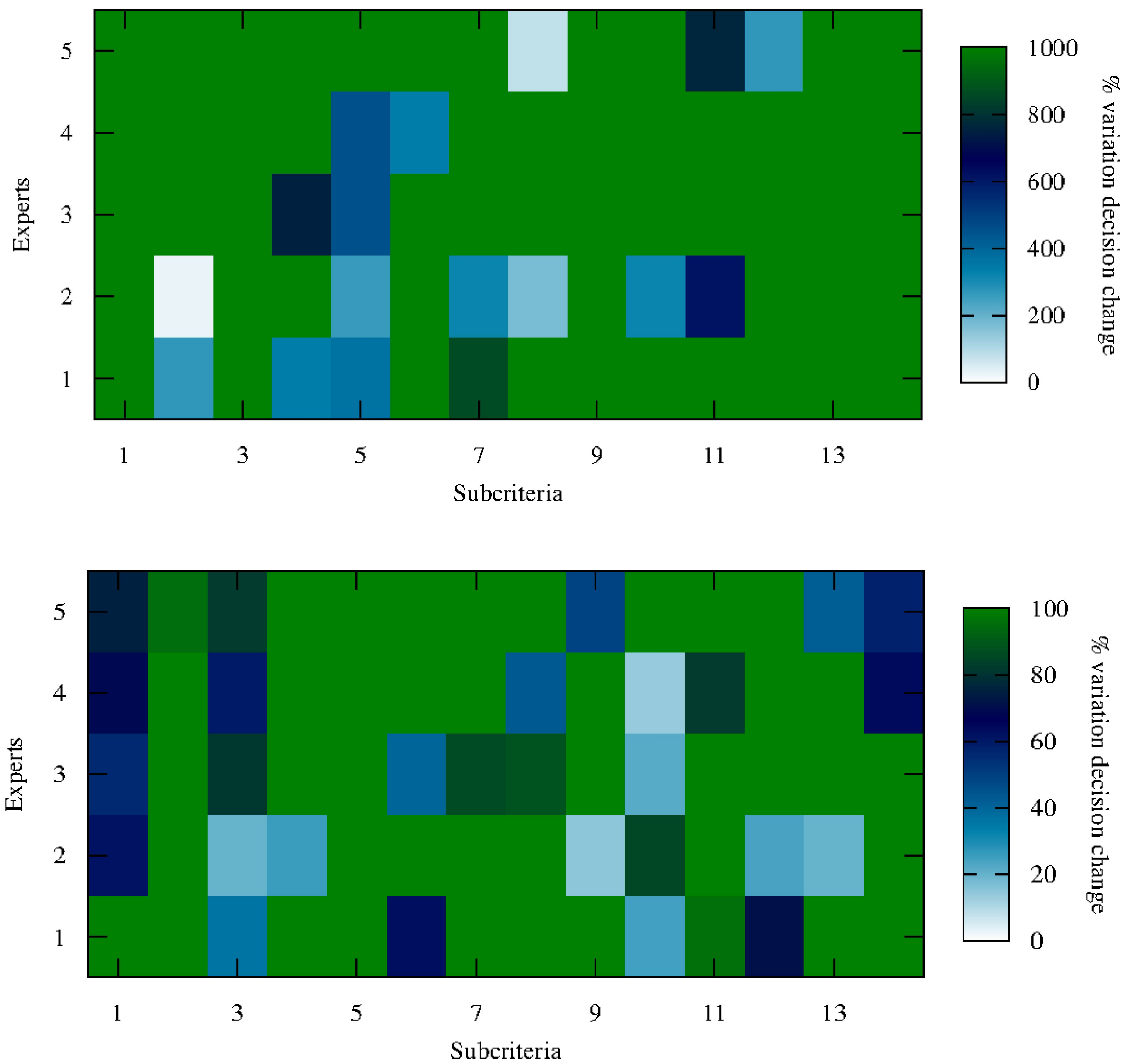


Figure 5. (a) Percentage variation of the individual sub-criteria weights at which the ideal solution changes for the case of small and medium scale distributed photovoltaic systems. (b) Average of 1000 realizations of percentage variation of the inividual sub-criteria together with random errors in all the other sub-criteria of size equal or less than the percentage variation in the considered sub-criteria. Each point shows the percentage at which he ideal solution changes for the case of small and medium scale distributed photovoltaic systems.

