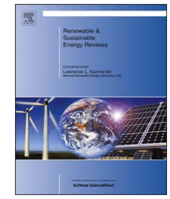
Renewable and Sustainable Energy Reviews 81 (2018) 2088–2103

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser



GIS-based assessment of photovoltaic (PV) and concentrated solar power (CSP) generation potential in West Africa

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ARTICLE INFO

Keywords:
GIS
Photovoltaics
Concentrated solar power
West Africa
Multi-criteria decision making
Analytic Hierarchy Process

ABSTRACT

This paper presents estimates of the geographical and technical potentials for solar electricity generation in rural areas of West Africa (ECOWAS region). The study is performed by application of Geographic Information Systems (GIS) and Multi-Criteria Decision Making (MCDM) methods. We study both opportunities for large-scale grid-connected solar systems (photovoltaic, and concentrated solar power technologies), and for off-grid solar systems (photovoltaic). Locations are evaluated according to their suitability for solar systems' deployment according to topographical, legal, and social constraints, as well as factors that could facilitate or impede solar generation development. The study is conducted on a regional scale. The results can be used for identification of potential areas of interest for solar generation deployment, and as a support for integration between electricity grid expansion and off-grid electrification policies.

1. Introduction

Nowadays lack of access to electricity is one of the major problems in the developing countries. It is an important barrier to economic, and social development. Worldwide, approximately 1.5 billion people are lacking access to electricity and most of them live in rural areas with low population densities [1]. West Africa is one of the regions where the share of population having no access to electricity is the highest [1]. Fifteen countries constitute the region and form the Economic Community of West African States (ECOWAS): Benin, Burkina Faso, Cape Verde, Côte d'Ivoire, Gambia, Ghana, Guinea, Guinea Bissau, Liberia, Mali, Niger, Nigeria, Senegal, Sierra Leone, and Togo. Energy consumption in the region is on average 50–100 times lower than in the developed countries [2]. For example, in 2013 yearly electricity consumption was 50 kWh/capita in Niger and 386 kWh/capita in Ghana compared to 584 kWh/capita in Africa, 7022 kWh/capita in Germany and 12987 kWh/capita in the USA [3]. There is no universally agreed minimal acceptable level of electricity consumption per capita. According to IEA [4], a minimum threshold value is 50 kWh/capita per year. According to Javadi et al. [5] electricity consumption of 1000 kWh/capita per year "is known as the boundary between basic life condition and guaranteed survival".

One potential way to provide access to electricity is the development of renewable energy generation. It can allow to minimize environmental impacts and avoid dependency on fossil fuel prices and supply. In addition, renewable energy development can contribute to economic growth and job creation [6–13]. Nowadays all West African countries have adopted renewable energy targets [14]. However, current renewable power generation capacities in the region are still very limited. For example, in 2014 only two countries had grid-connected photovoltaic capacities installed, Cape Verde and Ghana [15]. In order to develop renewable energy, governments, NGOs and investors need data on resource availability and suitable locations. Currently there are few studies on renewable energy potential for the region, most of which are limited to the estimation of resource availability [1].

Against this background it is the objective of this study to estimate the geographical and technical potential of photovoltaic (PV) and concentrated solar power (CSP) electricity generation in rural areas of ECOWAS region. Both grid-connected and off-grid potentials are

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http://dx.doi.org/10.1016/j.rser.2017.06.021
Received 19 April 2016; Received in revised form 7 February 2017; Accepted 9 June 2017
Available online 16 June 2017
1364-0321/

evaluated at the regional scale. We develop our methodology based on literature review, but propose an alternative approach with regard to treatment of protected areas and use of different scenarios. If deemed successful, the methodology can be implemented in studies for other locations. The results of our study can help to find potential areas of interest for solar generation deployment in ECOWAS countries. They can also facilitate decision making with regard to coordination of electricity grid expansion and off-grid electrification policies, which is important for attracting investment and ensuring best possible synergies between these two policy efforts [16].

2. Theoretical background

2.1. Photovoltaic technology overview

Solar photovoltaic (PV) technology is based on PV cells that allow direct conversion of solar radiation to electricity [17]. PV nowadays may be considered as mature technology from both a technical and an economic perspective [17]. The PV market is growing at an annual rate of 35–40% [17], which makes PV one of the most expanding renewable energy technologies.

PV technology may be classified into the following categories [17]:

- PV based on crystalline silicon materials, including monocrystalline, polycrystalline, and gallium arsenide cells;
- Thin-film solar cells based on amorphous silicon, cadmium telluride (CdTe), cadmium sulphide (CdS), or copper indium gallium selenide/copper indium selenide materials;
- Organic and polymer cells;
- Hybrid solar cells;
- Dye-sensitized solar cells;
- PV based on nanotechnology.

The above-mentioned technologies differ in terms of efficiency and costs of PV modules [17]. Currently, crystalline silicon materials are dominating the market [17], with monocrystalline materials accounting for about 80% of the total PV market [18]. At the same time, thin film technology is increasing its market share [19]. Other types of technologies are still in the R & D stage [17].

Efficiency of PV technology has improved considerably in recent years. According to Tyagi et al. [17], the nominal efficiency of a monocrystalline silicon solar cell was about 15% in 1950s and increased up to 28% nowadays.[1] Polycrystalline solar cell's nominal efficiency has achieved a value of 19.8% [20]. However, the nominal efficiency of commercially available PV cells and modules is lower. According to Razykov et al. [20] the nominal efficiency of commercially available PV cells ranges from 15% and 22% for monocrystalline cells, and from 12% to 15% for polycrystalline cells. Devabhaktuni et al. [17] performed an overview of nominal efficiencies of PV modules claimed by manufacturing companies and reported monocrystalline module efficiency values between 13.3% and 16.2%, and polycrystalline module efficiency values between 12.65% and 15.67%. The highest nominal module efficiency of monocrystalline solar cell achieved by Sunpower in 2009 is 20.4% [18].

There are a number of factors that reduce the efficiency of a PV module in practice compared to standard testing conditions. These include higher ambient temperatures, dust cover and humidity, as well as decreased solar irradiance [17]. Therefore, when evaluating technical potential for PV generation it is important to take into account the performance ratio (PR) of PV systems, which represents the difference between the nominal efficiency and efficiency achievable in practice. The PR of modern PV systems is over 80% (with maximum values around 90%) [21] but lower values between 70% and 85% for mono- and polycrystalline systems are also reported [22].[2]

PV technologies are implemented in grid-connected and off-grid systems [23]. Grid-connected systems can be in large-scale and distributed form. Large-scale PV systems have capacities from 10 MW to over 100 MW [23,24], and generally require a surface exceeding 1 km^2 [25]. One of the advantages of these systems is economy of scale. Distributed grid-connected systems allow valorization of solar energy potential in settlements (i.e., roof-mounted systems). Off-grid systems may supply energy to a single consumer, or a number of consumers via a midi-grid (with no connection to major electricity grid lines). Off-grid systems provide opportunities for power supply in remote areas while avoiding costly investments in distribution and transmission systems [26].

