Environ Monit Assess (2020) 192:297
https://doi.org/10.1007/s10661-020-08267-5

Geographic information system-based investment system for photovoltaic power plants location analysis in Turkey

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Received: 28 October 2019 / Accepted: 31 March 2020
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Abstract The motivation of this research, development, demonstration, deployment, and diffusion (RD^3&D) study is to present the progress of designing the GIS-based location selection module of autonomous investment decision support system and its experimental application for photovoltaic power plants (PVPPs) in Antalya, Burdur, and Isparta planning region Turkey. The other motivation of this RD^3&D study is to start investigating in combinations the applicability and usability of weighted linear combination with 4 subjective weighting approaches (rank sum weight method (RS), inverse or reciprocal weights method (RR), rank order centroid (ROC), point allocation (PA)) for 5 main criteria, 14 sub-criteria, and 79 value ranges. The results show that 38.48% of the planning region is unsuitable, 61.52% is suitable. Only 2.07% of this region is very highly suitable according to RS. 7.13%, 9.22%, and 5.58% are respectively very highly suitable according to RR, ROC, and PA. Similarities between RS, RR, ROC, and PA methods are presented such as RS-RR: 0.7834, RS-ROC: 0.8510, and RS-PA: 0.6384 with covariance and correlation analysis. A backward-looking performance verification and validation analysis is also performed with 7 PVPPs for only 4 decisive success factors (capacity factor, annual energy/land use, project cost/capacity, project cost/energy). This study is thus able to evaluate the optimal locations for future investments, as well as the suitability conditions of the available investments. This study will contribute to provide some useful recommendations for decision makers to identify and assess the hotspots which are suitable for PVPPs in the planning region.

Keywords Geographic information system · Land suitability · Multi-criteria decision-making · Photovoltaic · Spatial analysis · Subjective weighting

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Introduction

Cheap and reliable energy resources are preferred to maintain sustainable socio-economic development. Fossil fuels are consumed as the main energy source in this

Published online: 19 April 2020

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day and age. Hence, many costly and serious environmental problems are observed all over the world (Alamdari et al. 2013; Zoghi et al. 2017). It is clear that short- and long-term adverse effects of those problems will have devastating consequences on the societies and ecosystem (Omer 2008). In this case, renewable energy (RE) sources are the most promising choice to address environmental and social issues (Oyedepo 2014; Hafeznia et al. 2017). Accordingly, utilization of RE resources is expected to increase by 73% between 2012 and 2035, while non-RE sources are expected to run out in the future (Hirsch 2008; Jakobsson et al. 2009; Lloyd and Forest 2010; IEA 2014).

Electricity generation from solar photovoltaic (PV) technology has become more widespread in recent years due to technical and technological breakthroughs such as increasing efficiencies of PV systems (cells, modules, systems) while reducing costs of them. Costs can be minimized through the advantage of the economies of scale by designing very large PV power plants (VLPVPP/PVPP) (Saracoglu et al. 2018). Turkey is one of the fortunate countries in terms of solar power plant investments due to its high solar irradiation values and energy potential (WB 2019; SG 2019). Turkey is also among many countries that try to develop some sustainable energy models with RE sources. Geographic information system (GIS) is a powerful tool that helps to process and evaluate a large number of spatial data related to political, economic, social, technological, technical, legal, environmental, ethical, demographic, ecological, and similar criteria from different sources and to analyze them. Therefore, it has recently become very popular in assessing suitability of RE sources such as solar farms, and wind farms (Azizi et al. 2014; Asakereh et al. 2017; Hafeznia et al. 2017; Yushchenko et al. 2018; Uzar and Sener 2019). There is a wide variety of pure, stand-alone, and combined decision-making methods and tools ranging from artificial intelligence to deterministic multi-criteria decision-making (MCDM) methods, from fuzzy logic to game theory approaches, that can be employed in GIS (Malczewski 2000; Jozi et al. 2012; Roszkowska 2013; Nasiri et al. 2013; Blachowski 2015; Ohunakin and Saracoglu 2018; Kazemi-Beydokhti et al. 2019). In the assessment of land suitability, it is necessary to standardize different scale criteria by bringing them together or to be converted into a common suitability value. Weighted linear combination (WLC) is an analytical method that can be used when multiple attributes must be taken into consideration, for example, in suitability modeling or site selection. A general decision-making procedure of WLC is transforming spatially defined all data set into a common digital decision-making map (Malczewski 2000; Blachowski 2015).

GIS and multi-criteria decision-making (MCDM) methods should be integrated to analyze all criteria affecting the selection of PV solar farms simultaneously. It was realized that various studies had been conducted to select the best PVPPs' locations at different scales using GIS and MCDM methods in the literature (Sanchez-Lozano et al. 2015; Asakereh et al. 2017; Zoghi et al. 2017; Aly et al. 2017; Doljak and Stanojevic 2017; Merrouni et al. 2018; Firozjaei et al. 2019; Doorga et al. 2019). Aly et al. (2017) identified the appropriate large-scale PV and concentrated solar power (CSP, also concentrating solar power, and concentrated solar thermal power) plants' fields using analytic hierarchy process (AHP) and GIS methods in Tanzania. They used global horizontal irradiance (GHI), distance (water resources, roads, utility grids, mines, cities) as evaluation criteria. Asakereh et al. (2017) evaluated solar farms locations based on Fuzzy-AHP and GIS in Khuzestan, Iran. Doljak and Stanojevic (2017) evaluated the PVPPs locations in Serbia with AHP and GIS. They preferred factors like GHI, duration of sunshine, air temperature, relative humidity, slope, and aspect. They used the Corine Land Cover (CLC) 2012 land cover map to determine the excluded areas (Copernicus 2019a). Doorga et al. (2019) identified areas in Mauritius that had been excluded primarily for the PVPPs' assessment with some exclusion criteria like world heritage sites, native vegetation, and wildlife, airport, permanent water bodies, and major settlements areas. They determined the appropriate sites through AHP and GIS integration among the remaining areas with evaluation criteria of GHI, sunshine duration, temperature, relative humidity, elevation, slope, aspect, and distance (road network, transmission lines).

This paper presents an experimental application of a multi-criteria decision-making (MCDM) and geographic information system (GIS)-based spatial model for photovoltaic power plants (PVPPs) analysis at a regional scale. It is an RD^3&D activity of the proposed autonomous investment decision support system (IDSM). Weighted linear combination (WLC) method with rank sum weight method (RS), inverse or reciprocal weights method (RR), rank order centroid (ROC), and point allocation (PA) subjective weighting approaches are

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studied and analyzed in order to determine the weights of different criteria used in the model. Suitability analysis of PVPPs sites in Antalya, Burdur, and Isparta test regions in Turkey is performed and presented on ESRI ArcGIS 10.4.1. This land suitability analysis will contribute to making some useful recommendations for the preliminary assessment of new PVPPs and spatial planning at regional scale. It can also be used as verification process for existing PVPPs.

Materials and methods

Framework of PV farm suitability decision-making

A general decision-making procedure is specifically designed for transforming spatially defined data set into a common digital decision-making map in this RD^3&D experimental PVPPs selection MCDM model. The discrete steps are shortly as follows: (1) Determine criteria (evaluation/assessment): 14 criteria are selected as basic criteria with authors' common joint decision. They are grouped without any mathematical method under 5 main criteria but by perception and intuition of simple factors clustering approach in this study (Table 1). (2) Prepare maps for each evaluation criterion and its value ranges (Figs. 2, 3, 4, 5, 6, 7, and 8). (3) Eliminate unsuitable zones and present suitable zones. (4) Collect expert weight evaluations and calculate weights: Subjective weighting approaches need expert evaluations as inputs until modeling sufficient possibilistic or probabilistic approaches in accordance with the proposed autonomous IDSM. There are 5 single experts and 1 expert group in this study. Single experts make their own evaluations without any mentoring; however, expert group makes their evaluations as a common joint decision with the mentorship of a single expert among 5 single experts. (5) Apply MCDM: The current RD^3&D experimental MCDM model has 5 main criteria, 14 criteria, and 79 value ranges. WLC MCDM method is directly applied on ESRI ArcGIS 10.4.1 for desktop software. (6) Calculate PV solar suitability index (PVSSI) and produce PV land suitability digital maps. For four weighting approaches, all PV land suitability digital maps in 5 suitability classes (i.e., low suitability, high suitability) are produced in digital formats in this study. All PV power plants in operation, investment, and planning stages are planned to be presented in these digital maps. (7) Compare the results produced by four weighting approaches. (8) Discuss findings: Forward-looking and backward-looking analysis are made to validate, verify, and improve the proposed system and its RD^3&D studies.

Experimental application test study region

Antalya, Isparta, and Burdur provinces in Turkey, which are located on the southwest coast of the Anatolian Peninsula, are selected as the RD^3&D experimental application test study region, because of up-to-date information and data availability and richness (Fig. 1). The study region lies between 29°-33° East meridians 36°-39° North parallels. It is surrounded by Mersin, Karaman. and Konya in the East, the Mediterranean Sea in the South, Mugla, Denizli, and Afyon in the West, and Afyon in the North. The planimetric surface areas of Antalya, Isparta, and Burdur provinces are respectively 20,177 km^2, 8946 km^2, and 7175 km^2 so that the total surface area of the study region is 36,298 km^2.

The terrain of the study region is almost hilly with 0–70% slopes. The highest elevation is 3070 m above sea level. The study region is in the Mediterranean climatic region with characteristics such as hot in summers and warm/rainy in winters. The potential opportunities and activities of the agricultural and tourism industries are high, because of the geographical location, climate, and natural conditions and properties of the region, so that it is wise to expect high power demand increase in the long-term future.

Criteria definitions and explanations

Many different studies on how to find suitable sites for PVPPs in the literature have been reviewed to determine the parameters of this RD^3&D experimental application. Table 1 summarizes different criteria combinations in different GIS-MCDM integration publications that influence the selection of PVPPs' locations in various study regions. Fourteen criteria have been selected in this study in accordance with those previous publications.

