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Supplementary Information for "Determination of the optimal size of photovoltaic systems by using Multi-Criteria Decision Making Methods"

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Supplementary Materials A: Large-scale PV system evaluation

In this appendix, the results for those photovoltaic installations adding up to one GW of installed capacity, but exceeding five MW, are presented. The analysis follows the methodology described in the main text for the small and medium-size installations; hence, it will not be repeated here.

Table S1. presents the criteria and sub-criteria chosen by the experts to optimise large-scale installations.

Table S1. Parameters determining the large-scale size of a distributed generation photovoltaic system.

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, Conditions of the lines, substations, and distribution network topology, Grid disturbances, Distance to transformation substations*
	Geolocation (GEO)	Qualitative	*Geographic location, Solar resource available, Site surface, Wind conditions, Performance ratio*
	System Power Efficiency (SPE)	Qualitative	*Power loss index, Power flow, Electrical conversion efficiency*
	Functionality of the System (FUS)	Qualitative	*Technical and operational constraints, System reliability, System degradation, Energy waste, System security elements*
Economic (CE)	Economic Costs (EC)	Quantitative	*Operating costs, Investment cost, Maintenance cost, Cost of electricity supplied by the network, Price of the floor*
	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), Saving transmission*
Environmental (CM)	Physical Impacts on the Ground (PIG)	Qualitative	*Natural restrictions in the topography of the land, Land availability, Loss of arable land*
	Environmental viability (EV)	Qualitative	*Environmental impact, Reducing greenhouse gas emissions, Recovery end of life photovoltaic project, Impacts on the ecosystem, 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, Distance from Nor I project site, Social perception negative of impacts added*
	Socio-economic Viability (SV)	Qualitative	*Promotion of energy savings and awareness of environmental problems, Development of local infrastructure, Production of goods and services, Economic development, Industrial fabric in the area*
	Electric Supply Service (ESS)	Qualitative	*Energy utilization, Local dispatch ability, Degree of user satisfaction, Demand coverage*

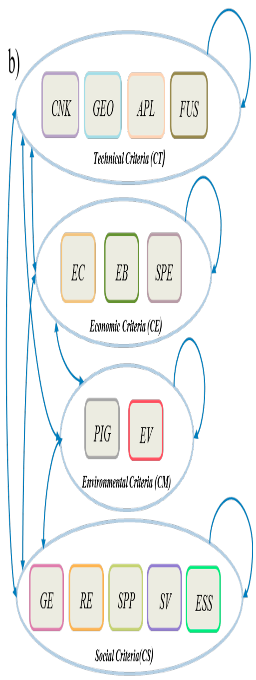

Figure S1. The interrelation among the criteria used for the evaluation of big scale systems. Notice that the arrows indicate that each cluster has relations with criteria within other clusters as well as within the same cluster.

- The same procedure of ANP-TOPSIS is applied to the large size group, where a size range from five MW to 333 MW is used. Full results can be found at S.I.D. The following four scales have been weighted as alternatives:
- Alternative 1 (AL1)—50 solar farms with 20 MWp of power located in land near the city.
- Alternative 2 (AL2)—20 photovoltaic systems with 50 MWp of power distributed between solar farms and small power plants according to regulations.
- Alternative 3 (AL3)—10 power plants with 100 MWp of power in places meeting the required restrictions.
- Alternative 4 (AL4)—Three power plants with 333 MWp of power contemplating the best available location and complying with the established regulations.

The relative proximity of each alternative per expert is displayed in Figure S.I.A2.