2.2. Concentrated solar power technology overview

Concentrated solar power technology (CSP) makes use of mirrors that transform solar energy into heat which is then converted to electricity by means of steam turbines, gas turbines or Stirling engines [27]. The CSP market is currently developing, mainly in Europe (with leading Spain) and the United States [27]. The types of the CSP plants include parabolic trough, power towers, parabolic dish type systems, and Fresnel trough technology [27]. These technologies differ in investment costs, land requirements, and efficiencies [19]. Parabolic trough systems dominate the CSP market. In 2010, parabolic trough technology represented 100% of CSP plants in operation and construction, and 75% of the planned CSP plants [27].

There are differences in reported “solar-to-electricity” efficiencies of CSP technologies. The following efficiency ranges of CSP plants were mentioned by Gastli and Charabi [28]: 15–21% for parabolic trough, 18–20% for power tower, 25–30% for parabolic dish. A study by Ziuku et al. [29] reports 15% efficiency of parabolic trough technology, 20–35% efficiency of solar towers, 25–30% efficiency of parabolic dish systems, and 8–10% efficiency of linear Frensel reflectors. Viebahn et al. [27] performed a case study of a 50 MW parabolic trough power plant, and estimated the plant's efficiency at 14.7%. The authors also mentioned an expected 15.5% efficiency of a 15 MW tower plant. In their study for Canada, Djebbar et al. [30] report an efficiency value for parabolic trough technology of 11%. These differences may be related to evolution of CSP technologies and field conditions. In particular, efficiency of CSP power plants highly depends on the level of solar irradiance [31]. In the report prepared by Hermann et al. [31] for the International Renewable Energy Agency (IRENA) CSP efficiency ranges from 12% at direct normal irradiance (DNI) of 1800 kW/m^2/year to 16% at DNI 4000 kW/m^2/year.[3]

CSP is currently represented by centralized grid-connected power plants, with capacities that may exceed 100 MW [32]. However, dish type systems have a potential to be used in decentralized applications [27], with the respective capacities ranging between 5 and 35 kW [29,33]. According to Devabhaktuni et al. [26] one of the advantages of CSP technology includes involvement of a thermal intermediary, which offers opportunities for thermal storage and hybridizing with fossil fuels. Among the disadvantages are high land and water requirements (unless dry cooling is used) [29,34].

2.3. Definitions of solar power potentials

Potential of solar generation may be classified into three categories: geographical, technical, and economic [22]. *Geographical potential* of solar generation in a chosen area may be defined as the amount of the

[1] The nominal efficiency can be defined as efficiency achieved under standard testing conditions (i.e., claimed by manufacturer).

[2] PR is strongly dependent on field conditions, and therefore it values vary for different locations.

[3] CSP efficiency value used by authors for calculations is 14%.

total yearly solar radiation available in that area taking into account existing geographical constraints (for example, land covered by forests or waterbodies) [22]. *Technical potential* of solar generation in a chosen area may be defined as the amount of geographical potential in that area that can be converted into electricity given the available solar power technologies [22]. *Economic potential* accounts for the amount of technical potential that could be realized in practice at a cost compatible with conventional electricity sources [22].

2.4. Estimation of solar power potential in rural areas with a use of GIS and MCDM methods

There is an important and constantly growing number of *GIS*-based studies that estimate solar resource availability [35–38] and locations suitable for solar power generation in both urban [38–41] and rural [22,28–34,42–55] environments. The majority of studies that focus on rural areas are performed for Europe, North America, Middle East and Asia. Uyan evaluated site suitability for solar farms in Karapinar region, Turkey [42]. Opportunities for solar farms location in Colorado, USA, were studied by Janke [44]. Brewer et al. used GIS combined with survey-based social acceptance data to determine sites suitable for large-scale solar power plants in the southwestern United States [43]. Studies on solar PV generation potential in rural areas of China have been performed by Sun et al. for the Fujian Province [22] and by Byrne et al. for western territories [56]. Sánchez-Lozano et al. evaluated site suitability for the optimal placement of PV power plants in Cartagena [45] and Murcia [46], Spain. Other studies for Spain were performed by Carrión et al. to define sites suitable for PV plants in Andalusia [57,58]. Sabo et al. determined optimal sites for large-scale PV plants connected to smart grids in Malaysia [47]. Gunderson et al. estimated the PV power generation potential in the Black Sea region in the context of climate and land-use change [48]. A number of studies on PV and CSP potentials, as well as site suitability were performed for Oman by Gastli, Charabi et al. [28,32–34,49]. Anwarzai and Nagasaka determined suitable locations for PV and CSP plants in Afghanistan [50]. The potential for grid-connected PV and CSP plants was evaluated for Vietnam by Polo et al. [51]. Evaluation of CSP potential was also performed for Canada by Djebbar et al. [30]. Jahangiri et al. determined suitable locations for hybrid power plants, combining solar and wind power technologies in the Middle-East [52]. Location suitability for solar (and wind) farms was also evaluated by Watson et al. for southern England [53]. Among the studies for Africa are the work by Ziuku et al. on the CSP power potential in Zimbabwe [29], estimates performed by IRENA for West Africa [54] and the African continent as a whole [31], as well as the assessment of the CSP power potential in North Africa performed by Broesamle et al. [55]. Most of the reviewed studies focus on large-scale grid-connected solar systems situated outside urban settlements. Only in the study performed by IRENA for West Africa [54] the potential of off-grid systems in remote areas is evaluated.

In general, as the first step, the studies use *restrictive criteria* to eliminate areas not suitable for solar power development. These criteria may be based on topographical and legal constraints [45]. As the second step, different *factors* may be considered in order to classify the remaining areas according to their suitability. The factors are often assigned *weights* depending on their relative importance in decision-making process. Therefore, the resulting classification of areas depends on the choice of factors and their weights. *Multi-criteria decision making (MCDM)* methods are often used in this context [47,50], including *Ordered Weighted Averaging (OWA)* [34,44], and *Analytic Hierarchy Process (AHP)* [29,34,42,45,53,58]. A summary of restrictive criteria and factors used (or discussed) in the reviewed literature is presented in Appendix A. A summary of weights of factors (and restrictive criteria) is presented in Appendix B. One can conclude that there is relatively little variation in the choice of restrictive criteria, while the choice of factors and their weights differ considerably among the studies. This may be caused by multiple reasons, including

Table 1
Restrictive criteria used in the study.

Parameter	Description	Off-grid PV	Grid-connected PV	Grid-connected CSP
Urban settlements	Urban settlements (> 10'000 inhabitants), with 1 km buffer	All urban settlements	All urban settlements	All urban settlements
Land cover	Surface occupied by selected land use classes	Surface occupied by built-up areas (other than urban), agricultural zones, forests, wetlands, and water bodies	Surface occupied by built-up areas (other than urban), agricultural zones, forests, wetlands, and water bodies > = 75%	Surface occupied by built-up areas (other than urban), agricultural zones, forests, wetlands, and water bodies > = 75%
Risk areas	Flood zones in which the expected average number of flood event per 100 years is equal or over 1	All flood zones	All flood zones	All flood zones
Protected areas	IUCN class I - VI and not classified	Only Ia class (Strict Nature Reserve)	All included	All included
Land slope	Cells in which over 75% of surface has a slope exceeding a threshold value	None[a]	10% (or 5.71°) threshold[b]	2% (or 1.15°) threshold
Population density	Rural cells in which population density exceeds a threshold value	None	> 500 inhabitants/km^2 threshold	> 500 inhabitants/km^2 threshold

[a] Off-grid PV systems may not be necessarily ground-mounted (e.g., could be instead roof-mounted). Therefore, we do not take the land slope into account.
[b] The threshold values are taken in percent of slope (and not in degrees) based on the information available in the initial dataset (the dataset is described further in the text).