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Table 1 Summary of GIS-MCDM PVPPs' site selection models in the literature

Authors	Methods*, **	Evaluation criteria	Study area
Sanchez-Lozano et al. (2015)	AHP, TOPSIS, ELECTRE	Agrological capacity; solar irradiation; average temperature; slope; aspect; plot areas; distance (villages, roads, substations, power lines)	Coast of the Region of Murcia, Spain
Al Garni and Awasthi (2017)	AHP	Solar irradiation; annual average temperature; slope; aspect; distance (urban areas; roads; power lines)	Arabian Peninsula, Saudi Arabia
Zoghi et al. (2017)	Fuzzy Logic, AHP	Land use; protected area; wetlands and water resource; elevation; slope; aspect; location (city, power line, transport network); sunshine hours; cloudy days; dusty days; solar radiation; rainy and snowy days; humidity	Isfahan, Iran
Hafeznia et al. (2017)	Fuzzy Logic, Boolean	Solar irradiation; average annual temperature; precipitation; slope; aspect; elevation; faults; road network; rivers and lakes; urban and rural areas; electric power transmission lines; mining activities; land use; environmental and socio-economic conservation areas	South Khorasan, Iran
Merrouni et al. (2018)	AHP	GHI; slope; distance (residential areas, road, and railway network, electricity grid, waterways, dams, groundwater)	Eastern Morocco
Yushchenko et al. (2018)	AHP	Solar irradiation; distance (electricity grid lines, roads, population density, settlements); protected areas	West Africa
Firozjaei et al. (2019)	OWA	Solar irradiation; slope; distance (road, cities); normalized difference vegetation index (NDVI)	Iran
This study	RR, RS, ROC, PA, WLC	(1) Electricity generation resource features (GHI, slope, aspect, elevation); (2) Essential features (land use, allocation and availability, distance from faults, ground conditions); (3) Obligatory features (distance from protected areas, distance from residential areas); (4) Infrastructural and complementary features (distance from power network, distance from rivers; distance from other water bodies); (5) Logistics features (distance from land transportation network, distance from railway transportation network)	Antalya-Burdur-Isparta Region, Turkey

**AHP* analytic hierarchy process, *ELECTRE* elimination and choice translating reality, Elimination Et Choix Traduisant la Realite, *OWA* ordered weighted average, *TOPSIS* technique for order preference by similarity to ideal solution

***WLC* weighted linear combination, *RS* rank sum weight method, *RR* inverse or reciprocal weights method, *ROC* rank order centroid, *PA* point allocation

Electricity generation resource features (C_1)

Global horizontal irradiance (GHI) (C_{11})

Solar irradiance is used to measure instantaneous peak power output performance of any solar power device (Gevorkian 2011). There are three important main components of solar radiation for solar power subjects: direct, diffused, and reflected (ground-reflected). They are presented in the datasets and respective digital, poster or printed maps as direct normal irradiation (DNI), diffuse horizontal irradiation (DHI), and global horizontal irradiation (GHI) (Maxwell 1987; Soulayman 2017; NREL 2019). GHI is taken into consideration in the PV

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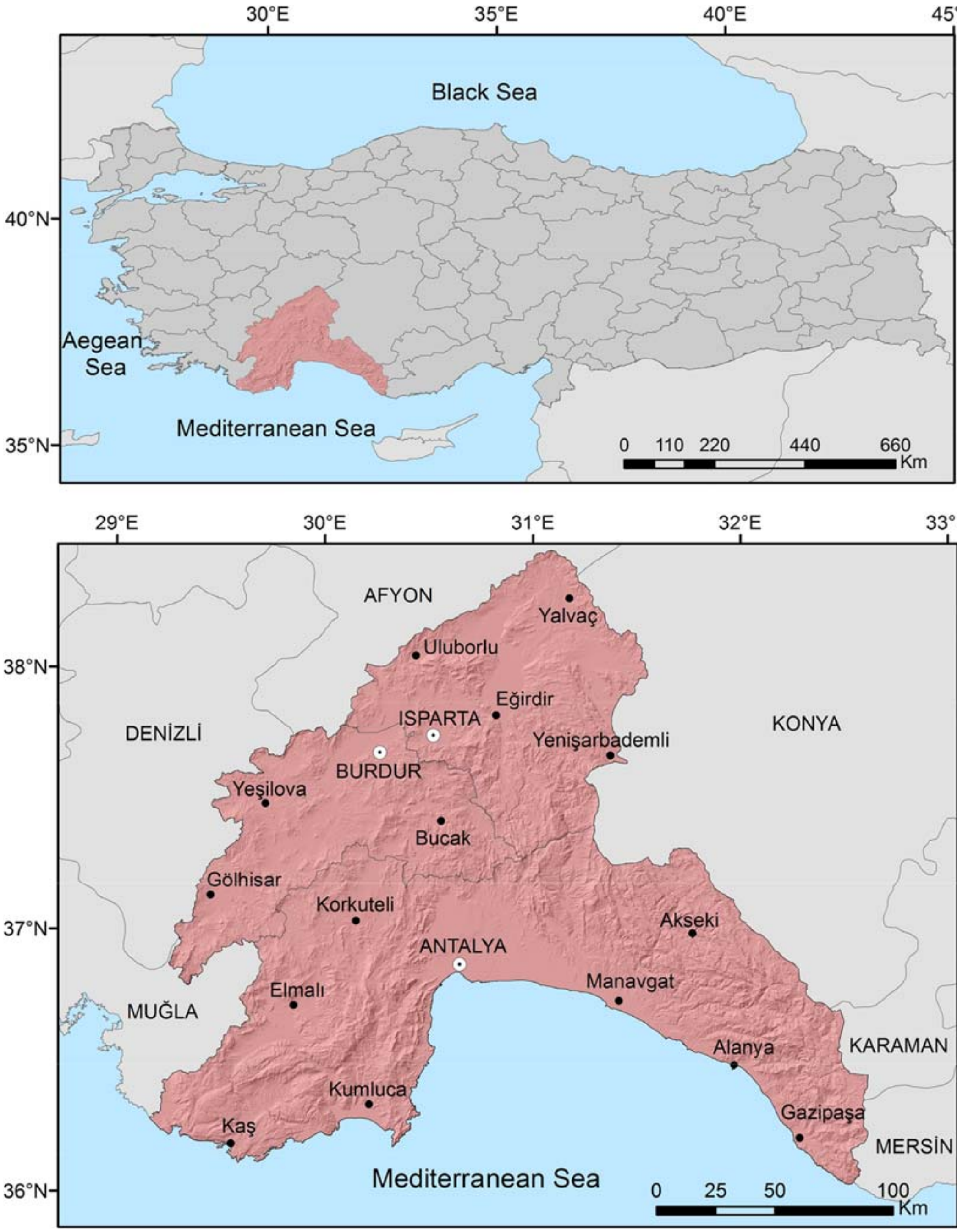

Fig. 1 Study region

technology and PVPPs. It is the total sunlight amount on the PV module (panel) surface (Saracoglu et al. 2018).

In short, GHI is modeled as an objective benefit criterion (more is better ↑ ↑). Global horizontal irradiation (GHI) (kWh/m^2) digital maps, data, and information for Turkey are provided from one of the reliable and trustworthy sources, Global Solar Atlas (WB 2019). Global Solar Atlas GHI (kWh/m^2) GIS

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raster (grid) data with a resolution (pixel size) 30 arcsec (nominally 1 km) in GeoTIFF and AAIGRID (Esri ASCII Grid) formats are downloaded on the official website. Figure 2a shows the value ranges and the reclassified GHI map.

Aspect (C_{12})

All solar technologies including PV technology depend on the sunlight. Hence, the Sun and its motions together with the Earth are very important. PV technology has several mounting and orientation options (e.g., fixed, tilted, 1-axis tracking, 2-axis tracking, azimuth tracking) to gain as much sunlight as possible (SG 2019). Accordingly, aspect (orientation) is one of the most important factors to maximize the power and energy yield of PV panels. Generally, PV panels have to be facing true south in Turkey, which is located in the Northern Hemisphere, in order to maximize the energy and power of PVPPs (Rimstar 2019). However, it should be noted that there are also several different orientations according to several different design aims and criteria (non-south oriented PV systems) (Velik 2013). In short, aspect is modeled as an objective cost criterion (less is better ↓ ↑).

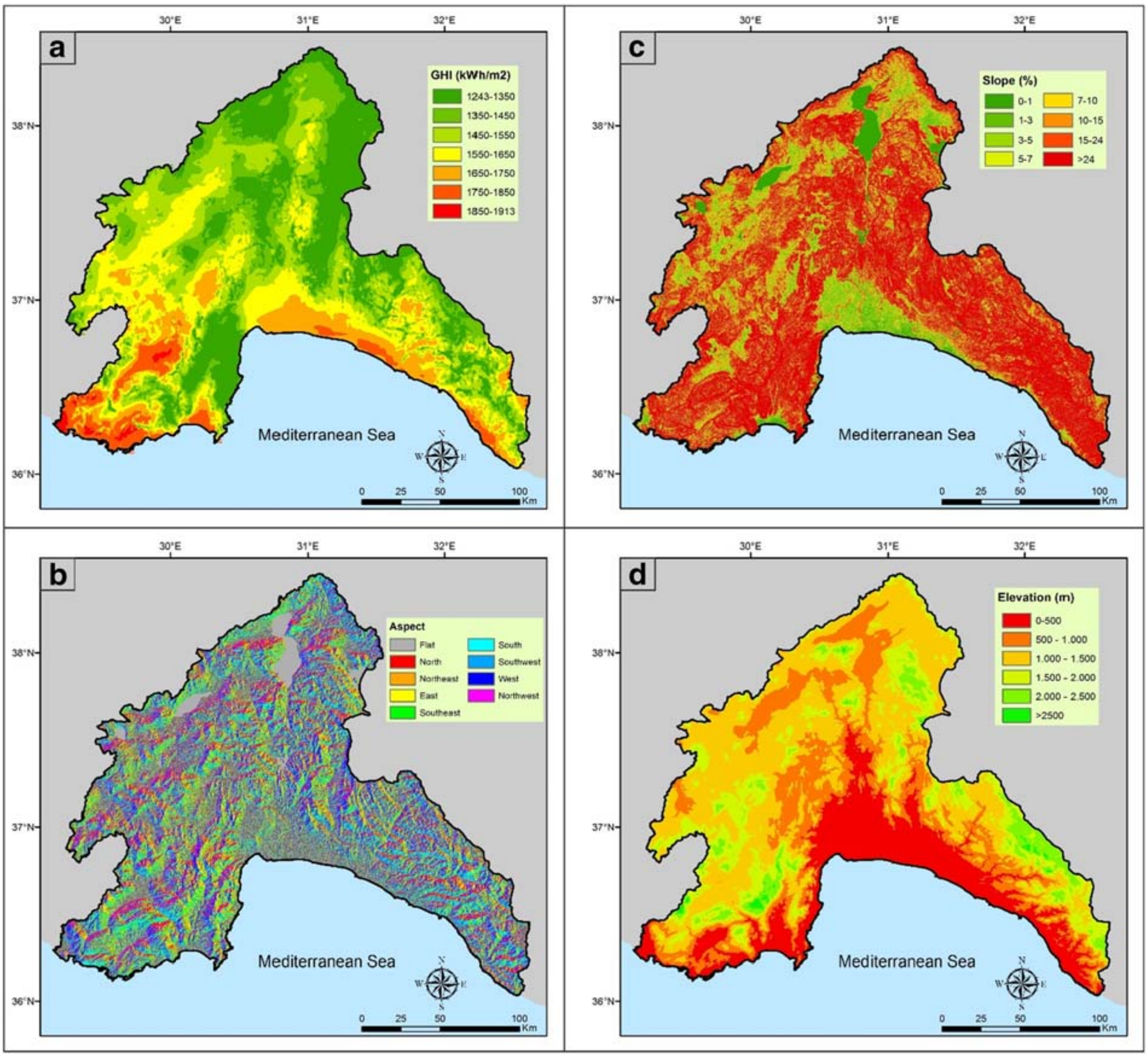

Fig. 2 Electricity generation resource features (**a** GHI, **b** aspect, **c** slope, **d** elevation)

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The least angular difference to the true south is the design objective of the current model. The digital terrain elevation data and maps (DTED-2) of Turkey with a resolution (grid cell) of 30 m × 30 m (1° × 1°) is obtained from one of the reliable and trustworthy sources, the General Directorate of Mapping (GDM 2019). DTED-2 is created from the contour lines which are digitized from 1:25000 scale standard topographic maps. Figure 2b shows the value ranges and the reclassified aspect map.