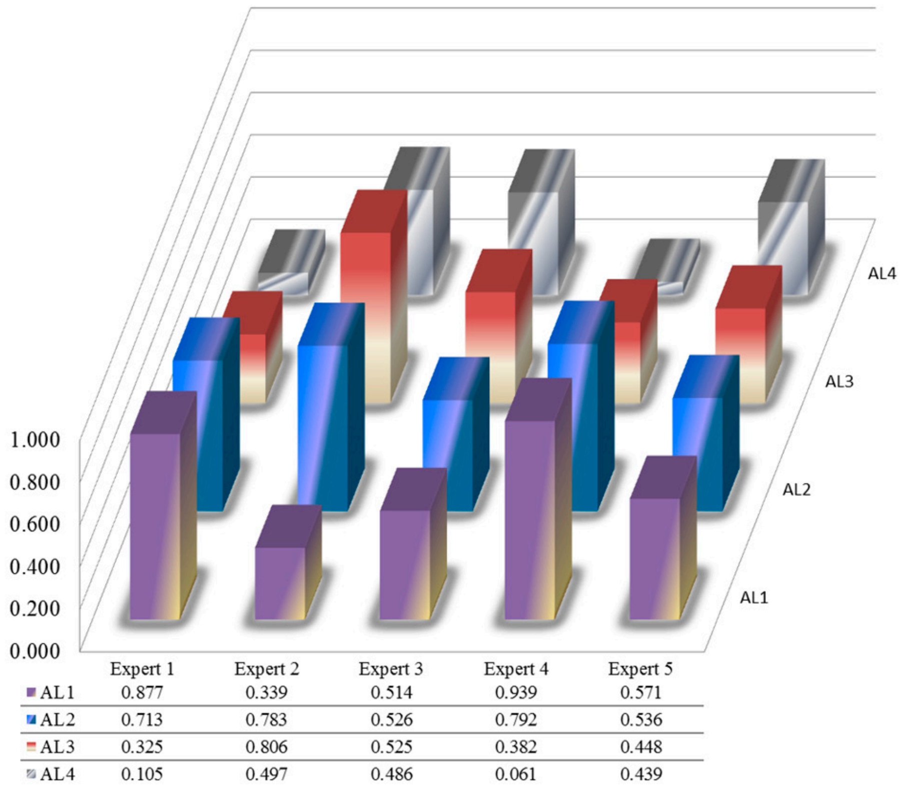

Figure S2. Relative proximity of each of the alternatives composing the size choices in large-scale distributed photovoltaic systems.

The comparison of the results obtained from the alternatives is shown in Table S.I.A2 for both cases: small–medium and large size, where the ranking of sizes for each of the experts and the trend that finally prevails is presented.

Table S2. Ranking of alternatives as classified by the relative distance calculated from the analysis of each expert.

	Expert 1	**Expert 2**	**Expert 3**	**Expert 4**	**Expert 5**
Ranking case large-scale	AL1>AL2>AL3>AL4	AL3>AL2>AL4>AL1	AL2>AL3>AL1>AL4	AL1>AL2>AL3>AL4	AL1>AL2>AL3>AL4

The most repeated trend is, as in the case of small and medium sizes (see main text), A1 > A2 > A3 > A4. Therefore, the predominant alternative is 50 solar farms of 20 MWp of power each.

a)

b)

Figure S3. (a) Percentage variation of the individual sub-criteria weights at which the ideal solution changes for the case of large-scale distributed photovoltaic systems. (b) Average of 1000 realizations of percentage variation of the individual sub-criteria together with random errors in all of the other sub-criteria of a size equal or less than the percentage variation in the considered sub-criteria. Each point shows the percentage at which the ideal solution changes for the case of large-scale distributed photovoltaic systems.

The results of the sensitivity analysis are presented in Figure S.I.A3(a) and (b). In (a), the individual weights' variations show that the smallest error for which a change in the ideal alternative appears is 28% for expert 2. Expert 3 is in this case an anomaly deserving more attention, as it is the only one that shows extreme sensitivity to variations. In fact, all of the distances to the ideal solution for this expert are within a narrow margin. Hence, it means that for this expert, more questions are needed to clarify the answer. In fact, the analysis that was just shown demonstrates the ability of the ANP-TOPSIS method to learn from the experts and point toward the weak sub-criteria that might benefit from additional questioning. In (b), where all of the other weights (or alternatives) are allowed to have an error equal to or smaller than the one that is being analyzed, we see that for most of the sub-criteria, an error higher than 100% in all of the sub-criteria is necessary in order to see a change in the ideal solution, being even more robust than when only individual variations are considered, which again demonstrates the robustness of the method that we have employed and the fiability of the results obtained.