Table 2
Factors and weights chosen for evaluation of solar power production potential of large-scale grid-connected PV and CSP systems.

Parameter	Objective and classes	Weight, %	
		Scenario 1	Scenario 2
Solar irradiance	For PV: maximize GHI[a] Less suitable: < 1800 kWh/m^2/year Moderately suitable: 1800–2100 kWh/m^2/year Suitable: 2100–2300 kWh/m2/year Best suitable: > 2300 kWh/m2/year For CSP: maximize DNI Less suitable: < 1800 kWh/m^2/year Moderately suitable: 1800–2300 kWh/m^2/year Suitable: 2300–2700 kWh/m^2/year Best suitable: > 2700 kWh/m^2/year	46.9%	35.0%
Distance to electricity grid lines	Minimize distance Less suitable: > 30 km Moderately suitable: 5–30 km Suitable: 1–5 km Best suitable: < 1 km	24.9%	46.3%
Distance to roads	Minimize distance Less suitable: > 5 km Moderately suitable: 3–5 km Suitable: 1–3 km Best suitable: < 1 km	14%	10.1%
Population density	Minimize density Less suitable: > 500 inhabitants/km^2 Moderately suitable: 100–500 inhabitants/km^2 Suitable: 1–100 inhabitants/km^2 Best suitable: 0 inhabitants/km^2	9.5%	5.4%
Distance from settlements	Optimize distance from urban settlements (> 10'000 inhabitants) Less suitable: < 1 km Moderately suitable: 1–2 km Suitable: 2–5 km Best suitable: > 5 km	4.7%	3.1%

[a] GHI – global horizontal irradiance.

differences in characteristics of studied locations, individual evaluators' reasoning, and data availability. For example, for areas with abundant solar resources, the distance to transmission lines may be considered as more important factor than solar irradiance [45]. In addition, there are a number of methodological differences in evaluation of potential for different technology and system types. For example, in the study performed by IRENA for West Africa [54] there is a preference to minimize the distance to grid for grid-connected systems, and maximize the respective distance for off-grid systems.

3. Methodology

In this study we estimate the geographical and technical potentials for three types of solar systems: large-scale grid-connected PV and CSP, and off-grid PV. All datasets are transposed to a reference grid in geographic coordinate system *D WGS 1984* and the projection *Africa Albers Equal Area Conic*, so that the information is displayed by pixels representing 1 km^2. Detailed information on datasets used and data sources is presented in Supplementary material 1.

Table 3
Factors and weights chosen for evaluation of solar power production potential of off-grid PV systems.

Parameter	Objective and classes	Weight, %
Solar irradiance	For PV: maximize GHI Less suitable: < 1800 kWh/m^2/year Moderately suitable: 1800–2100 kWh/m^2/year Suitable: 2100–2300 kWh/m^2/year Best suitable: > 2300 kWh/m^2/year	11.7%
Distance to electricity grid lines	Maximize distance Less suitable < 1 km Moderately suitable: 1–5 km Suitable: 5–30 km Best suitable: > 30 km	23.1%
Protected areas	Preference to locations classified as protected Less suitable: non-classified as protected areas Best suitable: classified as protected areas	16.8%
Population density	Maximize density Less suitable: 0 inhabitants/km^2 Moderately suitable: 1–100 inhabitants/km^2 Suitable: 100–500 inhabitants/km^2 Best suitable: >500 inhabitants/km^2	48.4%

3.1. Estimation of the geographical potential

Firstly, we determine *restrictive criteria* and their values for each type of solar system studied (Table 1).

The approach chosen for *protected areas* is based on similar studies [31,45,54], the IUCN Guidelines for applying protected area management categories [59], as well as review of GIS data on population within the protected areas prepared by GRID-Geneva (*population density* dataset). The parameter *land cover* is treated differently for large-scale grid-connected and off-grid systems. In the first case *land cover* dataset is used in calculation of *restrictive criteria* dataset. The aim is to choose pixels where the size of restricted area is relatively big, so the space available for constructing a large-scale solar system would be insufficient. In the second case, *land cover* dataset is not used in calculation of *restrictive criteria* dataset, but it is used in the formula for off-grid power generation potential (see Section 3.2). The *slopes* dataset is used to choose pixels where the size of restricted area is relatively big, so it potentially causes technical difficulties and higher investment costs for construction of large-scale solar systems.

Secondly, we choose which *factors* to account for, based on the datasets available and the literature review (Appendix A). We use *Analytic Hierarchy Process (AHP)* to assign *weights* to factors, as this method is one of the most common in this type of studies [29,34,42,45,53,58]. The AHP method is well-described in the literature [60] and consists of grouping the factors (alternatively called "criteria") in a square matrix and performing their pair-wise comparison with the scale 1–9, where 1 means equal importance and 9 extremely higher importance of one criteria compared to another. To perform such comparison, we used the examples of the reviewed studies (Appendix B) and we consulted specialists in the field of solar energy (see Acknowledgments). Based on the pair-wise comparison, the overall weights for each criteria are derived. Our evaluation has some deviations compared with the reviewed literature, which is due to differences in data used and different reasoning. For example, we use relatively high thresholds for solar irradiance due to abundance of solar resource in the region (see Supplementary material 2 and Section 4 for more details). We evaluate land suitability factors according to four classes and their respective scores: best suitable (score 4), suitable (score 3), moderately suitable (score 2), and less suitable (score 1).

Table 4
Assumptions on technical characteristics of solar technologies proposed for the study.

Parameter	Off-grid PV	Grid-connected PV	Grid-connected CSP
Technology type	Monocrystalline cells	Monocrystalline cells	Parabolic trough
Efficiency[a]	Module efficiency claimed by manufacturer 15.5%, PR 85%	Module efficiency claimed by manufacturer 15.5%, PR 85%	System efficiency 15%
Land occupancy factor	5	1.4	3

[a] System efficiency is module efficiency multiplied by PR.

We develop two scenarios for large-scale grid-connected solar systems. In the *first scenario* solar irradiance is chosen as main criterion, which is a rather typical approach [29,34,44]. We base the *second scenario* on the example of a study performed by Charabi and Gastli for Oman [34]. We consider that in West Africa the general level of solar irradiance is satisfying for solar power production. Therefore, we assume that the focus should be on minimization of potential investment costs, represented by limitation of the distance to electricity grid lines (for lower connection costs) and major roads (for lower accessibility costs). Therefore, we assign relatively high weights to these two parameters. The proposed factors and their weights for large-scale grid-connected systems with regard to two scenarios are presented in Table 2. The pair-wise comparison of factors is presented in Supplementary material 3.