Slope (C_{13})

Slope is one of the most important factors in choosing the location of PVPPs, because of considerations like planning, design, engineering, procurement, and construction (DEPC/EPC), operation, and maintenance (O&M) easiness and their respective costs. Higher slope areas such as valleys and steep lands should be avoided, but differences in topographic conditions should be taken into consideration while determining a slope threshold value to get reasonable results. In short, the slope is modeled as an objective cost criterion (less is better ↓ ↑). The same DTED-2 digital data and maps of Turkey in aspect criterion are used also in this factor. Figure 2c shows the value ranges and the reclassified slope map.

Elevation (C_{14})

Elevation is one of the interesting and complex factors in PVPPs' location selection problems with respect to electricity (power/energy) generation and cost considerations in DEPC/EPC, and O&M stages. A few crucial examples of how elevation affects the PV technology in the generation perspective are as follows: GHI often increases with increasing elevation, because of the thickness of the Earth's atmosphere, cloud cover, water vapor, air pollution (i.e., dust, dirt, particles), aerosols, and similar (Piazena 1996; Ramirez and Munoz 2012; Reno et al. 2012; Sengupta 2016; Zoghi et al. 2017). In contrast, the temperature often decreases with increasing elevation in the troposphere (Hafeznia et al. 2017; CWB 2019). As a result, increase in elevation effects power/electricity generation positively. While there is a positive causal relation between elevation and generation (see temperature, efficiency, generation relation (Razak et al. 2016; King et al. 1997)), there is a negative causal relation between elevation and cost, due to transportation networks, power line networks, geology, and similar difficulties and problems. In short, the elevation is modeled as an objective benefit criterion (more is better ↑ ↑) in perspective of only generation, because difficulties and problems due to elevation are taken into account in other factors (e.g., transportation, powerline, geology). The same DTED-2 digital data and maps of Turkey in aspect and slope criteria are also used in this factor. Figure 2d shows the value ranges and the reclassified elevation map.

Essential features (C_2)

Land cover/use, allocation, and availability (C_{21})

It is a necessity to find and present suitable and unsuitable zones for VLPVPPs/PVPPs. In that sense, it is wise to use and adopt starting from the most common land cover classes of the biosphere to the least common ones from different inventories and databases on the World. The CORINE system (coordination of information on the environment) is one of those datasets. The main approach in this factor is to maximize the suitable zone assignments of VLPVPPs/PVPPs to the low-quality land covers like dump sites and use valuable land covers for human and animal needs such as olive groves and vineyards. The special applications for VLPVPPs/PVPPs like vegetation or vegetated zone selection for dust prevention actions like in Solar Star Projects have not taken into account in this study (Saracoglu 2018). In short, land use, allocation, and availability is modeled as a subjective benefit criterion (more is better ↑ ↑). Evaluations are made according to this modeling approach. A higher rank is better than a lower rank and a higher weight is better than a lower weight. Similarly, a lower rank is worse than a higher rank and a lower weight is worse than a higher weight. At first, categorical land use classes are grouped under 9 discrete categories (classes) and then converted into ranks and respective weights by expert subjective judgments. Which land use class is better than another one is gathered by that subjective evaluation and their

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ranks are sorted with subjective benefit criterion (more is better ↑ ↑) approach. The official 2012 Corine Land Cover (CLC) land cover map of Turkey is gathered from Copernicus (2019a).

CLC classes are divided into two sets as excluded and evaluated CLC classes (Copernicus 2019b). The excluded CLC classes are directly eliminated from Antalya, Isparta, and Burdur study area. They are directly selected from updated CLC illustrated nomenclature guidelines by common expert evaluation and decision. Figure 3 shows the value ranges and the reclassified land use map. Specific types of excluded and evaluated CLC classes are shown in Table 2.

Earthquake risks (distance from faults) (C_{22})

A site closer to a fault line is prone to a higher risk of an earthquake and consequent damage. It may pose potential or actual threats to all project activities in any DEPC/EPC, and O&M stages (Yousefi et al. 2018; Ohunakin and Saracoglu 2018). For this reason, it is very important to locate solar farms away from the faults. In short, distance from faults is modeled as an objective benefit criterion (more is better ↑ ↑). The fault lines specified in the active fault map of the General Directorate of Mineral Research and Exploration of Turkey in 1:250000 scale are used in this factor. Figure 4a shows the value ranges and the reclassified distance from faults map.

Ground conditions (geology/lithology) (C_{23})

Ground conditions are one of the fundamental issues for any structure. It compromises many conditions such as geology, hydrology, and soil that affect foundation conditions (BGS 2019). Although there are only a few heavy load and not very heavy load equipment (e.g., central inverters, administrative buildings) in any VLPVPPs/PVPPs, the overall constructability and supportability of equipment (support structures, mounting systems, and inverters) and buildings are always taken into consideration. In that sense, geology is one of the crucial issues and scientific research fields of ground conditions. Hence, the geology/lithology is a factor that should be taken into account when selecting suitable VLPVPPs/PVPPs sites. In short, ground conditions are modeled as a subjective benefit criterion (more is better

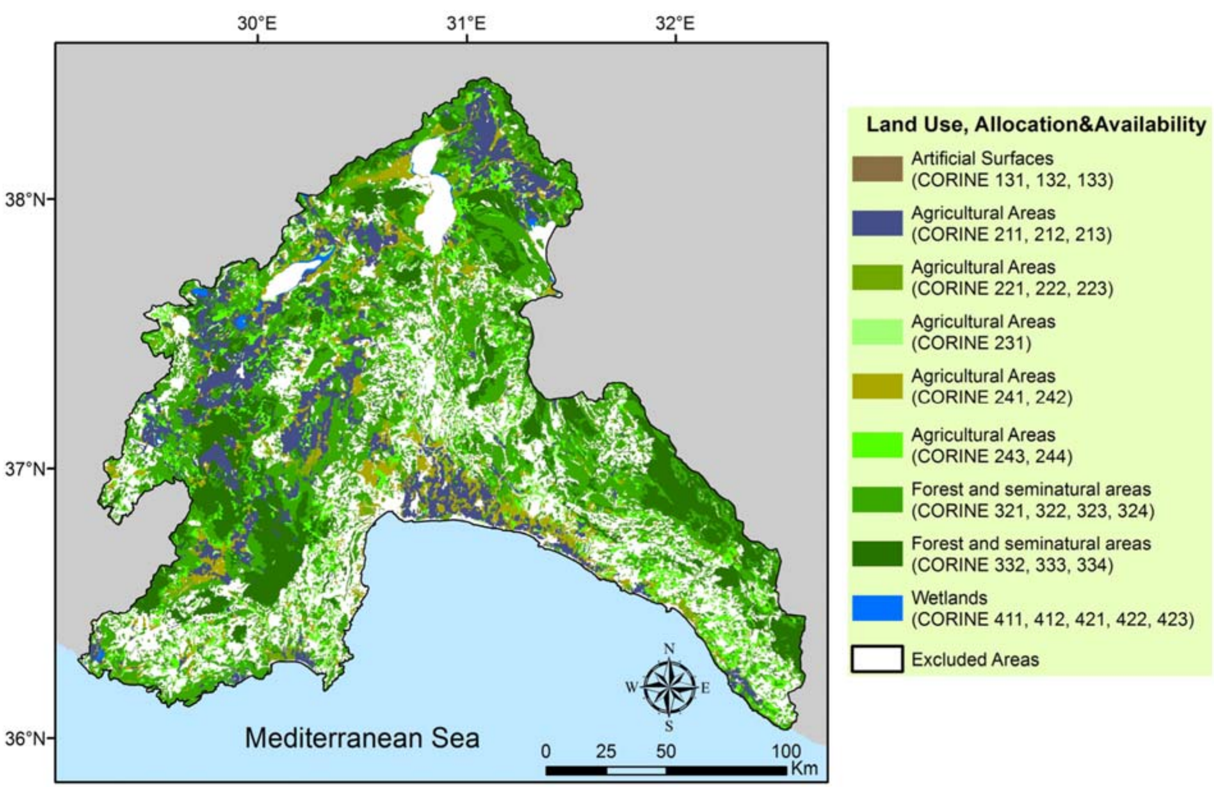

Fig. 3 Essential features (land cover/use, allocation, and availability)

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Table 2 Reclassification of CORINE Land Cover classes

Excluded CLC classes	Evaluated CLC classes
111 (continuous urban fabric); 112 (discontinuous urban fabric); 121 (industrial or commercial units); 122 (road and rail networks and associated land); 123 (port areas); 124 (airports); 141 (green urban areas); 142 (sport and leisure facilities); 311 (broad-leaved forest); 312 (coniferous forest); 313 (mixed forest); 331 (beaches, dunes and sand plains); 511 (water courses); 512 (water bodies); 521 (coastal lagoon); 522 (estuaries); 523 (sea and ocean)	131 (mineral extraction sites); 132 (dump sites); 133 (construction sites); 211 (non-irrigated arable land); 212 (permanently irrigated land); 213 (rice fields); 221 (vineyards); 222 (fruit trees and berry plantations); 223 (olive groves); 231 (pastures); 241 (annual crops associated with permanent crops); 242 (complex cultivation patterns); 243 (land principally occupied by agriculture with significant areas of natural vegetation); 244 (agro-forestry areas); 321 (natural grassland); 322 (moors and heathland); 323 (sclerophyllous vegetation); 324 (transitional woodlands shrub); 332 (bare rock); 333 (sparsely vegetated areas); 334 (burnt areas); 411 (inland marshes); 412 (peatbogs); 421 (salt marshes); 422 (salines); 423 (intertidal flats)

↑ ↑). Evaluations are made according to this modeling approach. A higher rank is better than a lower rank and a higher weight is better than a lower weight. Similarly, a lower rank is worse than a higher rank and a lower weight is worse than a higher weight. At first, ground conditions are grouped under 6 discrete categories (classes) and then converted into ranks and respective weights by expert subjective judgments. Which ground condition is better than another one is gathered by that subjective evaluation and their ranks are sorted with subjective benefit criterion (more is better) approach. The geology/lithology map is produced by digitizing the map of the General Directorate of Mineral Research and Exploration of Turkey on its Geoscience Map Viewer and Drawing Editor Version 2.9 (MTA 2019) in this factor. Figure 4b shows the value ranges and the reclassified geology/lithology map.