Supplementary Materials B: Specific ANP-TOPSIS references

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Supplementary Materials C: Full numerical results of the evaluation of small–medium and large PV systems

Table S3. Result of the weight of the sub-criteria of the small and medium-sized distributed photovoltaic systems.

Sub-criteria	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5
CNK	0.078	0.037	0.065	0.020	0.064
GEO	0.105	0.174	0.094	0.197	0.130
APL	0.011	0.019	0.021	0.018	0.021
FUS	0.059	0.037	0.029	0.022	0.022
EC	0.094	0.077	0.114	0.123	0.092
EB	0.035	0.132	0.033	0.097	0.057
IEP	0.067	0.058	0.066	0.033	0.074
PIG	0.155	0.128	0.126	0.023	0.061
EV	0.100	0.131	0.080	0.017	0.187

GE	0.059	0.013	0.042	0.071	0.007
RE	0.127	0.089	0.207	0.018	0.180
SPP	0.018	0.023	0.026	0.236	0.040
SV	0.028	0.073	0.055	0.118	0.028
ESS	0.063	0.011	0.042	0.007	0.038
Total	1.00	1.00	1.00	1.00	1.00

Table S4. Decision matrix of the small and medium-sized distributed photovoltaic systems.

Expert 1						
Sub-criteria	w_c	Unit of measurement	A1	A2	A3	A4
CNK	0.078	min:1,max:10	8	7	6	5
GEO	0.105	min:1,max:10	5	7	5	5
APL	0.011	min:1,max:10	2	3	4	6
FUS	0.059	min:1,max:10	4	6	7	8
EC	0.094	€/wp	1.56	1.50	1.20	1.10
EB	0.035	min:1,max:10	4	8	8	8
IEP	0.067	min:1,max:10	7	8	5	5
PIG	0.155	min:1,max:10	5	6	7	8
EV	0.100	min:1,max:10	7	6	6	5
GE	0.059	Number of jobs	1,000,000	977,500	950,000	925,000
RE	0.127	min:1,max:10	9	5	5	5
SPP	0.018	min:1,max:10	8	7	5	5
SV	0.028	min:1,max:10	7	7	7	9
ESS	0.063	min:1,max:10	10	8	7	7
Expert 2						
CNK	0.037	min:1,max:10	6	7	9	9
GEO	0.174	min:1,max:10	5	6	8	9
APL	0.019	min:1,max:10	8	8	4	5
FUS	0.037	min:1,max:10	5	5	9	8
EC	0.077	€/wp	1.56	1.50	1.20	1.10
EB	0.132	min:1,max:10	9	8	7	7
IEP	0.058	min:1,max:10	8	9	6	6
PIG	0.128	min:1,max:10	5	7	7	7
EV	0.131	min:1,max:10	7	6	8	6
GE	0.013	Number of jobs	1,000,000	977,500	950,000	925,000
RE	0.089	min:1,max:10	7	6	6	6
SPP	0.023	min:1,max:10	5	8	9	8
SV	0.073	min:1,max:10	5	6	10	8
ESS	0.011	min:1,max:10	8	8	9	10
Expert 3						
CNK	0.065	min:1,max:10	9	6	4	2
GEO	0.094	min:1,max:10	10	9	6	4
APL	0.021	min:1,max:10	3	4	5	7
FUS	0.029	min:1,max:10	4	7	9	10
EC	0.114	€/wp	1.56	1.50	1.20	1.10
EB	0.033	min:1,max:10	1	5	7	9
IEP	0.066	min:1,max:10	8	7	5	2
PIG	0.126	min:1,max:10	1	2	4	7
EV	0.080	min:1,max:10	10	10	9	6
GE	0.042	Number of jobs	1,000,000	977,500	950,000	925,000
RE	0.207	min:1,max:10	9	7	7	4
SPP	0.026	min:1,max:10	10	10	9	7