Figure 5a shows the percentage variation of either weight or alternative at which the original ideal solution changes. Results are shown for variations in each of the sub-criteria and for each of the experts. We have extended the variations up to 1000% error in order to show on the one hand, real changes, and on the other, the extreme robustness of the ANP-TOPSIS method, as it is very unlikely that an error of 1000% is produced. In particular, the smallest error for which a change in the ideal alternative appears is 33% for expert 1. Furthermore, only three of the variations produce a change within the 100% error, displaying the robustness of the method. Moreover, such changes appear in experts for which the solution differed from the common A1 > A2 > A3 > A4 solution, and the tendency is for the changes induced by errors to drift towards the A1 > A2 > A3 > A4 solution. With this analysis we gain insight on the influence that each of the weights has on the final solution. However, it is as well instructive to study the possibility of joint errors.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 12 November 2018 doi:10.20944/preprints201811.0267.v1

Peer-reviewed version available at *Sustainability* **2018**, *10*, 4594; doi:10.3390/su10124594

In Figure 5b we have again performed a sensitivity analysis by varying each of the weights adding an error, in this case up to 100%. The difference is that here all the other weights (or alternatives) are allowed to have an error equal or smaller than the one that is being analysed. To do so, 1000 realizations of random errors for each of the percentages are calculated and averaged to obtain how the ideal solution changes with error. The percentage at which the ideal solution changes is represented in the heatmap on Fig. 5b. We see that for most subcriteria, an error higher than 100% in all of the subcriteria is necessary in order to see a change in the ideal solution. Moreover, in any case such an error has to be higher than 15%. This again demonstrates the robustness of the method we have employed and the fiability of the results obtained. This analysis shows as well the degree of interrelation existing among subcriteria, demonstrating that except for subcriteria three, were the sensitivity to errors in the other subcriteria produces a change in the ideal solution for all experts, the choice of interrelations by the experts that leads to the relative weights is well justified, as the interrelations are already taken into account and they do not exert more influence. In that sense, the sensituvity analysis demonstrates that the results obtained from the experst analysis is robust.

The robustness of the ANP-TOPSIS mehtod comes mainly from the fact that any error that is produced on sub-criteria gets normalized and thus spreads on all the sub-criteria, causing just a shift without order change in the results when the whole ANP-TOPSIS is implemented. In fact, if error is introduced in more than one of the alternatives (weights), the results show that the percentage variation needed to see a change in the ideal solution increases for most of the sub-criteria. Correlations between sub-criteria seem to be small and are only important whenever it coincides that both weights are similar, and both correspond to either a maximum or minimum in the distance to the ideal solution. In general, this means that the possible correlations tend just to reinforce the final solution instead of changing it, again due to the normalization procedure introduced.

In conclusion, the robustness analysis shows that solutions are resilient to errors both in the valuation of alternatives and in the comparison of the relative importance of the different sub-criteria, and demonstrates the capabilities and power of the ANP-TOPSIS method.

4. Discussion

Distributed generation photovoltaic plants can be defined through the installed capacity. Provided a desired capacity, the PV plant can be constructed out of modules whose size range from small, domestic installations, to huge solar parks. Moreover, any installed single system can always be scaled up, thus benefiting from previous investments in the same location due to the flexibility of the technology. Therefore, the size of the system is, unlike other energy technologies, a free parameter that stakeholders (including end-users, investors, and policy makers) have to decide by themselves with few technical limitations and scant constraints. In this article, we have presented a possible classification of the different PV module sizes according to power capacity and target installation location. From few kW to MW and from private, mostly house installations to industrial size, large solar plants.

Determining the optimal module size for a given power capacity is a highly non-trivial problem, where several technical, socio-economic, and environmental parameters can be assigned to each size. In this article, a methodology to obtain the optimum decision about the size of the system in terms of best socio-economic impacts is proposed and tested. For that purpose, a panel of experts have been interviewed in order to assign the qualitative socio-economic and environmental parameters to different PV systems according to its size, for example, the amount of new jobs created or the physical impact on the ground. Once the deciding criteria are selected, and weights correspondingly assigned, we have, in what to our knowledge is a first in photovoltaic technologies, applied a combination of ANP and TOPSIS multi-criteria decision methods to evaluate the different PV systems and obtain the best fitting solution within each size group. This is achieved by combining the relative weights of each of the different criteria and sub-criteria, with the either numerical values for each sub-criterion (e.g. jobs generated) or the relative importance of the sub-criteria. In addition, we have implemented a sensitivity and robustness analysis of the method by performing a cross-correlation and error study which indicates that the proposed solution is robust, that there is no superfluous correlation between parameters, and that the methodology itself is built so that possible errors tend to smooth out and become relatively irrelevant.