We develop only one scenario for off-grid PV systems (Table 3). The highest weight is assigned to population density in order to indicate in which locations energy demand would be the highest. Distance to electricity grid lines is integrated in order to identify remote locations that are unlikely to be easily connected to the grid. We also include a preference to locations classified as protected areas, as they may face constraints with regard to electricity grid line development. Therefore, off-grid energy production may be a preferable (if not the only possible) option for inhabitants of protected areas to get access to electricity. Solar irradiance is given the lowest weight, as solar resource availability in the region is generally sufficient for PV production.

Description of workflow for estimating the geographical potential is given in Supplementary material 4.

3.2. Estimation of the technical potential

Assumptions on technical characteristics of solar technologies used in this study are presented in the Table 4.

Electricity generation potential is calculated according to the formula:

$$Electricitygenerationpotential_{(xy)} = DNI_{(xy)}(orGHI_{(xy)})*Efficiency *PR(incaseofPV)*\frac{AvailArea_{(xy)}}{LandOcc}$$

where:

Electricity generation potential$_{(xy)}$ is the technical potential in GWh/year for the cell at xy coordinates.

$DNI_{(xy)}$ or $GHI_{(xy)}$ are the solar irradiance values for the cell at xy coordinates. Solar irradiance values are taken from *GHI* dataset in the case of PV systems, and *DNI* dataset in the case of CSP systems (Supplementary material 1).

Efficiency is the assumed PV module or CSP system efficiency (Table 4).

PR is the assumed performance ratio for PV modules (Table 4).

$AvailArea_{(xy)}$ is the area outside restrictive criteria zones. In the case of *large-scale grid-connected systems*, the corresponding cell outside the restrictive criteria zone is assigned a value of 1. If the cell belongs to restrictive criteria zone, it is assigned a value of 0 and is therefore excluded from estimations. In the case of *off-grid PV systems*, cell value is calculated as a difference between total area ($1\ km^2$ = value of 1) and area occupied by land use classes accounted in restrictive criteria (for example, if 30% of cell is occupied by restrictive criteria zones, the cell is assigned a value of 0.7) (Table 1).

LandOcc is land occupancy factor. It represents a ratio of total land requirements to the surface of PV panels or CSP collectors. The chosen values (Table 4) are taken from the reviewed literature [30,49,55,61]. We take conservative approach with regard to *off-grid PV systems* due to the adopted preference for proximity to rural settlements (where PV modules can be installed on free land surface as well as in built-up areas), and to account for alternative land use needs (as the available land can also be used for infrastructure, agricultural or other purposes).

4. Results and discussion

We classify the resulting geographical and technical potentials into four categories: best suitable (general score > 3.5), suitable (2.5 < general score <= 3.5), moderately suitable (1.5 < general score <= 2.5), and less suitable (1 < general score <= 1.5) (for details see Supplementary material 4).

The results on estimated geographical potential are presented in land suitability maps (Figs. 1–5).[4]

The results on estimated technical potential are presented in Tables 5–7.[5]

The results do not contain data on solar generation potential in Cape Verde as *solar irradiance* datasets do not include data on this location. We provide data on generation potential per capita in case of large-scale grid connected systems (taking into account total population). For off-grid PV system a more refined analysis by location is needed (i.e., taking into account local solar power generation potential and local population).

The results show that the choice of restrictive criteria, factors, and their weights have a critical role in estimation of solar power potential, mainly with regard to land suitability evaluation. It is demonstrated in Scenarios 1 and 2 for large-scale grid-connected systems (Figs. 1–4). When adopting Scenario 1, the majority of cells are scored with a higher land suitability class compared to Scenario 2 (especially in the northern part of the region). This is due to the fact that solar irradiance resource availability is generally high in the region, while there are fewer locations where electricity grid lines are present, planned, or proposed. Therefore, the applied methodology should be taken into account while interpreting the results of the present study. The preference of one scenario over another should depend on the objectives of the evaluator. A better insight could be obtained if the results on grid-connected, and off-grid generation potentials are evaluated together. It would be also preferable to analyze these results together with electricity grid expansion planning data.

The results should be treated with caution with regard to data

[4] Higher resolution maps can be found in Supplementary material 5.
[5] Differences in totals of technical potential between the scenarios are due to rounding and are less than 0.1%. Detailed results by country may be found in Supplementary material 6.

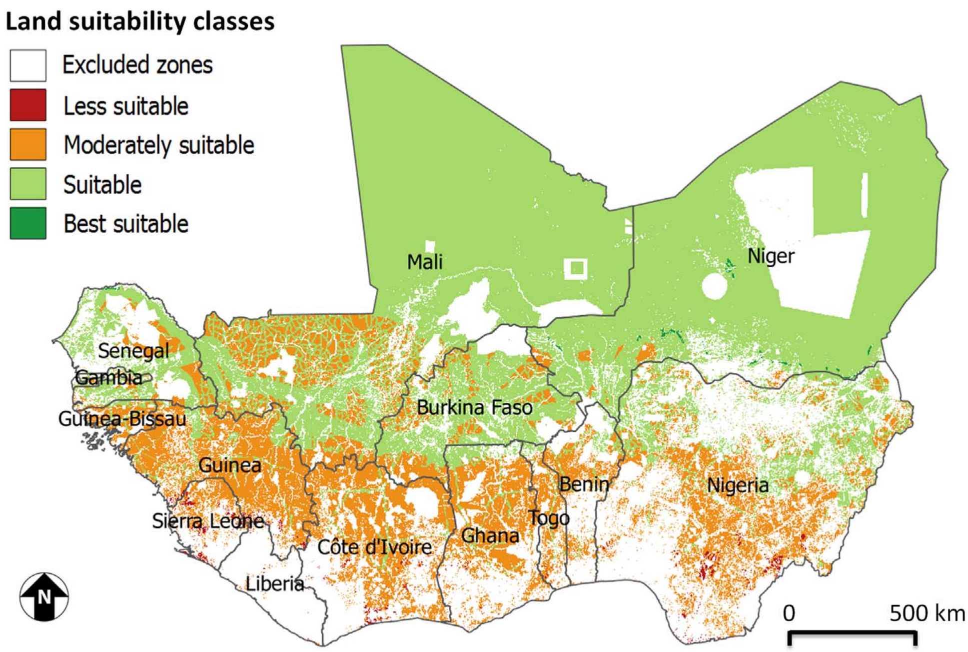

Fig. 1. Map of land suitability classes for large-scale grid-connected CSP systems according to Scenario 1.