Obligatory features (C_3)

Distance from protected areas (C_{31})

Protected areas are crucial for conserving biodiversity, ecosystem, life, nature, heritage, and culture on the Earth. All RE power plants including VLPVPPs/PVPPs have to take into account protected areas not only for environmental or similar concerns (e.g., land and water contamination with Cadmium telluride (CdTe) and plastics) (NREL 2020) but also duration and cost of legal permissions, because of poor manual bureaucratic and procedural studies and activities (not good online systems). Hence, the protected areas should

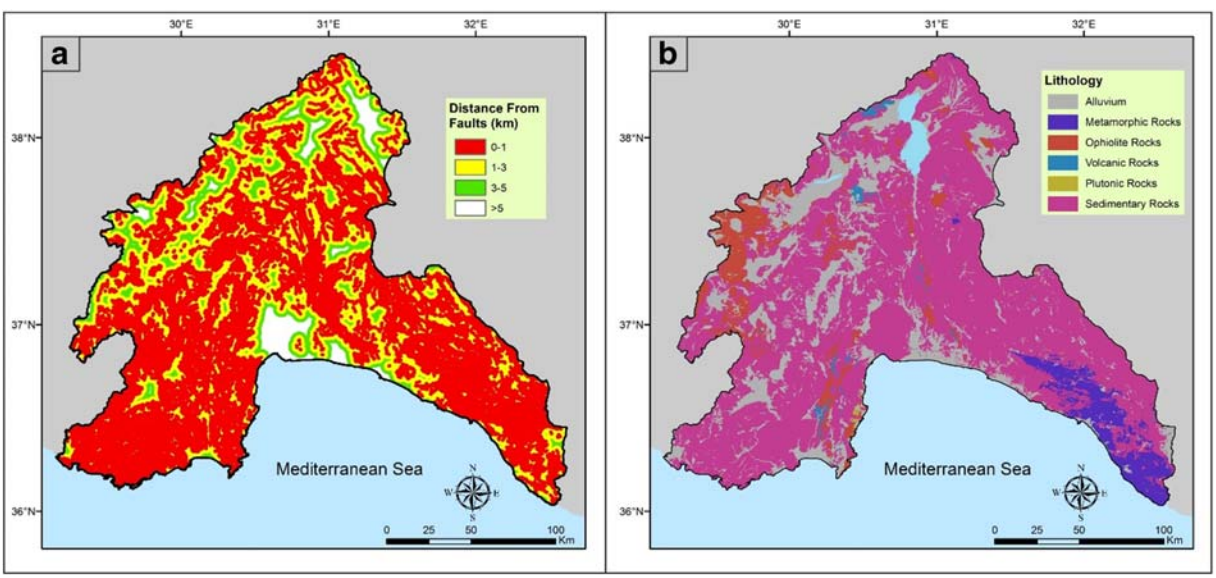

Fig. 4 Essential features (**a** distance from faults, **b** ground conditions (lithology))

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be taken into account during the selection of suitable VLPVPPs/PVPPs sites. The protected areas such as nature, archeological and historic sites, tourist areas, wildlife protection and development areas, national and natural parks, doline areas (Lamelas et al. 2008; Pueyo-Anchuela et al. 2010), turtle nesting area, and biologically important fields are directly classified as excluded areas. In short, distance from protected areas is modeled as an objective benefit criterion (more is better ↑ ↑). The protected areas map is produced by digitizing the 1/100.000 scale map of Antalya-Burdur-Isparta Environmental Layout Plan of Ministry of Environment and Urbanisation (MEU 2019) in this factor. Figure 5a shows the value ranges and the reclassified distance from protected areas map.

Distance from residential areas (C_{32})

Power and electricity consumption centers are probably the most important factor for power plants' location selection problems, because of several complex issues such as community attitude, transportation quality and cost, substation quality and cost, electric power transmission and distribution losses, transportation safety (e.g., air traffic safety in respect of blinding pilots) conditions in DEPC/EPC, and O&M stages. A few examples of those major consumption centers are metropolitan cities, very large towns, iron and steel plants, and large manufacturing and production plants. On one hand, power plants should be located as close as possible to the consumption centers to minimize the costs and maximize the electricity quality, and on the other hand, they should be placed as far as possible from the consumption centers especially city central areas to minimize negative effects of civilization on the power plants such as air pollution (i.e., dust, dirt, particles), accidents, theft, burglary, and sabotage; and also negative effects of power plants on the plant, animal and human lives such as health risks due to air and noise pollution. In short, distance from residential areas is modeled as an objective cost criterion (less is better ↓ ↑). The urban and metropolitan (residential) area as layer map is produced by digitizing the 1/100.000 scale map of Antalya-Burdur-Isparta Environmental Layout Plan of Ministry of Environment and Urbanisation (MEU 2019) in this factor. All urban, metropolitan, and rural residential/development areas are defined as excluded areas, and directly eliminated from study area. Figure 5b shows the value ranges and the reclassified distance from residential areas map.

Infrastructural and complementary features (C_4)

Distance from power network (C_{41})

Power network with all its components and units such as its substations, high voltage direct current (HVDC), and high voltage alternating current (HVAC) lines is one of

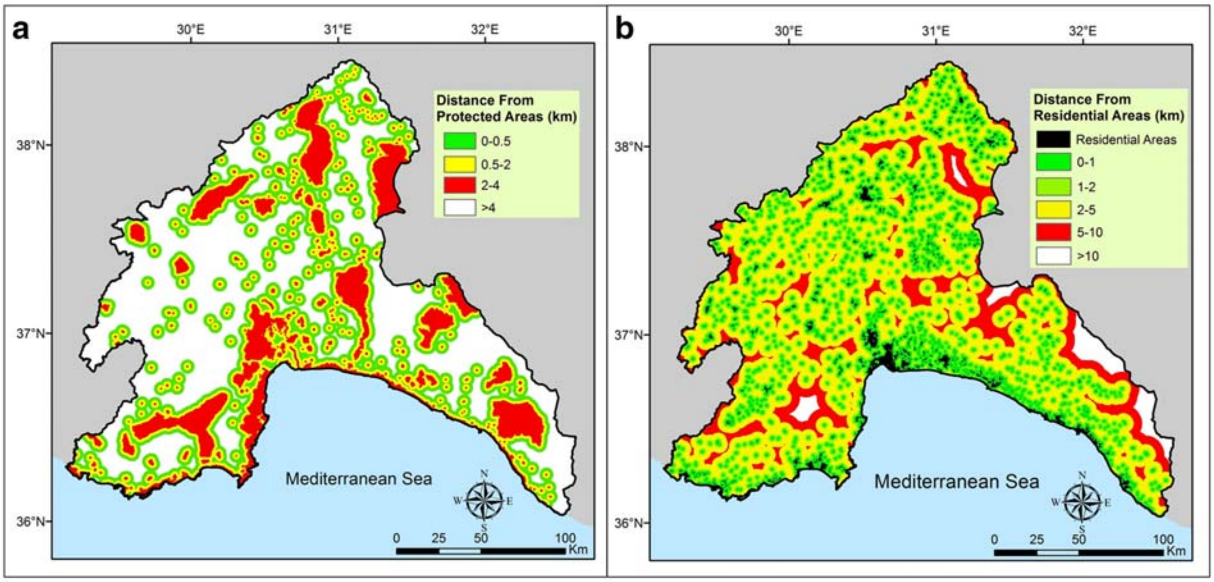

Fig. 5 Obligatory features (**a** distance from protected areas, **b** distance from residential areas)

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the most important criteria for power plants' location selection problems, because of several issues such as cost, electric power transmission and distribution losses, O&M, transportation, security, and accessibility in DEPC/EPC, and O&M stages (Saracoglu and de Simon Martin 2018; Ayodele et al. 2018). Hence, the power network is a factor that should be taken into account during the selection of suitable VLPVPPs/PVPPs sites. In short, distance from power network is modeled as an objective cost criterion (less is better ↓ ↑). The power network layer map is produced by digitizing the 1/100.000 scale map of Antalya-Burdur-Isparta Environmental Layout Plan of Ministry of Environment and Urbanization (MEU 2019) in this factor. Figure 6 shows the value ranges and the reclassified distance from the power network map.

Water resources (distance from rivers (C_{42}) and distance from other water bodies (C_{43}))

Generally, PVPPs consume water for cleaning modules, and domestic daily purposes (Merrouni et al. 2018). If PVPPs are designed with back or front water cooling systems, then they consume water for cooling modules too (Bahaidarah et al. 2013; Odeh and Behnia 2009; Dorobanţu et al. 2013; Moharram et al. 2013). Although water and its resources are very important factors for all power plants' location selection problems including the PVPPs', very few studies in the literature take into account this criterion (Aly et al. 2017; Merrouni et al. 2018; Saracoglu et al. 2018). Hence, the water resource is a factor that should be taken into account during the selection of suitable VLPVPPs/PVPPs sites. In short, water resources are modeled as an objective cost criterion (less is better ↓ ↑). The water resources are split into two criteria: distance from rivers (km), distance from other water bodies (km) (e.g., natural lakes, artificial lakes, and dams). The distance from rivers and the distance from other water bodies layer map are produced by digitizing the 1/100.000 scale map of Antalya-Burdur-Isparta Environmental Layout Plan of Ministry of Environment and Urbanisation (MEU 2019) in this factor. A 50-m buffer zone from all water bodies such as rivers, natural lakes, artificial lakes, or dams is defined as excluded areas, and directly eliminated.

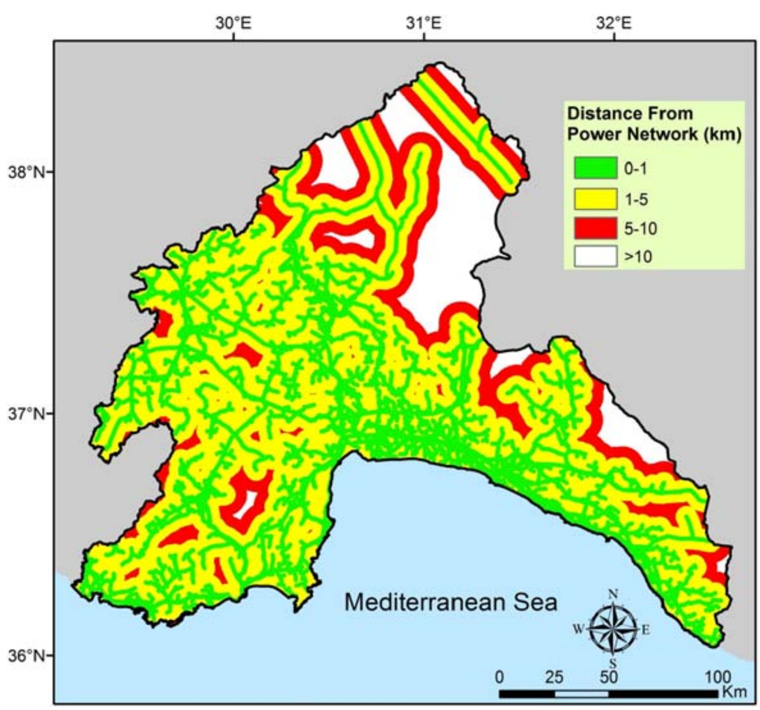

Fig. 6 Infrastructural and complementary features (distance from power network)

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Figure 7a and b show respectively the value ranges and the reclassified distance from rivers map and other water bodies map.