The results obtained show clearly that within each size category (i.e. small and medium vs. large systems), the best solution to optimize both the socio-economic and the environmental impacts is the smallest one. This is an important conclusion: the best use of investment regarding the socio-economic impacts of the future PV facilities is to design and build smaller and more distributed PV systems instead of very large plants, which seems to be the actual tendency. Moreover, the decision making support methodology, a combination of ANP and TOPSIS used for this study which has provided a clear and robust result, can be extended to other PV studies (advantages of different technologies instead of different sizes for example) .

In conclusion, initial investment in small systems is recommended. Furthermore, future investment could also be used to expand those already existing installed systems in an optimal way by using the previous photovoltaic plant. Ours is thus a conscientious effort towards demonstrating, with robust tools and strong arguments, that the policy of "the larger the better" is not necessarily the best, neither for stakeholders nor for the environment, and that the community in general can greatly benefit from using sophisticated decision methods, and smaller photovoltaic installations.

In the aforementioned direction, future work should address the question of the number of experts. It is clear that given the size of the sample, and the technicality of the topic, finding suitable experts is a hard task. However, the sensitivity analysis provides the clue to resolve the issue. It is clear that both the correlation and the relative influence among sub-criteria varies greatly, having almost totally inconsequential sub-criteria, which could be ascertained from the responses of just a handful of experts, thus simplifying the questionnaires for increasing experts samples. Moreover, once a few different experts are known, simulations of experts via learning algorithms can provide with the necessary variations that provide robustness to the results by identifying the stronger trends. Another line of future research is to apply this methodology to specific regions, identifying and solving the particular needs of geographically localized places, which will require from local experts and specific sub-criteria.

Supplementary Materials: The following are available online at www.mdpi.com/xxx/s1, Figure S1: title, Table S1: title, Video S1: title.

Author Contributions: † This authors contributed equally. All authors contributed to the research and participated in the discussions and writing of this manuscript.

Funding: This research was done thanks to the financial support from MINECO (SPAIN), including FEDER funds: FIS2015-69512-R and ENE2016-79282-C5-5-R, and from Fundación Séneca (Murcia, Spain) Project No. 19882/GERM/15 and projects TIN2014-55024-P from MINECO (SPAIN) P11-TIC-8001 and TIN2017-86647-P from Junta de Andalucía (including FEDER funds) and project FIS2015-69512-R from MINECO (SPAIN) and a doctoral scholarship from MESCYT (Dominican Republic) with the contract No. BIM- 434-2017, respectively.

Conflicts of Interest: "The authors declare no conflict of interest." "The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results".

References

1. Ackermann, T., Andersson, G., Söder, L. Distributed generation: a definition. Electric Power Systems Research **2001,** 57(3), 195–204, 10.1016/S0378-7796(01)00101-8.