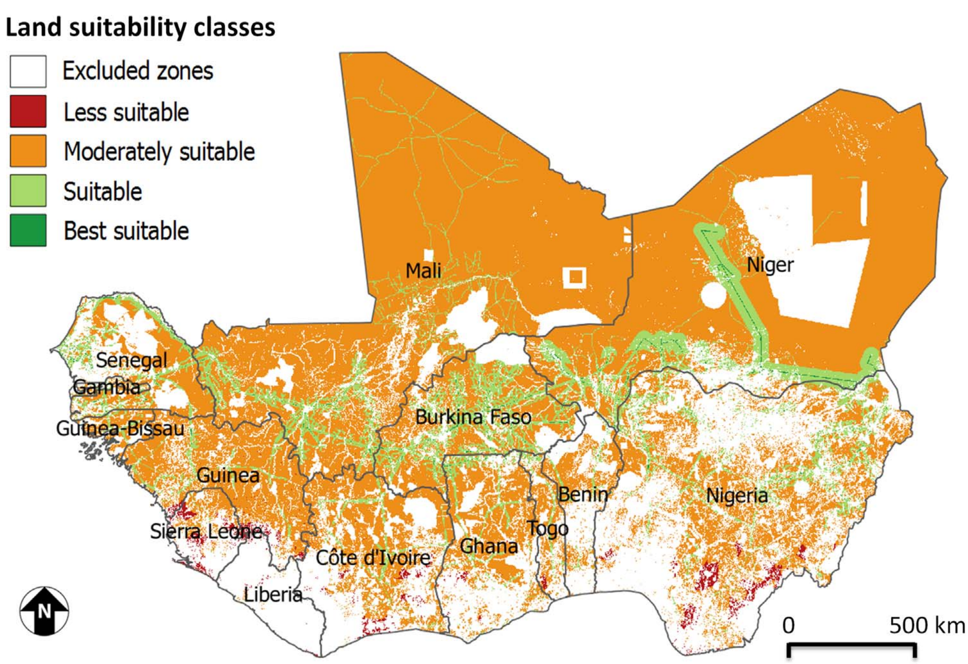

Fig. 2. Map of land suitability classes for large-scale grid-connected CSP systems according to Scenario 2.

quality, and hypotheses used. For example, in the case of PV systems we use GHI dataset where solar irradiance was measured on horizontal plane, while in the case of CSP systems we use DNI dataset where the measurement followed the Sun. In this case GHI values are lower than DNI, which lowers the results for PV systems.[6] Another example is a given preference to locations that are situated far from the *electricity grid lines* when evaluating the generation potential for the off-grid PV systems. In practice close distance to the grid is not a guarantee of connection (for example, in the case of a small village situated close to a high voltage electricity grid-line). The potential of off-grid PV systems is therefore likely to be underestimated while the opposite could be true for grid-connected systems.

The methodology applied for large-scale grid-connected installations is relatively similar to those applied in the reviewed studies [29,34,42,45]. There is no well-developed methodological base with regard to off-grid PV systems. The study performed by IRENA for West Africa [54] only accounts for *solar irradiance* values, *distance to*

[6] An alternative approach would be to estimate GHI as a sum of DNI and diffused irradiance, but that requires additional computation and is out of scope of the present study.

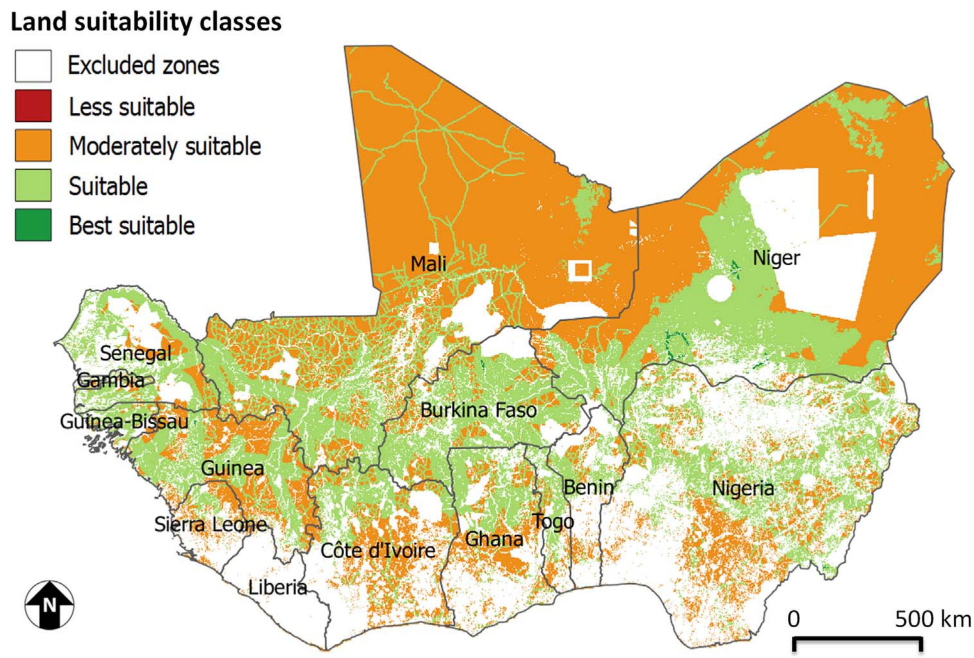

Fig. 3. Map of land suitability classes for large-scale grid-connected PV systems according to Scenario 1.

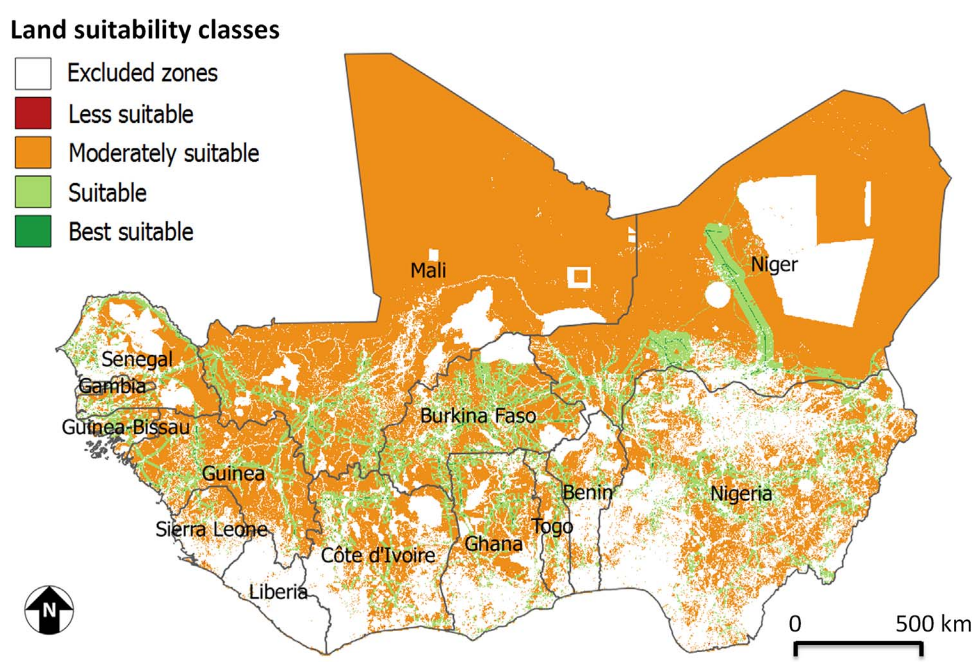

Fig. 4. Map of land suitability classes for large-scale grid-connected PV systems according to Scenario 2.

electricity grid, and *population density*. Restrictive criteria include *land cover* (forest, and water bodies only), and all *protected areas*. We do not follow the same approach, as we consider that people living within the protected areas should also have access to electricity. And while development of electricity grid lines may be restricted in such areas, use of off-grid PV systems may be one of the possible solutions. Based on the IUCN Guidelines for applying protected area management categories [59], we consider strict nature reserves as not suitable for off-grid PV systems. All other protected areas are considered as eligible for development of off-grid solar generation. However, some strict nature reserves are inhabited by indigenous people (*settlements* dataset). Therefore, it may be discussed whether to include all (or some) protected areas in further studies on off-grid PV generation potential on a regional scale, or to exclude all protected areas and treat them in separate studies that take national regulations into account.