Logistics/transportation network features (C_5)

Distance from land transportation network (C_{51}), and distance from railway transportation network (C_{52})

All transportation modes (e.g., road and rail) are very important for PVPPs, because of several complex issues such as equipments, components, materials, and human logistics in DEPC/EPC, and O&M stages. Hence, the transportation network is a factor that should be taken into account during the selection of suitable VLPVPPs/PVPPs sites. When traffic safety (e.g., pollution, accidents, theft, sabotage, terrorism, health), right of way width has been taken into consideration, for first class highway 80 m, for second class highway 40 m corridor has to be utilized. Similarly, a 50-m buffer zone along all railways is defined as a safety corridor, and so as excluded areas for the railway transportation network, and directly eliminated from this study area. In short, distance from land transportation network and railway transportation network are modeled as an objective cost criterion (less is better ↓ ↑). The distance from land transportation network (km) and the distance from railway transportation network (km) layer map are produced by digitizing the 1/100.000 scale map of Antalya-Burdur-Isparta Environmental Layout Plan of Ministry of Environment and Urbanisation (MEU 2019) in this factor. Figure 8a and b show respectively the value ranges and the reclassified distance from land and railway transportation networks map.

Theoretical background of methods

Definition and explanation of weighting methods (rank sum weight, inverse or reciprocal weights, rank order centroid, point allocation)

There are many objective and subjective weighting methods (OWM, SWM) in the literature that provide a weight estimation of a criterion or alternative relative to another one (performance) by using some equations (Stillwell et al. 1981; Kirkwood and Sarin 1985; Barron and Barrett 1996a; Barron and Barrett 1996b; Anagnostopoulos et al. 2010; Ahn 2011; Roszkowska 2013; Mateos et al. 2014; Zardari et al. 2015).

Four weighting methods are investigated in this RD^3&D study. These are rank sum weight method (RS), inverse or reciprocal weights method (RR), rank order centroid (ROC), and point allocation (PA). RS, RR, ROC, and PA methods are all SWMs, because of their dependence on expert subjective judgments (i.e., Roszkowska 2013; Zardari et al. 2015) (Table 3). RS,

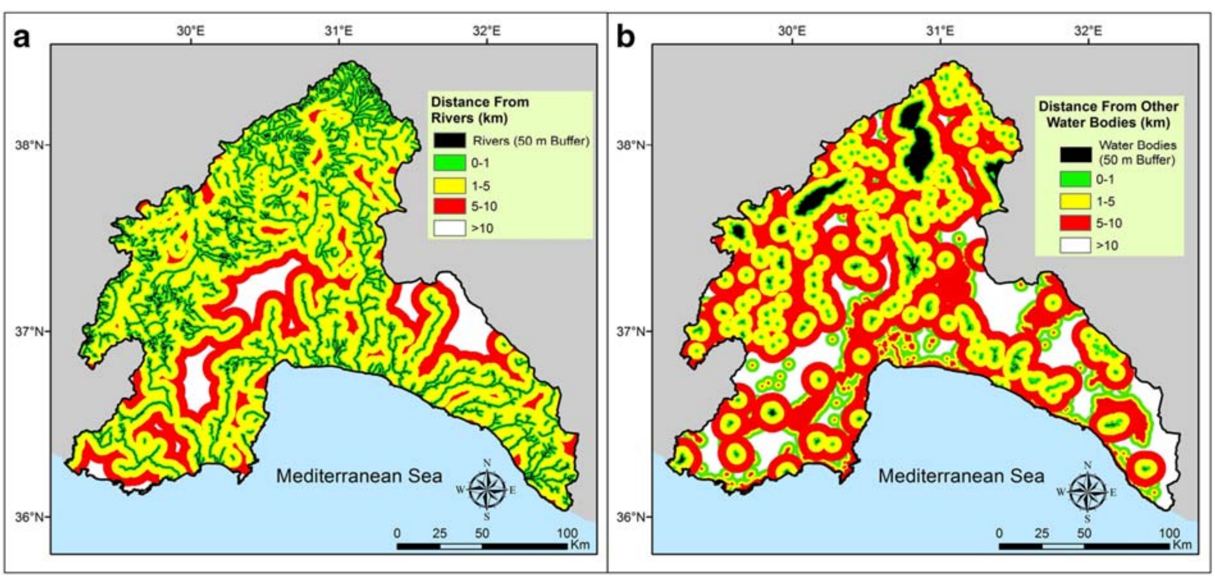

Fig. 7 Infrastructural and complementary features, (**a** distance from rivers, **b** distance from other water bodies)

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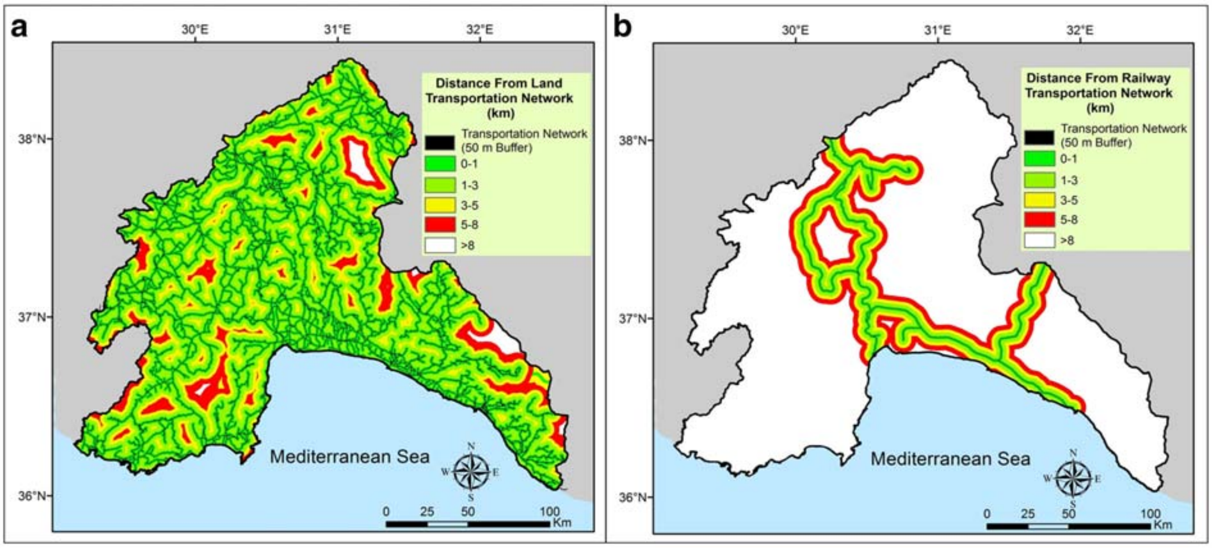

Fig. 8 Logistics/transportation network features, (**a** distance from land transportation network, **b** distance from railway transportation network)

RR, and ROC methods are all ranking methods. On the contrary, the PA method is a direct weighting method. Hence, two different SWMs are studied during this RD^3&D activity. The strengths of ranking methods (RS, RR, and ROC) are their reliability, easiness, and ability to use ordinal information (Roszkowska 2013). The weaknesses of ranking methods are their dependency on the total number of criteria, alternative (limitation), or range slices, expert perception and biases (Zardari et al. 2015). In general, these methods determine the relative weights in two steps as follows: (i) rank order criteria, alternative (limitation), or range slices according to their importance, (ii) weighting criteria, alternative (limitation), or range slices from their rank orders by one of the rank order weighting formulas (Roszkowska 2013). Commonly used ranking methods in the literature are RS, RR by Stillwell et al. (1981), and ROC methods Barron and Barrett (1996b).

RS calculates the weights by division normalization of the individual ranks by the sum of the ranks. RR normalizes the reciprocal of the ranks by the sum of the reciprocals. ROC estimates the weights by minimizing the maximum error of each weight with respect to the centroid of all possible weights (Roszkowska 2013). ROC is presented as a very stable method, especially when there are more criteria, because of less error for ranked criteria (Barron and Barrett 1996a; Roszkowska 2013). ROC and RR give more importance to the best rank orders, but RS emphasizes all at the same level. When ROC and RR are compared with each other, RR is insensitive to the worst rank orders than ROC (Mateos et al. 2014). Finally, the weight difference between the weights of the most important criterion and the least important criterion in ROC is the largest among RS, RR, and ROC, while there is a linearly reducing relation from the best criterion to the worst criterion in RS, and the weight difference between the weight of the first most important criterion and the second most important criterion is aggressively large, but gets flattered with the following descending criteria in RR (Roszkowska 2013).

RS, RR, and ROC do as simple conceptual description “more discussion of relative strengths and weaknesses of each weighting method” and “method would be most appropriate given different initial conditions”. Barron and Barrett 1996a, 1996b) showed that the ROC weights are superior to the other approximate weights by simulation analysis where the decision quality is measured by hit ratio and value losses with respect to various combinations of number of alternatives, number of attributes, and four different distributions from which the attribute values are generated.

The strengths of PA are its popularity with its numerical judgments, easiness, and ability to allocate criteria weights directly and normalization (Zardari et al. 2015). The weaknesses of it are its dependency on the fixed scale, imprecision, expert perception, and biases

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Table 3 Equations of weighting methods (Roszkowska 2013; Mateos et al. 2014; Sureeyatanapas 2016)

Method	Equation
Rank sum weights (RS)	$\forall$ criteria $w_j(RS) = \frac{n-r_j+1}{\sum_{k=1}^{n} n-r_k+1} = \frac{2(n+1-r_j)}{n(n+1)}$, where $j = 1, 2, \ldots, n$
Rank reciprocal weights (RR)	$\forall$ criteria $w_j(RR) = \frac{1/r_j}{\sum_{k=1}^{n} 1/r_k}$, where $j = 1, 2, \ldots, n$
Rank order centroid weights (ROC)	$\forall$ criteria $w_j(ROC) = \frac{1}{n}\sum_{k=j}^{n}\frac{1}{r_k}$, where $j = 1, 2, \ldots, n$

$\forall$ methods $0 \le w_j \le 1 \wedge \sum_{j=1}^{n} w_j = 1$

n: number of prioritized (ranked) criteria or alternative (limitation), $n \in \mathbb{N}^+$
$i \wedge j$: each criterion (criterion) or alternative (limitation), $i \wedge j \in \mathbb{N}^+$
w_j: numerical weight of j^{th} criterion (numerical weight of criterion j) or alternative (limitation), $r_j \in \mathbb{R}^+$
r_j: rank of j^{th} criterion (rank of criterion j) or alternative (limitation), $r_j \in \mathbb{N}^+$

(Bottomley and Doyle 2013; Zardari et al. 2015). In PA, experts often evaluate factors and alternatives with a fixed 100 points scale according to their importance, so that PA is also presented as a variant of direct rating (DR) method that typically has a fixed 0–10 scale in the literature (Bottomley and Doyle 2013). It should be noted that many analysts present the unfixed total number of points in their experiments and leave the scale decision to the experts; however, this approach has its own difficulties such as adjusting scaling and normalization. Although there are many academic discussions in the literature for which method (PA or DR) is more valid and reliable, the general conclusion for their findings is DR's linear relation between rank and numerical value, but PA's curvilinear relation between rank and value (Doyle et al. 1997; Doyle 1999; Bottomley and Doyle 2013; Bottomley and Doyle 2013; Zardari et al. 2015). Hence, PA is preferred to be investigated first in this RD^3&D study.