2. Prakash, P., Khatod, D.K., Optimal sizing and sitting techniques for distributed generation in distribution systems: A review. Renewable and Sustainable Energy Reviews **2016,** 57, 111–130, 10.1016/j.rser.2015.12.099.
3. Rezaee, J.A., Allocation of distributed generation units in electric power systems: A review. Renewable and Sustainable Energy Reviews **2016,** 56, 893-905, 10.1016/j.rser.2015.11.086.
4. Bagheri, A., Monsef, H., Lesani, H., Integrated distribution network expansion planning incorporating distributed generation considering uncertainties, reliability, and operational conditions. International Journal of Electrical Power & Energy Systems **2015,** 73, 56–70, 10.1016/j.ijepes.2015.03.010.
5. Lizi Luo, Wei Gu Xiaoing, Zhang Ge Cao, Weijun Wang, Gang Zhu, Dingjun You., Optimal siting and sizing of distributed generation in distribution systems with PV solar farm utilized as STATCOM (PV-STATCOM). Applied Energy **2018**, 210, pp 1092-1100, 10.1016/j.apenergy.2017.08.165.
6. Zeraati, Mehdi, Mohamad Esmail Hamedani Golshan, and Josep M. Guerrero., Distributed control of battery energy storage systems for voltage regulation in distribution networks with high PV penetration. IEEE Transactions on Smart Grid **2018**, 9.4: 3582-3593, 10.1109/TSG.2016.2636217.
7. Ali, E.S., Elazim, S.M., Abdelaziz, A.Y., Ant Lion Optimization Algorithm for optimal location and sizing of renewable distributed generations. Renewable Energy **2017**, 101, 1311-1324, 10.1016/j.renene.2016.09.023.
8. Ruiz-Romero, S., Colmenar-Santos, A., Gil-Ortego, R., Molina-Bonilla, A., Distributed generation: The definitive boost for renewable energy in Spain. Renewable Energy **2013**, 53, 354-364, 10.1016/j.renene.2012.12.010.
9. Lincy, G., M. Ponnavaikko, and Lenin Anselm., Economic of Distributed Photovoltaic Generation Installed in a Typical Distribution System. International Journal of Applied Engineering Research **2013**, 13.7: 4796-4801.
10. McKenna, Eoghan, Jacquelyn Pless, and Sarah J. Darby., Solar photovoltaic self-consumption in the UK residential sector: New estimates from a smart grid demonstration project. Energy Policy 2018, 118: 482-491, 10.1016/j.enpol.2018.04.006.
11. Renewable Energy Policy Network for the 21st Century. Renewables 2017 Global Status Report. c/o UNEP 1 Rue Miollis Building VII 75015 Paris France. ISBN 978-3-9818107-6-9. http://www.ren21.net/.
12. Kaldellis, J.K., Zafirakis, D., Kondili, E., Optimum sizing of photovoltaic-energy storage systems for autonomous small islands. International Journal of Electrical Power & Energy Systems **2010**, 32(1), 24-36, 10.1016/j.ijepes.2009.06.013.
13. Phillips, J., Determining the sustainability of large-scale photovoltaic solar power plants. Renewable and Sustainable Energy Reviews **2013**, 27, 435-444, 10.1016/j.rser.2013.07.003.
14. Markvart, T., Sizing of hybrid photovoltaic-wind energy systems. Solar Energy **1996**, 57(4), 277-281, 10.1016/S0038-092X(96)00106-5.
15. Prados, M.J., Renewable energy policy and landscape management in Andalusia, Spain: The facts. Energy Policy **2010**, 38(11), 6900–6909, 10.1016/j.enpol.2010.07.005.
16. Duailibe Ribeiro, A.E., Cardoso Arouca, M., Moreira Coelho, D., Electric energy generation from small-scale solar and wind power in Brazil: The influence of location, area and shape. Renewable Energy **2016**, 85, 554–563, 10.1016/j.renene.2015.06.071.
17. Lv, T., Ai, Q., Interactive energy management of networked microgrids-based active distribution system considering large-scale integration of renewable energy resources. Applied Energy **2016**, 63, 408–422, 10.1016/j.apenergy.2015.10.179.
18. Viral, R., Khatod, D.K., Optimal planning of distributed generation systems in distribution system: A review. Renewable and Sustainable Energy Reviews **2012**, 16(7), 5146-5165, 10.1016/j.rser.2012.05.020.
19. Liu K, Sheng W, Liu Y, Meng X, Liu Y. Optimal sitting and sizing of DGs in distribution system considering time sequence characteristics of loads and DGs. International Journal of Electrical Power & Energy Systems **2015**, 69: 430–440, 10.1016/j.ijepes.2015.01.033.
20. Abdmouleh, Z., Gastli, A., Ben-Brahim, L., Haouari, M., Ahmed Al-Emadi, N., Review of optimization techniques applied for the integration of distributed generation from renewable energy sources. Renewable Energy **2017**, 113, 266-280, 10.1016/j.renene.2017.05.087.
21. Saaty T.L. Fundamentals of the Analytic Hierarchy Process. In The Analytic Hierarchy Process in Natural Resource and Environmental Decision Making. Managing Forest Ecosystems. ; eds Schmoldt D.L.,

Peer-reviewed version available at Sustainability 2018, 10, 4594; doi:10.3390/su10124594

Kangas J., Mendoza G.A., Pesonen M. Springer, Dordrecht, Netherlands, **2001**. Volume 3, pp 15-35, 978-90-481-5735-8.