The methodology applied in this study may be further refined. For example, national regulations may differ with regard to the *classification of settlements* (urban vs. rural) [5], and restrictions to construct in *flood zones*. A different *minimum surface threshold* may be applied for large-scale grid-connected systems. And in the case of off-grid PV

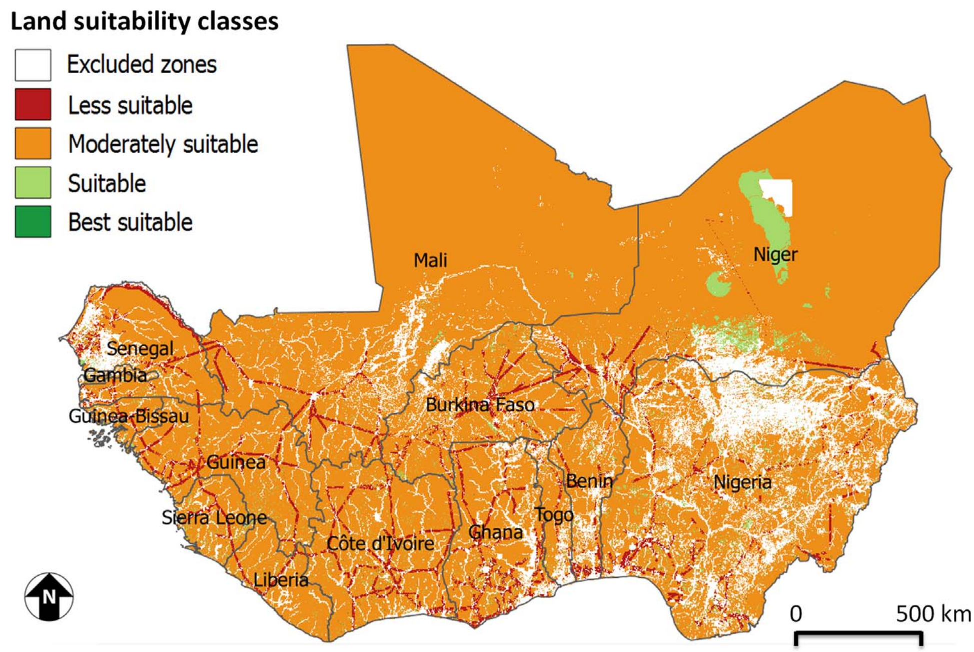

Fig. 5. Map of land suitability classes for off-grid PV systems.

Table 5
Electricity generation potential of large-scale grid-connected CSP systems by land class suitability.

Class	Scenario 1		Scenario 2	
	Total generation potential, TWh/year	Generation potential per capita, kWh/capita	Total generation potential, TWh/year	Generation potential per capita, kWh/capita
Less suitable	1483	4421	2589	7719
Moderately suitable	97,854	291,788	369,477	1,101,730
Suitable	330,407	985,231	56,594	168,757
Best suitable	689	2054	1777	5299
TOTAL	430,433	1,283,494	430,437	1,283,506

Table 6
Electricity generation potential of large-scale grid-connected PV systems by land class suitability.

Class	Scenario 1		Scenario 2	
	Total generation potential, TWh/year	Generation potential per capita, kWh/capita	Total generation potential, TWh/year	Generation potential per capita, kWh/capita
Less suitable	0	0	76	227
Moderately suitable	388,049	1,157,110	580,632	1,731,370
Suitable	297,469	887,016	102,803	306,546
Best suitable	929	2771	3175	9467
TOTAL	686,447	2,046,897	686,686	2,047,610

Table 7
Electricity generation potential of off-grid PV systems by land class suitability.

Class	Total generation potential, TWh/year
Less suitable	10,674
Moderately suitable	231,350
Suitable	9040
Best suitable	81
TOTAL	251,144

systems, *land occupancy factor* may have separate values for rural settlements (or built-up areas) and other available surface. However, when working on a regional scale it is difficult to determine the exact value of land occupancy factor for built-up areas. Further, *population density threshold* may be different for large-scale grid-connected systems. In the case of off-grid PV systems, a different classification of land suitability with regard to population density may be applied too. Namely, all inhabited pixels (population density > 0 inhabitants/km^2) may be classified as best suitable (score 4), non-inhabited pixels may be classified as less suitable (score 1). This principle is applied in the study of IRENA for West Africa [54]. At the same time it would be useful to consider pixels neighboring those which are inhabited by a certain number of people (e.g., villages), as they might be used for mini grids (PV systems not connected to the main electricity grid lines, but providing electricity for a number of consumers). In this view, land suitability may be evaluated with regard to solar resource availability by number of inhabitants within the settlements and its neighborhoods (kWh/capita per year). Also, a sensitivity analysis may be performed with regard to technical characteristics of the chosen technologies. For example, PV module and CSP system *efficiency* may be varied. Factor weights, as well as classification with regard to distance to *electricity grid lines*, and *roads* may be modified depending on the needs of local decision-makers. It is important to note that some CSP technologies require water for cooling [62]. Therefore, it might be useful to integrate proximity and availability of *water resources* as an additional weighted factor. This is not done due to a lack of information on yearly variation of water resources' availability in the region. Also, in our study we propose to locate large-scale grid-connected systems far from cities (i.e., preference is given to higher *distance from settlements*). The aim is to avoid constraints for urban development, and choose locations with lower land value. However, a maximum distance threshold may be applied in order to optimize electricity transmission losses.

In overall, our estimates confirm the results of other studies in terms of significant geographic and technical potential for solar power generation in West Africa [31,54]. Our results on technical potential of large-scale grid-connected PV and CSP systems are higher compared to the other studies, which can be explained by differences in assumptions. For example, we assume land occupancy factor values of 1.4 and 3 for PV and CSP systems respectively, while Hermann et al. use the values of 5 and 7 respectively [31] (for more details see Tables 1–4 and Appendix A).

The discussed uncertainty in methodological choices demonstrates a need for further research and dialogue (involving academia, policy-makers and other stakeholders actively involved in solar power deployment) with regard to approaches to estimate potentials for solar power generation on large scale (i.e., country and regional level). And more importantly, future estimates should not be limited to geographical and technical potentials, but include economic evaluation, as this information is essential for policy making and investment planning.

5. Conclusion

The present study estimates the geographical and technical potential for solar power generation in rural areas of West Africa. Opportunities for large-scale grid-connected PV and CSP systems, as well as off-grid PV systems are studied. Locations are evaluated according to their suitability for solar systems' deployment according to topographical, legal, and social constraints, and well as factors that could facilitate or impede solar generation development. According to our estimates deployment of large-scale grid-connected solar power systems in best suitable areas has a technical potential of about 700–1800 TWh/year (or 2–5 MWh/year per capita) in the case of CSP, and 900–3200 TWh/year (or 3–9 MWh/year per capita) in the case of PV. Off-grid PV technical potential is about 81 TWh/year in best suitable areas.