Multi-criteria decision-making methods definitions and explanations (weighted linear combination)

In the assessment of land suitability, it is necessary to standardize different scale criteria by bringing them together or to be converted into a common conformity value. WLC is an analytical method that can be used when multiple attributes must be taken into consideration, for example, in suitability modeling or site selection. Every attribute that is considered is called a criterion. Each criterion is assigned a weight based on its importance. The criteria are represented spatially by single-factor maps or layers, and the result is a multi-attribute map with the final score. The higher the score is the more suitable the area (Blachowski 2015). The combination of raster layers resulting from ranked and reclassified set of evaluation criteria is performed using the WLC in a GIS environment. The WLC method corresponds to the weighted overlay tool from ArcGIS (Doorga et al. 2019). Equation 1 was used to combine evaluation criteria by WLC method:

$$PVSSI_i = \sum_{j=1}^{n} W_j x_{ij} \quad (1)$$

Where $PVSSI_i$ is the photovoltaic solar suitability index for cell i, W_j is the relative importance weight of criteria j, x_{ij} is the standardized score of cell i for criteria j, and n is the total number of criteria (Malczewski 2000).

Results and discussion

Weighting calculations and results (rank sum weight, inverse or reciprocal weights, rank order centroid, point allocation)

An expert pool with 5 single experts and 1 expert group, which will evolve into an expert pool in the proposed system, are built during this RD^3&D study. Three authors of this paper are also single experts of this RD^3&D study. The other 2 single experts are from the General Directorate of Highways and 1 expert group is a direct

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PV investor that has their own PV power plants. Single experts make their own evaluations without any mentoring; however, the expert group makes their evaluations as a common joint decision with an author's mentorship. Moreover, an author also helps 2 non-author single experts during their evaluations. Each expert makes 196 evaluations in this study so that totally there are 1176 evaluations. All experts have the same expert weights; hence, their decision affects as same (weight of expert i to n is 1/6 (0.16666666667)).

RS, RR, and ROC findings are shortly as follows. 1st expert ranks the main criteria as 1st (electricity generation resource), 2nd (essential features), 3rd (infrastructural and complementary features), 4th (logistics features: transportation infrastructure), and 5th (obligatory features). 2nd expert has a different point of view with an evaluation of 1st (electricity generation resource), 2nd (essential features), 3rd (obligatory features), 4th (infrastructural and complementary features), and 5th (logistics features). They have common views in 1st and 2nd ranks, but different decisions in other factors. 3rd expert has a common view with 1st expert. 4th expert's opinions differ only in 3rd (logistics features), and 4th (infrastructural and complementary features) with 1st expert. 4th expert's opinions differ only in 4th (obligatory features), and 5th (logistics features) with 1st expert. 3rd expert has a common view with 1st expert. As a result, all experts rank electricity generation resource at 1st rank and essential features as 2nd rank. When electricity generation resource factor is studied in detail, it is realized that all experts have a common view of 1st (global horizontal irradiation (GHI)), 2nd (aspect), 3rd (slope), and 4th (elevation). Actually, this is not a surprise, but it is expected. When GHI criterion and its value ranges are studied in detail, it is understood that all experts have a common view of 1st (1850–1913), 2nd (1750–1850), 3rd (1650–1750), 4th (1550–1650), 5th (1450–1550), 6th (1350–1450), and 7th (1243–1350). When aspect criterion and its value ranges are studied in detail, it is observed that all experts have common views for value ranges as 1st (South), 4th (West), 5th (East), 6th (Northwest), 7th (Northeast), 8th (North), and 9th (Flat). Besides, 5 experts have a common view of 2nd (Southwest), and 3rd (Southeast), but 1 expert (2nd expert) has different opinions in these value ranges as 2nd (Southeast), and 3rd (Southwest). In brief, experts have many common evaluations; however, they also have some different evaluations too.

PA findings are shortly as follows. There is not any same direct weight evaluation in the main criteria, so their descriptive statistics presentation is difficult. The descriptive statistics can be presented in ranges of 100 points scale. For instance, electricity generation resource criterion gets the highest point weights between 35 and 50 (35–50), essential features (25–34), obligatory features (5–15), infrastructural and complementary features (7–15), and logistics features (5–12).

These PA evaluations are relevant and consistent with RS, RR, and ROC evaluations. Furthermore, there is more space for appointing numerical weights representing experts' decisions. For instance, 2nd expert is different in RS, RR, and ROC of these main criteria, but may be indifferent in PA as presented with the current observations of obligatory features (3rd, 15), and infrastructural and complementary features (4th, 15). It should be noted that experts observe the evaluation difficulty in PA too.

These findings for method comparisons are in compliance with the literature (Stillwell et al. 1981; Kirkwood and Sarin 1985; Barron and Barrett 1996a; Barron and Barrett 1996b; Anagnostopoulos et al. 2010; Ahn 2011; Roszkowska 2013; Mateos et al. 2014; Zardari et al. 2015).

RS, RR, ROC, and PA weight calculations are made one by one in a simple manner with their respective formulas on the spreadsheets of Microsoft Excel. RS, RR, and ROC weights are based on their own equations (Table 3). There is no need for normalization in those calculations, but there is a simple normalization step by the division of direct weights to 100 at PA. The mean weights are also presented in Table 4 and Appendix Table 7. It is observed that electricity generation resource and essential criteria get the same values in RS, RR, and ROC; however, other factors have different values in those methods (Table 4 and Appendix Table 7). The summary of findings is presented in the Table 4. According to the results of all methods, GHI, aspect, land use, distance from land transportation network, and distance from power network are the dominant criteria.

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Table 4 The weights and ranks of main and sub-criteria used in the GIS model

Main criteria	W_{RS}	W_{RR}	W_{ROC}	W_{PA}	Sub-criteria	W_{RS} (rank)	W_{RR} (rank)	W_{ROC} (rank)	W_{PA} (rank)
Electricity generation resource features	0.333	0.438	0.457	0.425	Global horizontal irradiation	0.132 (2)	0.210 (1)	0.237 (1)	0.185 (2)
					Aspect	0.100 (3)	0.105 (3)	0.124 (3)	0.126 (3)
					Slope	0.067 (7)	0.070 (5)	0.067 (6)	0.076 (4)
					Elevation	0.033 (13)	0.053 (8)	0.029 (12)	0.039 (8)
Essential features	0.267	0.219	0.257	0.295	Land use, allocation and availability	0.134 (1)	0.119 (2)	0.157 (2)	0.189 (1)
					Distance from faults	0.052 (10)	0.043 (9)	0.036 (9)	0.039 (8)
					Ground conditions	0.082 (6)	0.057 (7)	0.064 (7)	0.066 (6)
Obligatory features	0.100	0.101	0.067	0.087	Distance from protected areas	0.039 (12)	0.039 (10)	0.023 (11)	0.029 (9)
					Distance from residential areas	0.061 (8)	0.062 (6)	0.045 (8)	0.058 (7)
Infrastructural and complementary features	0.167	0.128	0.123	0.103	Distance from power network	0.084 (5)	0.070 (5)	0.075 (4)	0.074 (5)
					Distance from rivers	0.028 (14)	0.023 (13)	0.014 (13)	0.013 (12)
					Distance from other water bodies	0.056 (9)	0.035 (12)	0.034 (10)	0.016 (11)
Logistics features	0.133	0.114	0.096	0.090	Distance from land transportation network	0.089 (4)	0.076 (4)	0.072 (5)	0.066 (6)
					Distance from railway transportation network	0.043 (11)	0.038 (11)	0.023 (11)	0.024 (10)

Suitability maps of experimental application test study area

The final result suitability map of the GIS-based MCDM analysis (the weighted overlay tool in ArcGIS) is presented in Fig. 9. Suitable sites of the study region are graded between high and low potential. After removal of the exclusion areas for PVPPs, the final result maps of the study region are divided 5 suitability levels by standard deviation method, very highly suitable, highly suitable, moderately suitable, low suitable, and very low suitable. Percentages of the evaluation results are given in Table 5.

The study region is very rich especially in terms of natural and artificial lakes and water resources. There are many archeological and cultural heritage sites (Patara, Myra, Aspendos, Side, Rhodiapolis etc.) in the study region. The frequency of dense forest areas in the middle and high slope areas, the density of rural and urban settlements in low slope areas, especially the tourism areas and activities in the Antalya coastline are other factors limiting the suitability of PVPPs.

According to solar suitability map of all approaches, the results show that Korkuteli and Elmalı districts and coastal sections (e.g., Kumluca, Manavgat, Alanya) of Antalya province are the most suitable zones for the installation of photovoltaic farms. The results indicate that Yalvaç district and city center of Isparta province are the most suitable zones. In addition, Gölhisar and Yeşilova districts and city center of Burdur province are the most suitable. All suitable zones can be utilized as PV farms that constitute the infrastructure of sustainable management of renewable energy resources.

The correlation matrix shows the values of the spatial correlation coefficients that depict the relationship between two maps (Fig. 10). In the case of a set of raster maps, the correlation matrix presents the cell values from one raster map as they relate to the cell values of another raster map. Correlation between methods is calculated from every raster cell and finds the differences between cell values. So, deviation of cell value can be calculated and we can compare different methods results like similar or not. The correlation between the two maps is a measure of dependency between the maps. It is the ratio of the covariance between the two maps divided by the product of their standard deviations. Because it is a ratio, it is a unitless number. The Eq. 2 to calculate the correlation is as follows (Loomes 1988; Beecham and Piantadosi 2015):