22. Hwang, C. L., Yoon, K.. Multiple Attribute Decision Methods and Applications. Springer, Berlin Heidelberg, Germany, **1981**, 978-3-540-10558-9
23. Lee Amy, H.I., Hung, M.C., Kang, H.Y., Pearn, W.L., A wind turbine evaluation model under a multi-criteria decision making environment. Energy Conversion and Management **2012**, 64, 289-300, 10.1016/j.enconman.2012.03.029.
24. Cheng-Shiung, W., Chin-Tsai, L., Chuan, L., Optimal marketing strategy: A decision-making with ANP and TOPSIS. International Journal of Production Economics **2010**, 127(1), 190–196, 10.1016/j.ijpe.2010.05.013.
25. Singh, R.K., Benyouce, L., A fuzzy TOPSIS based approach for e-sourcing. Engineering Applications of Artificial Intelligence **2011**, 24(3), 437–448, 10.1016/j.engappai.2010.09.006.
26. Sánchez-Lozano, J.M., Teruel-Solano, J., Soto-Elvira, P.L., García-Cascales, M.S., Geographical Information Systems (GIS) and Multi-Criteria Decision Making (MCDM) methods for the evaluation of solar farms locations: Case study in south-eastern Spain. Renewable and Sustainable Energy Reviews **2013**, 24, 544–556, 10.1016/j.rser.2013.03.019.
27. Aragonés-Beltrán, P., Chaparro-González, F., Pastor-Ferrando, J.P., An AHP (Analytic Hierarchy Process)/ANP (Analytic Network Process)-based multi-criteria decision approach for the selection of solar-thermal power plant investment projects. Energy **2014**, 66, 222–238, 10.1016/j.energy.2013.12.016.
28. Yunn W., Geng S., Multi-criteria decision making on selection of solar–wind hybrid power station location: A case of China. Energy Conversion and Management **2014**, 81, 527–533, 10.1016/j.enconman.2014.02.056.
29. Yahyaoui, I., Atieh, A., Tadeo, F., Tina, G.M., Energetic and economic sensitivity analysis for photovoltaic water pumping systems. Solar Energy **2017**, 144, 376-391, 10.1016/j.solener.2017.01.040.
30. Kabalci, Y., Kabalci, E., Modeling and analysis of a smart grid monitoring system for renewable energy sources. Solar Energy **2017**, 153, 262-275, 10.1016/j.solener.2017.05.063.
31. Muhsen, D.H., Khatib, T., Abdulabbas, T.E., Sizing of a standalone photovoltaic water pumping system using hybrid multi-criteria decision making methods. Solar Energy **2018**, 159, 1003-1015, 10.1016/j.solener.2017.11.044.
32. Guerrero-Liquet, G.C., Sánchez-Lozano, J.M., García-Cascales, M.S., Lamata, M.T., Verdegay, J.L. Decision-Making for Risk Management in Sustainable Renewable Energy Facilities: A Case Study in the Dominican Republic. Sustainability, **2016,** 8(5) 455, 10.3390/su8050455
33. Saaty, T.L. Decision Making with Dependence and Feedback: The Analytic Network Process : the Organization and Prioritization of Complexity. RWS Publications, **2001**, 0962031798
34. Shyur, H.J., COTS evaluation using modified TOPSIS and ANP. Applied Mathematics and Computation **2006**, 177(1), 251–259, 10.1016/j.amc.2005.11.006.
35. Chang, K.L., Liao, S.K., Tseng, T.W., Liao, C.Y., An ANP based TOPSIS approach for Taiwanese service apartment location selection. Asia Pacific Management Review **2015**, 20(2), 49-55, 10.1016/j.apmrv.2014.12.007.
36. Ayağ, Z., Özdemir, R.G., Evaluating machine tool alternatives through modified TOPSIS and alpha-cut based fuzzy ANP. International Journal of Production Economics **2012,** 140(2), 630–636, 10.1016/j.ijpe.2012.02.009.
37. Shafiee, M., A fuzzy analytic network process model to mitigate the risks associated with offshore wind farms. Expert Systems with Applications **2015**, 42(4), 2143–2152, 10.1016/j.eswa.2014.10.019.
38. Sánchez-Lozano, J.M., García-Cascales, M.S., Lamata, M.T., Evaluation of suitable locations for the installation of solar thermoelectric power plants. Computers & Industrial Engineering **2015**, 87, 343-355, 10.1016/j.cie.2015.05.028.
39. Corona, B., de la Rúa, C., San Miguel, G., Socio-economic and environmental effects of concentrated solar power in Spain: A multiregional input output analysis. Solar Energy Materials and Solar Cells **2016**, 156, 112-121, 10.1016/j.solmat.2016.03.014.
40. Hangera, S., Komendantova, N., Schinke, B., Zejli, D., Ihlal, A., Patt, A., Community acceptance of large-scale solar energy installations in developing countries: Evidence from Morocco. Energy Research & Social Science **2016**, 14, 80–89, 10.1016/j.erss.2016.01.010.

41. Sheikh, N.J., Kocaoglu, D.F., Lutzenhiser, L., Social and political impacts of renewable energy: Literature review. Technological Forecasting and Social Change 108, **2016**, 102–110, 10.1016/j.techfore.2016.04.022.
42. Yang, H., Zhou, W., Lu, Lin., Zhaohong, F., Optimal sizing method for stand-alone hybrid solar-wind system with LPSP technology by using genetic algorithm. Solar Energy **2008**, 82(4), 354-367, 10.1016/j.solener.2007.08.005.
43. IRENA (2018), Renewable Power Generation Costs in 2017. International Renewable Energy Agency, Abu Dhabi. ISBN 978-92-9260-040-2. http://www.irena.org.