The results can be used by governments, NGOs, private investors and other stakeholders seeking to identify potential areas of interest for PV, and CSP generation deployment in ECOWAS region. They can be also used to facilitate integration between electricity grid expansion and off-grid electrification policies. However, the present study is made on a regional scale. For actual implementation of solar power projects, a detailed analysis based on high resolution spatial data, and other types of local data is needed.

From a methodological point of view our study represents a contribution to a growing body of knowledge on estimation of solar power generation potentials with a use of GIS and MCDM methods. We performed a detailed literature review on solar technologies and related GIS and MCDM-based studies, and proposed an alternative evaluation method that advocates for inclusion of protected areas in evaluation of off-grid PV generation potential, as solar power might be one of a few options for people living in protected areas to get access to electricity. In addition, we demonstrated the importance of using alternative scenarios in evaluation of land suitability for solar power deployment. The methodology proposed in this study may be further developed and used for other locations and scales. Among the major axes for further research with regard to ECOWAS region are estimation of economic potential for solar power generation and comparison of this potential to energy supply needs.

Data availability

Data is available upon request and will also be accessible on www.ecowrex.org.

Acknowledgements

This work was funded by the Secretariat of the African, Caribbean and Pacific (ACP) Group of States in the context of the project ECOWREX 2 led by ECREEE on promoting sustainable energy access through the use of Geospatial technologies in West Africa [63]. The views expressed by the authors do not necessarily reflect the views of the Secretariat or any other organization. We would like to thank Dr. Pierre Ineichen and Dr. David Parra from the University of Geneva for providing information and advice.

Appendix A

See Table A.1.

Table A.1
Summary of restrictive criteria and factors used in the reviewed literature.

Criteria	Ziuku et al. [29]	Uyan [42]	IRENA studies [31,54]	Studies by Charabi, Gastli et al. [28,32–34,49]	Sun [22]	Janke [44]	Sánchez -Lozano et al. [45,46]	Djebbar et al. [30]	Anwarzai et Nagasaka [50]	Sabo et al. [47]	Watson et al. [53]	Brewer et al. [43]	Polo et al. [51]	Carrión et al. [57,58]
Settlements[a]	Non-restricted	Restricted	Restricted: cities and urban settlements	Restricted[b]	Restricted	Restricted	Restricted	Restricted: urban agglomerations	Restricted: settlement and urban areas	Restricted: urban, build-up areas	Restricted: residential areas (all dwellings and single properties)	Restricted		Restricted: in accordance with urban planning constraints
Distance to settlements		Preference to lower value lands; buffer distance 0.5 km to residential areas; zone categories: < 0.5 km, 0.5–2 km, 2–5 km and > 5 km	Max. 200 km to the nearest city (50,000 inhabitants or more) for large-scale systems if no data on grid is available	Preference to lower value lands		Far away from cities	Maximize distance		Only lands 10 km around the cities / urban areas		Buffer distance 500 m; maximize distance	Optimize distance with regard to social acceptance data		Not far from cities to allow urban development, but minimize transmission losses; distance categories: < 5 km, 5–10 km, > 10 km if > 5000 inhabitants, and < 1 km, 1–5 km, > 5 km if < 5000 inhabitants
Population density for gird-connected plants			Low for grid-connected systems (500 persons/km2 max.); high for off-grid (no min. level)			low								preferred proximity to consumer areas
Roads		Restricted	Restricted	Restricted	Restricted	Restricted	Restricted			restricted		restricted	restricted	restricted
Distance to major roads		Buffer distance 0.1 km; minimize distance; categories: < 0.1 km, 0.1–1 km, 1–3 km, 3–5 km, > 5 km		minimize distance		minimize distance	minimize distance		only areas within 10 km of roads	> 500 m < 10000 m	minimize distance	minimize distance; 6 km max.		buffer accounted; minimize distance; distance categories: < 1 km, 1–2 km, 2–3 km, > 3 km

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Table A.1 *(continued)*

Criteria	Ziuku et al. [29]	Uyan [42]	IRENA studies [31,54]	Studies by Charabi, Gastli et al. [28,32–34,49]	Sun [22]	Janke [44]	Sánchez -Lozano et al. [45,46]	Djebbar et al. [30]	Anwarzai et Nagasaka [50]	Sabo et al. [47]	Watson et al. [53]	Brewer et al. [43]	Polo et al. [51]	Carrión et al. [57,58]
Agricultural zones	Non-restricted	Restricted	Restricted		Restricted	non-restricted	restricted Minimize agrological capacity		Restricted: irrigated land	Restricted: paddy areas	Restricted: high fertility lands	Optimize distance with regard to social acceptance data		Restricted: lands of agricultural value
Vegetation	Restricted: forests	Restricted: forests; incl. buffer distance 0.5 km	Restricted: forests			Restricted: tall vegetation[c]			Restricted: forests, high shrubs areas, fruit trees, gardens, vineyards	Restricted: forests				Preference to areas without vegetation[d]
Protected areas	Restricted: national parks, safari areas	Restricted: archeological sites, wildlife protection areas, biologically significant areas, environmental protection areas	Restricted: all	Restricted: historical and touristic monuments	Restricted: natural reserves		Restricted: all[e]		Restricted: all	Restricted: environmentally protected / sensitive areas	Restricted: landscape designations,[f] wildlife designations,[g] historically important areas[h]	Restricted: breeding or nesting sites, cultural and historic areas, recreation areas		Restricted: national parks, nature parks, areas of community interest, bird sanctuary, livestock paths, natural cattle trails, cultural heritage sites
Distance to protected areas		Buffer distance 0.5 km									Buffer distance 1 km; maximize distance to wildlife designations and historically important areas	Optimize distance with regard to social acceptance data		Preference to areas with minimum-value scenery
Water bodies (i.e., rivers and lakes, wet-lands)	Restricted	Restricted	Restricted	Restricted	Restricted	Restricted	Restricted	Restricted: major lakes and rivers, and wetlands	Restricted: lakes, rivers, marshland	Restricted: water bodies, rivers, wetlands			Restricted: water bodies, rivers	Restricted: rivers, coastlines
Risk areas				Restricted: flood zones and windy areas					Restricted: areas within 100 m from rivers	Restricted: flood plains, areas vulnerable to landslides				Restricted: buffer accounted for rivers, coast-affected zones