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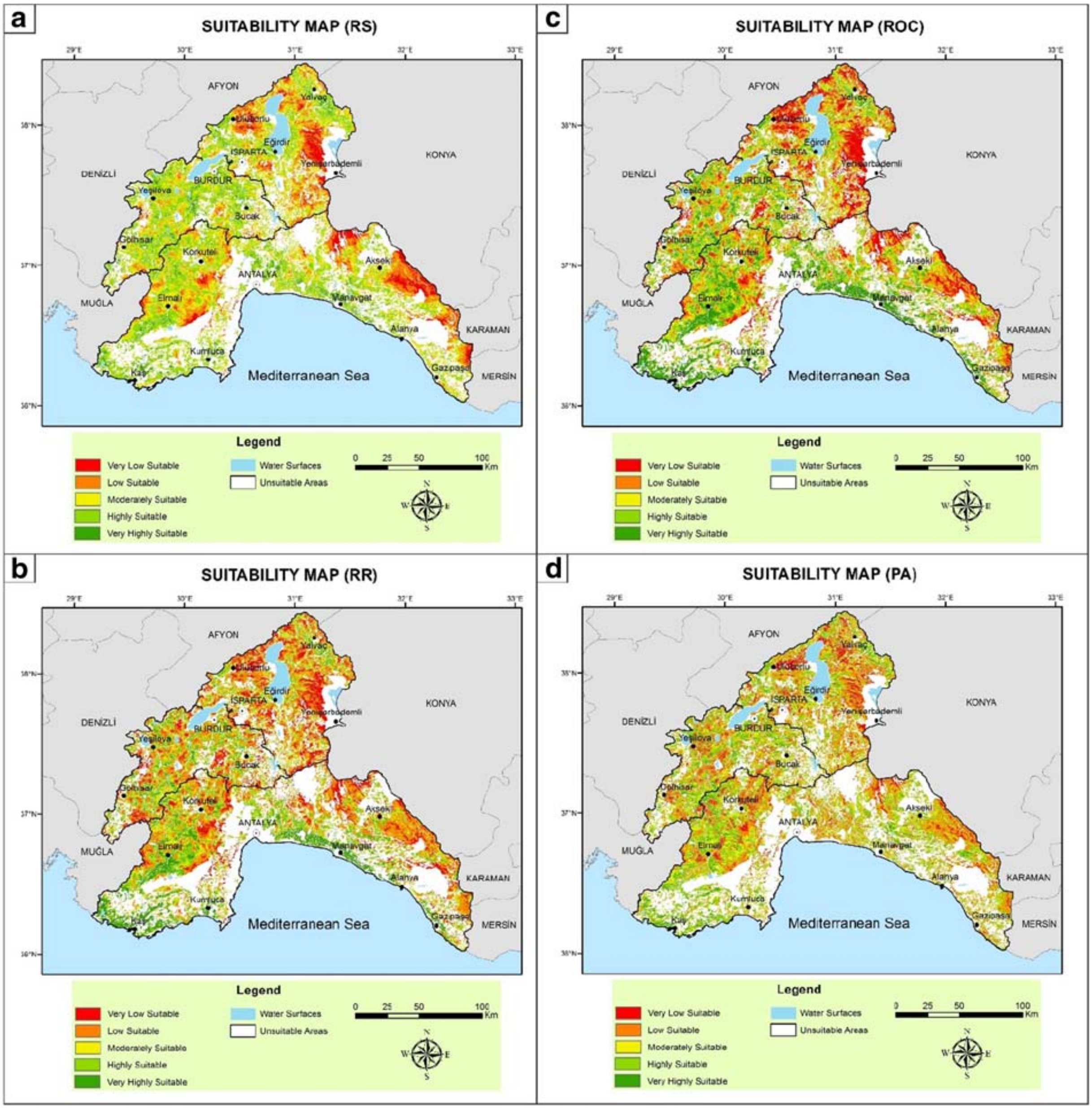

Fig. 9 Solar suitability map (**a** rank sum method, **b** rank reciprocal method, **c** rank order centroid, **d** point allocation method)

Table 5 The percentages of evaluation results

Suitability index	RS (%)	RR (%)	ROC (%)	PA (%)
Unsuitable	38.48	38.48	38.48	38.48
Very low suitable	3.32	8.00	8.10	5.51
Low suitable	13.11	20.57	14.66	17.10
Moderately suitable	19.77	12.37	13.12	16.35
Highly suitable	23.26	13.44	16.42	16.98
Very highly suitable	2.07	7.13	9.22	5.58

$$\mathrm{Corr}_{ij} = \frac{\mathrm{Cov}_{ij}}{\delta_i \delta_j} \tag{2}$$

where, Cov_{ij} is the covariance; δ_i, δ_j are the standart deviations of dataset i and j, respectively.

In order to interpret the analysis results of this study, the common, conceptual, and specific findings and of several studies presented in the literature about weighting approaches have been

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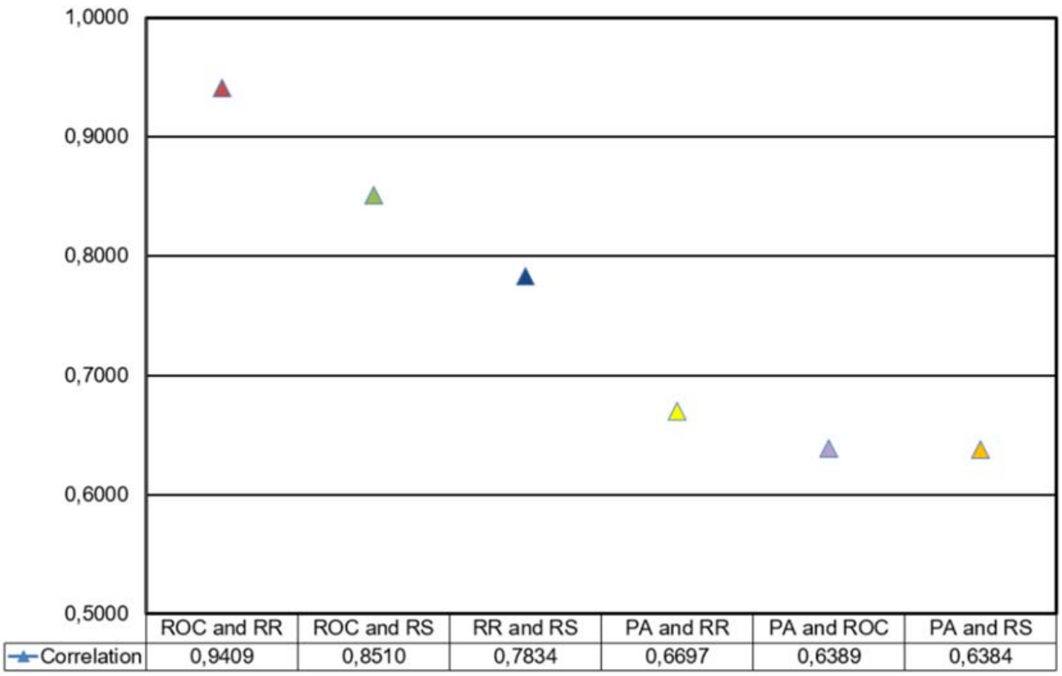

Fig. 10 Correlation values between methods

explained and evaluated in the following sentences. Similarities between RS, RR, ROC, and PA methods are presented such RS-RR: 0.7834, RS-ROC: 0.8510, and RS-PA: 0.6384 with covariance and correlation analysis. The analysis results indicate that there are more similar outcomes between RR and ROC approaches compared to other binary comparisons, because RR and ROC give more importance to the best rank orders. When ROC and RR are compared with each other, RR is insensitive to the worst rank orders than ROC (Mateos et al. 2014). There are partially similar outcomes between RS-RR and RS-ROC approaches, because there is a linearly reducing relation from the best criterion to the worst criterion in RS, and the weight difference between the weight of the first most important criterion and the second most important criterion is aggressively large (Roszkowska 2013). On the one hand, a low correlation was calculated between PA and other approaches, because the PA method is a direct weighting method. The advantages of PA are easiness, and ability to allocate criteria weights directly and normalization (Zardari et al. 2015). However, the weights calculated are dependent on its dependency on the fixed scale, imprecision, expert perception, and biases (Bottomley and Doyle 2013; Zardari et al. 2015). Results obtained do not mean that one approach is always more meaningful and accurate than the other approach. The accuracy depends on the ideas and intuition of decision makers or experts regarding the relative importance of criteria or the distribution of actual weights (Sureeyatanapas 2016).

Consensus and performance verification and validation of the experimental model

The experimental model is tested by some real-world PV investments in this RD^3&D stage with a basic site comparison approach. There are only 7 PV power plants in this analysis in several different investment stages. The titles and preliminary license or license numbers of these projects are not presented in this paper, because their investment stages are not known exactly. When the applications for the licenses and Environmental Impact Assessment (EIA) reports of power plants are handed over to the governmental organizations, all technical and cost data and information can

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Table 6 Test analysis on the test sites

PVPP[1]	1	2	3	4	5	6	7
SF[2]							
License application*	Terminated	Granted	Terminated	Terminated	Granted	Terminated	Granted
EIA[3,*]	Granted	Granted	Granted	Granted	Granted	Granted	Granted
Capacity[4,*]	23.40	20.00	18.61	18.00	10.39	6.00	5.60
Energy[5,*]	46,736,532	40,000,000	38,000,000	36,000,000	20,751,739	11,983,680	11,184,768
Capacity factor[6,**]	22.8	22.8	23.3	22.8	22.8	22.8	22.8
Land use[7,*]	370,687	410,300	328,746	360,000	207,000	116,159	111,370
Energy/land use[8,**]	126.10	97.50	115.60	100.00	100.20	103.20	100.40
Cost[9,**]	112,391,632	65,580,000	84,452,500	88,000,000	50,581,269	21,024,720	23,500,000
Cost/capacity[10,**]	4803	3279	4538	4889	4868	3504	4196
Cost/energy[11,**]	2.40	1.64	2.22	2.44	2.44	1.75	2.10
Methods							
RS	Highly suitable	Highly suitable	Moderately suitable	Highly suitable	Highly suitable	Highly suitable	Highly suitable
RR	Very highly suitable	Highly suitable	Low suitable	Moderately suitable	Moderately suitable	Moderately suitable	Very highly suitable
ROC	Very highly suitable	Very highly suitable	Moderately suitable	Moderately suitable	Highly suitable	Highly suitable	Very highly suitable
PA	Moderately suitable	Highly suitable	Moderately suitable	Moderately suitable	Very highly suitable	Highly suitable	Moderately suitable
SF[2]							
Energy/land use[8,**]	1	7	2	6	5	3	4
Cost/capacity[10,**]	5	1	4	7	6	2	3
Cost/energy[11,**]	5	1	4	7	6	2	3
Methods							
RS	1	1	2	1	1	1	1
RR	1	2	4	3	3	3	1
ROC	1	1	3	3	2	2	1
PA	3	2	3	3	1	2	3

[1] *PVPP* solar photovoltaic power plants

[2] *SF* success factors

[3] *EIA* environmental impact assessment

[4] Installed capacity (MW_e), peak installed power (MW_p)

[5] Expected annual energy (year 1) (kWh)

[6] Expected capacity factor (year 1) (%)

[7] Land use (m^2)

[8] Expected annual energy/land use (kWh/m^2)

[9] Project cost (Turkish Lira: TL)

[10] Project cost/capacity (peak installed power (kW_p)) (TL/kWe)

[11] Project cost/energy (TL/kWh)

*Data and information from open sources

**Calculated in this study

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be presented publically in an organized manner. However, all valuable data and information for this analysis can be gathered in this section (Table 6). There are several success factors for this analysis. Some of them are license application, EIA, expected capacity factor, cost/capacity, and cost/energy. The data and information for license application and EIA are not decisive and distinguishing for this analysis, because all of them have granted their EIA and the termination of their licenses are not exactly known in this RD^3 period. Hence, the best decisive and distinguishing success factors for the current study are expected capacity factor (%) (more is better ↑ ↑), expected annual energy/land use (kWh/m^2) (more is better ↑ ↑), project cost/capacity (TL/kWe) (less is better ↓ ↑), and project cost/energy (TL/kWh) (less is better ↓ ↑). The best to worst order of project cost/capacity (TL/kWe) and project cost/energy (TL/kWh) are almost the same as PVPP #2 (40,00 GWh/20,00 MWe), #6 (11,98/6,00), #7 (11,18/5,60), #3 (38,00/18,61), #1 (46,74/23,40), #5 (20,75/10,39), and #4 (36,00/18,00), but it is different for annual energy/land use (kWh/m^2) as PVPP #1 (46,74 GWh/23,40 MWe), #3 (38,00/18,61), #6 (11,98/6,00), #7 (11,18/5,60), #5 (20,75/10,39), #4 (36,00/18,00), and #2 (40,00/20,00). The order also differs for capacity factor (%) from those three success factors as PVPP #3 (38,00 GWh/18,61 MWe), #2 (40,00/20,00), #4 (36,00/18,00), #1 (46,74/23,40), #5 (20,75/10,39), #6 (11,98/6,00), and #7 (11,18/5,60). The capacity factor (%) is not so decisive as others, but it is still usable with its current number precision.