SV	0.055	min:1,max:10	9	7	7	9
ESS	0.042	min:1,max:10	10	10	10	9
			Expert 4			
CNK	0.020	min:1,max:10	10	8	6	5
GEO	0.197	min:1,max:10	10	10	6	4
APL	0.018	min:1,max:10	4	6	7	9
FUS	0.022	min:1,max:10	5	6	8	9
EC	0.123	€/wp	1.56	1.50	1.20	1.10
EB	0.097	min:1,max:10	6	5	4	4
IEP	0.033	min:1,max:10	6	7	7	7
PIG	0.023	min:1,max:10	1	2	4	8
EV	0.017	min:1,max:10	8	8	6	6
GE	0.071	Number of jobs	1,000,000	977,500	950,000	925,000
RE	0.018	min:1,max:10	8	7	5	4
SPP	0.236	min:1,max:10	9	9	7	4
SV	0.118	min:1,max:10	8	8	6	4
ESS	0.007	min:1,max:10	10	10	7	3
			Expert 5			
CNK	0.064	min:1,max:10	2	8	8	8
GEO	0.130	min:1,max:10	2	3	6	7
APL	0.021	min:1,max:10	7	5	4	4
FUS	0.022	min:1,max:10	7	7	6	6
EC	0.092	€/wp	1.56	1.50	1.20	1.10
EB	0.057	min:1,max:10	9	8	7	7
IEP	0.074	min:1,max:10	4	6	8	8
PIG	0.061	min:1,max:10	2	3	5	7
EV	0.187	min:1,max:10	2	2	4	5
GE	0.007	Number of jobs	1,000,000	977,500	950,000	925,000
RE	0.180	min:1,max:10	8	7	7	7
SPP	0.040	min:1,max:10	9	8	6	4
SV	0.028	min:1,max:10	2	4	4	5
ESS	0.038	min:1,max:10	2	3	6	7

Table S5. Result of the weight of the sub-criteria of the large-scale distributed photovoltaic systems.

Sub-criteria	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5
CNK	0.065	0.046	0.063	0.040	0.071
GEO	0.165	0.118	0.146	0.171	0.180
SPE	0.017	0.045	0.013	0.003	0.048
FUS	0.034	0.084	0.025	0.013	0.020
EC	0.076	0.083	0.180	0.132	0.084
EB	0.065	0.131	0.039	0.040	0.043
IEP	0.079	0.062	0.027	0.033	0.087
PIG	0.147	0.039	0.135	0.034	0.124
EV	0.094	0.098	0.108	0.023	0.111
GE	0.067	0.112	0.063	0.236	0.008
RE	0.085	0.030	0.024	0.011	0.163
SPP	0.011	0.029	0.112	0.209	0.016
SV	0.025	0.029	0.051	0.045	0.007
ESS	0.072	0.093	0.014	0.009	0.038
Total	1.00	1.00	1.00	1.00	1.00

Table S6. Decision matrix of the large-scale distributed photovoltaic systems.