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Table A.1 *(continued)*

Criteria	Ziuku et al. [29]	Uyan [42]	IRENA studies [31,54]	Studies by Charabi, Gastli et al. [28,32–34,49]	Sun [22]	Janke [44]	Sánchez -Lozano et al. [45,46]	Djebbar et al. [30]	Anwarzai et Nagasaka [50]	Sabo et al. [47]	Watson et al. [53]	Brewer et al. [43]	Polo et al. [51]	Carrión et al. [57,58]
Distance to water for CSP	Distance to water bodies 30 km max.		Factor discussed	2 km max	n/a		n/a		Areas within 100 m – 10 km of rivers			Minimize distance to rivers; 45 km max.		
Other land cover		Restricted: dams with no buffer distance, military areas with buffer distance 0.5 km		Restricted: sand dunes		Restricted: dunes, bedrock scree, ice, cliffs, canyons, alpine tundra, mines, federal lands	Restricted: mountains, military zones		Restricted: large hills and big mountains, sand dunes, permanent snow areas preferred: rock outcrop / bare soil, sand covered area					Restricted: public channels, police areas
Solar irradiance for PV		Not evaluated as criteria, as solar irradiance is between 1650 and 1700 kWh/ m^2/ year	Min. GHI 1000–1500 kWh/ m^2/ year	Factor accounted		Maximize kW/ m^2/ day	Maximize kJ/ m^2/ day		GHI > 3.5 kWh/ m^2/ day	Classified: <= 5 kWh/ m^2/ day; > 5 kWh/ m^2/ day	Maximize kWh/ m^2/ year	Maximize irradiation; 3 kWh/ m^2/ day min.		Maximize GHI, diffuse radiation and annual equivalent sun hours
Solar irradiance for CSP	Min. DNI 2000 kWh/ m2/ year; in literature review DNI > 4.1–7 kWh/ m^2/ day		Min. DNI 1800 kWh/ m^2/ year	Factor accounted		Maximize W/ m^2/ day		Min. DNI 1500 kWh/ m^2/ year	DNI > 5 kWh/ m^2/ day			Maximize irradiation; 3 kWh/ m^2/ day min.	Min. DNI 1500 kWh/ m^2/ year	
Distance to grid (i.e. electricity grid lines)	Distance to electricity grid lines 30 km max; in literature review distance < 1–40 km	Minimize distance to electricity grid lines; categories: < 3 km, 3–6 km, 6–10 km, > 10 km.	Distance to electricity grid lines up to a max. threshold for grid-connected systems; from a min. threshold for off-grid; categories (centralized systems only): 20, 75, 100, 150 km	Minimize distance		Minimize distance	Minimize distance			> 500 m < 10000 m	Minimize distance	Minimize distance; 85 km max.		Minimize distance to transmission lines and substations; categories of distance to substations: < 1 km, 1–2 km, 2–10 km, > 10 km

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Table A.1 (continued)

Criteria	Ziuku et al. [29]	Uyan [42]	IRENA studies [31,54]	Studies by Charabi, Gastli et al. [28,32–34,49]	Sun [22]	Janke [44]	Sánchez -Lozano et al. [45,46]	Djebbar et al. [30]	Anwarzai et Nagasaka [50]	Sabo et al. [47]	Watson et al. [53]	Brewer et al. [43]	Polo et al. [51]	Carrión et al. [57,58]
Max. slope for PV plants		3°; categories: < 1°, 1–2°, 2–3°, > 3°.	45° (for grid-connected systems), no limits for off-grid	5°	4°		Minimize slope		5°	5°, elevation < 60 m	10%	Minimize slope	3°	2%, no shadows; OR minimization preference from 30% to 3%
Max. slope for CSP	3°; classes: < 3° suitable, 3–7° moderate, > 7° unsuitable; in literature review slope < 1–7° depending on technology.		2.1°	1° for parabolic trough and power tower, 3–5° for parabolic dish				1–4°	1–3°			Minimize slope	3°	
Field orientation							Southwards				Only SE-SW aspect			Preference to southwards
Required area for grid-connected PV							1000 m^2 min.; maximize plot area		0.4 km^2 min.	> = 165 acre				
Required area for CSP plant	0.25–5km² for parabolic trough; 0.36–7.2 km2 for solar tower; 0.00011–0.0044 km2 for parabolic dish; 0.08–1.6 km2 for linear Frensel reflector			2 km^2 Min.[i]					2.2 km^2 min.					
Land occupancy factor[j] for a			5	1.43[k]					1.4386					

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Table A.1 *(continued)*

Criteria	Ziuku et al. [29]	Uyan [42]	IRENA studies [31,54]	Studies by Charabi, Gastli et al. [28,32–34,49]	Sun [22]	Janke [44]	Sánchez -Lozano et al. [45,46]	Djebbar et al. [30]	Anwarzai et Nagasaka [50]	Sabo et al. [47]	Watson et al. [53]	Brewer et al. [43]	Polo et al. [51]	Carrión et al. [57,58]
large-scale PV plant														
Land occupancy factor for CSP			5–10 (7.5 used in calculations)					2.9[l]	10					
Average annual temperature							Factor accounted							Factor accounted

[a] Settlements represent a restriction criteria for ground-based technologies. For roof-top technologies a part of built-up area may be used. However, this option is out of the scope of the present study.
[b] Including dams.
[c] Preferable vegetation includes "shrubs, prairie, grasses, scrub, steppe, agriculture, logged areas, or barren lands". Not suitable areas include "taller vegetation (pinon, juniper, or ponderosa woodlands)". Non-ideal vegetation includes "pine, subalpine, and aspen forest".
[d] In order of preference: « Area without vegetation", "Dryland herbaceous crops", "Irrigated herbaceous crops", "Herbaceous and woody crops", "Woody crops", "Other uses" [58]..
[e] According to the authors, installation of solar power plant in a protected area would require "an environmental impact assessments and therefore, this area would be considered as unsuitable as the location" [45]. Therefore, they adopt a conservative approach and remove all protected areas from the analysis. Protected areas namely include protected and undeveloped lands, areas of high landscape value, archeological and paleontological sites, cultural heritage, community interest sites and cattle trails.
[f] Including National Parks and Areas of Outstanding National Beauty.
[g] Including UK Sites of Special Scientific Interest, National and Local Nature Reserves, European Special Protection Areas and Special Areas of Conservation and international Ramsar sites.
[h] Including battlefields, national scheduled monuments and UNESCO world heritage sites.
[i] According to Gastli and Charabi a 100 MW CSP power plant consumes about 2.4 km2 of land [33]. However, land requirements highly depend on type of technology used [28].
[j] Land occupancy factor represents the ratio of total land requirements to the surface of PV panels or CSP collectors.
[k] The authors use a term "area factor" and give the following definition: "The area factor, indicates what fraction of the calculated areas can be covered by solar panels". They use the area factor value of 70% for large PV farms [49]. The same value is used in the study performed by Khan and Rathi for India [61].
[l] The similar value is mentioned by Broesamle et al. and equals 3 [55].

Appendix B

See Table B.1.

Table B.1
Summary of weights of factors and restrictive criteria used in the reviewed literature.

Factor	Ziuku et al. [29]	Charabi et Gastli [34]	Uyan [42]	Sánchez -Lozano et al. [45]	Janke [44]	Watson et al. [53]	Brewer et al. [43]	Carrión et al. [58]
Solar irradiance	26.83	0.545		23.802	3	0.489	1.1	30
Equivalent sun hours								25
Distance to power lines	2.15		0.748	32.539	2	0.259	0.8	
Distance to substations				8.946				2
Distance to major roads		0.168	0.071	4.291	1	0.069	1	2
Distance from settlements (maximization)			0.250		1	0.049		
Distance to settlements (minimization)				2.849				2
Distance to water bodies	10.73						0.8	
Distance from historically important areas						0.065		
Distance from wildlife designations						0.069		
Visual impact								4
Land slope	10.73		0.180	11.203			1	9
Land orientation				4.815				7
Plot areas				1.241				
Land cover (various content depending on a study)	3.22		0.750		1			5
Agrological capacity				5.553				
Population density					1			
Average temperature				4.7604				14
Restrictive criteria (various content depending on a study)		0.287			1			

Appendix C. Supplementary material

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.rser.2017.06.021.

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