When RS findings are studied in detail, it is observed that there is only one different class "moderately suitable" for PVPP #3. All others are in the same class "highly suitable" (#1, #2, #4, #5, #6, #7). RS does not decisively and distinguishingly perform very well for the success factors above, and these RS findings are irrelevant with all success factors. Under these conditions, RS is not a very promising chance for using in the proposed system because there are many irrelevancies in the current findings.

When RR findings are studied in detail, it is observed that there are 4 different classes as "very highly suitable" for PVPP #1 and #7, "highly suitable" for PVPP #2, "moderately suitable" for PVPP #4, #5 and #6, and finally "low suitable" for PVPP #4. RS performs decisively and distinguishingly well, but its findings are not very relevant for all above success factors. Under these conditions, RR is still a promising chance for using in the proposed system because there are some relevancies and also some irrelevancies in the current findings.

When ROC findings are studied in detail, it is observed that there are 3 different classes as "very highly suitable" for PVPP #1, #2, and #7, "highly suitable" for PVPP #5, and #6, and finally "moderately suitable" for PVPP #3, and #4. ROC performs decisively and distinguishingly, but its findings are not very relevant for all above success factors. Under these conditions, ROC is still a promising chance for using in the proposed system because there are many relevancies and also some irrelevancies in the current findings.

When PA findings are studied in detail, it is observed that there are 3 different classes as "very highly suitable" for PVPP #5, "highly suitable" for PVPP #2, and #6, and finally "moderately suitable" for PVPP #1, #3, #4, and #7. PA performs decisively and distinguishingly, but its findings are not very relevant for all above success factors.

Consequently, RR, ROC, and PA are still promising chances for using in the proposed system, because there are some relevancies and also some irrelevancies in the current findings. As it is observed, there are some mismatching problems (Table 6). For instance, while ranks of PVPP #3 in RS, RR, ROC, and PA are respectively 2, 4, 3, and 3, ranks of success factors (energy/land use, cost/capacity, cost/energy) are respectively 2, 4, and 4. Here, RS rank matches with energy/land use success factor rank (rank 2), and RR rank matches with cost/capacity and cost/energy success factor ranks (rank 4). It has to be added that RS should also be studied very much before selecting any weighting methods. Hence, it would be great to work with an expert pool with thousands of members (expert lake) for each factor and alternative, and also verification and validation power plants.

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Conclusions

RD^3&D progress of a GIS-based investment system and its integrated assessment framework for selecting the most suitable PVPPs locations is presented with an application of a test planning site (Antalya, Burdur, and Isparta in Turkey) in this paper. WLC was applied with 4 SWM (RS, RR, ROC, and PA) in a GIS environment. A decision tree-like structured RD^3&D experimental MCDM model is built with 5 main criteria, 14 criteria, and 79 value ranges. According to experts' opinions and the results of all methods, GHI, aspect, land use, distance from land transportation network, and distance from power network are the most dominant criteria for PVPPs. An expert pool is organized with 5 single experts and 1 expert group. A PV suitability index for area sorting and grouping is defined with 1 main (unsuitable and suitable) and 5 sub-classes or groups (suitable: very low, low, moderately, highly, and very highly). PVPPs suitability maps of the test site for 4 SWMs (RS, RR, ROC, and PA) are produced and presented in this paper. Moreover, the covariance and correlation analyses for these PVPPs suitability maps are also made and given to represent the differences and similarities of suitable regions for those 4 SWMs in this paper. Finally, performance verification and validation study are done based on the invested PVPPs in the test site.

This study will provide a decision support system to deeply investigate complex spatial location selection problems and to produce a spatial planning strategy for decision makers. As a result, the most suitable locations for the PVPPs were identified and the suitability assessment of the existing PVPPs was made. According to these findings, all of the existing projected PVPPs were defined as acceptable and most of these projects were generally classified as eligible zones. This decision support system can be implemented in other regions with similar conditions.

The data, information, model, modeling approach, and findings of this study can be used by international, national, or regional governmental bodies to present %100 public offering structured private PVPP investments (0% debt, 0% interest load, 100% private equity) to country's own citizens and foreign country's citizens (global citizens) on state controlled online websites in the way of several investment approaches, which is the fairest and true investment model, not to give any opportunity swindlers, inflationarists, monopolist, and similar.

Further use of this study

The current model, approach, datasets, digital maps, preliminary analyses, and validation-verification efforts were done, generated, and presented by authors' own work for this RD^3&D publication. All of them can be used as it is or with some revisions, modifications, and changes by international, national, or regional governmental bodies, private investors, or wealth-fund management, and investment groups. A few of those potential implementations are as follows: %100 initial public offering (IPO) structured private PVPPs investments (0% debt, 0% interest load, 100% private equity) at the appropriate largest sites according to studies based on this one can be presented to country's own citizens and foreign country's citizens (global citizens) in the way of several investment approaches, which is the fairest and true investment model, on the state/states controlled banking and investment online websites by governmental bodies, wealth-fund management and investment groups, or private and public banks. In these IPOs, all investment details and operations must be presented in advance and during operations on the open online platforms and specifically designed global computer-based support systems. Moreover, they must be designed as ordinary persons investment options and proposed direct social security, health, and retirement/pension options. The weight calculations and their probability analyses can be used to develop data pool of these factors and also to find the best fit probability density functions for robot systems and different studies in this subject or other subjects (e.g., urban planning of existing cities, and towns). The digital maps, which can be opened in ESRI ArcGIS 10.1 for desktop, ESRI ArcGIS Earth Version 1.8, Google Earth Pro 7.3.2.5491, HGM Kure or similar can directly be used for public relations (PR) by international, national, or regional governmental bodies.

Acknowledgements The authors thank to civil engineers Serhan Gedik and Mehmet Gülcemal, and also city and regional planner Mehmet Can Özkurt in the General Directorate of Highways, CW Energy.

Compliance with ethical standards

Conflict of Interest All authors states that there is no conflict of interest.

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Appendix

Table 7 Value ranges weights used in the GIS model

Sub-criteria	Value ranges	W_{RS}	W_{RR}	W_{ROC}	W_{PA}
Global horizontal irradiation	1243–1350	0.036	0.055	0.020	0.037
	1350–1450	0.071	0.064	0.044	0.070
	1450–1550	0.107	0.077	0.073	0.103
	1550–1650	0.143	0.096	0.109	0.136
	1650–1750	0.179	0.129	0.156	0.178
	1750–1850	0.214	0.193	0.228	0.216
	1850–1913	0.250	0.386	0.370	0.261
Aspect	North	0.044	0.044	0.026	0.018
	East	0.111	0.071	0.083	0.048
	West	0.133	0.088	0.111	0.053
	South	0.200	0.353	0.314	0.396
	Northeast	0.067	0.050	0.042	0.018
	Northwest	0.089	0.059	0.061	0.025
	Southeast	0.159	0.128	0.157	0.201
	Southwest	0.174	0.167	0.194	0.231
	Flat	0.022	0.039	0.012	0.008
Slope	< 1	0.250	0.386	0.370	0.278
	1–3	0.214	0.193	0.228	0.232
	3–5	0.179	0.129	0.156	0.192
	5–7	0.143	0.096	0.109	0.115
	7–10	0.107	0.077	0.073	0.082
	10–15	0.071	0.064	0.044	0.062
	15–24	0.036	0.055	0.020	0.040
Elevation	0–500	0.048	0.068	0.028	0.078
	500–1000	0.095	0.082	0.061	0.125
	1000–1500	0.143	0.102	0.103	0.157
	1500–2000	0.190	0.136	0.158	0.183
	2000–2500	0.238	0.204	0.242	0.213
	> 2500	0.286	0.408	0.408	0.243
Land use, allocation and availability	CLC 131,132,133	0.137	0.127	0.135	0.147
	CLC 211,212,213	0.037	0.043	0.022	0.013
	CLC 221,222,223	0.044	0.045	0.027	0.013
	CLC 231	0.100	0.069	0.075	0.047
	CLC 241,242	0.074	0.054	0.049	0.022
	CLC 243,244	0.144	0.103	0.129	0.148
	CLC 321,322,323,324	0.156	0.155	0.174	0.245
	CLC 332,333,334	0.196	0.324	0.296	0.312
	CLC 411,412,413,414,415	0.111	0.081	0.093	0.053
Distance from faults	< 1	0.100	0.120	0.063	0.158
	1–3	0.200	0.160	0.146	0.233
	3–5	0.300	0.240	0.271	0.265
	> 5	0.400	0.480	0.521	0.343

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Table 7 (continued)

Sub-criteria	Value ranges	w_{RS}	w_{RR}	w_{ROC}	w_{PA}
Ground conditions	Sedimentary rocks	0.278	0.374	0.381	0.258
	Metamorphic rocks	0.230	0.193	0.228	0.192
	Alluvium	0.167	0.153	0.154	0.167
	Volcanic rocks	0.103	0.085	0.068	0.100
	Ophiolite rocks	0.175	0.127	0.142	0.183
	Plutonic rocks	0.048	0.068	0.028	0.100
Distance from protected areas	< 0.5	0.100	0.120	0.063	0.167
	0.5–2	0.200	0.160	0.146	0.242
	2–4	0.300	0.240	0.271	0.270
	> 4	0.400	0.480	0.521	0.322
Distance from residential areas	< 1	0.333	0.438	0.457	0.287
	1–2	0.267	0.219	0.257	0.245
	2–5	0.200	0.146	0.157	0.203
	5–10	0.133	0.109	0.090	0.155
	> 10	0.067	0.088	0.040	0.110
Distance from power network	< 1	0.400	0.480	0.521	0.408
	1–5	0.300	0.240	0.271	0.308
	5–10	0.200	0.160	0.146	0.192
	> 10	0.100	0.120	0.063	0.092
Distance from rivers	< 1	0.400	0.480	0.521	0.383
	1–5	0.300	0.240	0.271	0.300
	5–10	0.200	0.160	0.146	0.200
	> 10	0.100	0.120	0.063	0.117
Distance from other water bodies	< 1	0.400	0.480	0.521	0.383
	1–5	0.300	0.240	0.271	0.300
	5–10	0.200	0.160	0.146	0.200
	> 10	0.100	0.120	0.063	0.117
Distance from land transportation network	< 1	0.333	0.438	0.457	0.358
	1–3	0.267	0.219	0.257	0.300
	3–5	0.200	0.146	0.157	0.202
	5–8	0.133	0.109	0.090	0.097
	> 8	0.067	0.088	0.040	0.043
Distance from railway transportation network	< 1	0.333	0.438	0.457	0.358
	1–3	0.267	0.219	0.257	0.300
	3–5	0.200	0.146	0.157	0.202
	5–8	0.133	0.109	0.090	0.097
	> 8	0.067	0.088	0.040	0.043

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