Sub-criteria	w_c	Unit of measurement	A1	A2	A3	A4
Expert 1						
CNK	0.065	min:1,max:10	9	9	10	10
GEO	0.165	min:1,max:10	6	5	4	4
SPE	0.017	min:1,max:10	7	7	8	8
FUS	0.034	min:1,max:10	8	9	9	10
EC	0.076	€/wp	0.98	0.96	0.87	0.85
EB	0.065	min:1,max:10	7	6	7	8
IEP	0.079	min:1,max:10	10	10	9	8
PIG	0.147	min:1,max:10	8	9	10	10
EV	0.094	min:1,max:10	5	5	3	2
GE	0.067	Number of jobs	900,000	782,000	700,000	540,000
RE	0.085	min:1,max:10	6	6	6	6
SPP	0.011	min:1,max:10	4	3	2	2
SV	0.025	min:1,max:10	6	5	3	3
ESS	0.072	min:1,max:10	8	8	6	3
Expert 2						
CNK	0.046	min:1,max:10	5	6	8	9
GEO	0.118	min:1,max:10	4	8	9	7
SPE	0.045	min:1,max:10	8	5	5	7
FUS	0.084	min:1,max:10	8	8	9	6
EC	0.083	€/wp	0.98	0.96	0.87	0.85
EB	0.131	min:1,max:10	8	4	4	5
IEP	0.062	min:1,max:10	4	4	4	4
PIG	0.039	min:1,max:10	4	5	6	9
EV	0.098	min:1,max:10	7	8	8	6
GE	0.112	Number of jobs	900,000	782,000	700,000	540,000
RE	0.030	min:1,max:10	3	3	3	3
SPP	0.029	min:1,max:10	5	7	7	4
SV	0.029	min:1,max:10	8	9	7	5
ESS	0.093	min:1,max:10	7	8	9	7
Expert 3						
CNK	0.063	min:1,max:10	9	9	7	6
GEO	0.146	min:1,max:10	9	9	8	5
SPE	0.013	min:1,max:10	10	9	8	7
FUS	0.025	min:1,max:10	6	6	7	9
EC	0.180	€/wp	0.98	0.96	0.87	0.85
EB	0.039	min:1,max:10	4	6	8	9
IEP	0.027	min:1,max:10	3	5	7	9
PIG	0.135	min:1,max:10	10	9	7	4
EV	0.108	min:1,max:10	9	8	6	4
GE	0.063	Number of jobs	900,000	782,000	700,000	540,000
RE	0.024	min:1,max:10	6	6	6	6
SPP	0.112	min:1,max:10	7	8	9	10
SV	0.051	min:1,max:10	8	8	9	10
ESS	0.014	min:1,max:10	9	9	7	4
Expert 4						
CNK	0.040	min:1,max:10	7	7	6	5
GEO	0.171	min:1,max:10	5	4	2	1
SPE	0.003	min:1,max:10	8	8	9	10

FUS	0.013	min:1,max:10	8	8	9	10
EC	0.132	€/wp	0.98	0.96	0.87	0.85
EB	0.040	min:1,max:10	4	4	4	4
IEP	0.033	min:1,max:10	5	5	5	5
PIG	0.034	min:1,max:10	8	8	9	10
EV	0.023	min:1,max:10	5	5	5	5
GE	0.236	Number of jobs	900,000	782,000	700,000	540,000
RE	0.011	min:1,max:10	5	5	5	5
SPP	0.209	min:1,max:10	3	3	2	1
SV	0.045	min:1,max:10	3	3	2	1
ESS	0.009	min:1,max:10	8	8	9	10
Expert 5						
CNK	0.071	min:1,max:10	7	8	9	10
GEO	0.180	min:1,max:10	5	5	6	6
SPE	0.048	min:1,max:10	8	8	8	9
FUS	0.020	min:1,max:10	5	5	5	6
EC	0.084	€/wp	0.98	0.96	0.87	0.85
EB	0.043	min:1,max:10	5	6	8	10
IEP	0.087	min:1,max:10	8	6	6	8
PIG	0.124	min:1,max:10	2	4	6	8
EV	0.111	min:1,max:10	3	5	6	8
GE	0.008	Number of jobs	900,000	782,000	700,000	540,000
RE	0.163	min:1,max:10	5	5	5	5
SPP	0.016	min:1,max:10	3	4	7	9
SV	0.007	min:1,max:10	7	7	5	3
ESS	0.038	min:1,max:10	5	5	6	7