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Geospatial Quantification of the Energy Economic Potential for Utility-Scale Photovoltaics: Case of the United Arab Emirates

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Abstract

An enhanced methodology for the assessment of energy economic potential for utility-scale photovoltaics is proposed in this paper. Independent methods are presented for the quantification of resource, technical, and economic potentials. The methodology is demonstrated through a case study focusing on the territory of the United Arab Emirates (UAE). The technical potential is computed by means of a locally validated PV plant performance model and the economic potential by estimating levelised cost of electricity (LCOE) based on detailed and spatially variable cost data. The results of the case study indicate a large potential for utility-scale photovoltaics in the UAE. At an electricity price of 0.07 USD per kWh, the economic potential is identified as approximately 10 EJ – 26-fold the country's electricity demand in 2013.

Keywords: solar photovoltaic, levelised cost of electricity, potential assessment

1. Introduction

Geospatial analysis based on geographic information systems (GIS) is a commonly used method for the site selection of solar photovoltaic (PV) power stations. The objective of such analysis is to identify the areas with the highest potential for PV power generation. The potential of a renewable energy source can be evaluated at three different levels: resource or theoretical potential (RP), technical potential (TP), and economic or energy economic potential (EP). Fig. 1 illustrates the potentials as three overlapping rectangles in two dimensions specified as surface area and unit-area-specific average energy content. RP assessment is a necessary first step when quantifying TP. TP, in turn, is the basis of EP assessment.

RP refers to the total amount of energy theoretically available in a renewable resource in the area of interest over a time period that is sufficiently long to cover most of the range of the resource's variability. Therefore, in the context of PV power generation, an appropriate definition of RP is the global normal irradiation (H_n) received in the area of interest during a typical meteorological year (TMY). There is a wide variety of scientifically validated models for geospatial solar resource assessment. Some of them are demonstrated by the International Renewable Energy Agency in their Global Atlas for Renewable Energy (International Renewable Energy Agency (IRENA), 2015). The maps visualising PV RP often show global horizontal irradiation (H) instead of H_n. Global horizontal irradiance (G) can be converted into global normal irradiance (G_n) by means of irradiance decomposition and transposition models. G and G_n are the first temporal derivatives of H and H_n, respectively.

TP is dependent on the energy conversion efficiency and land use-related limitations of the technology of interest. The power output of PV devices is reduced by loss mechanisms that are affected by ambient parameters. In accordance with RP, PV TP can be defined as the annual amount of electrical energy supplied by a group of PV power stations covering the entire technically suitable part of the area of interest. PV TP with and without territorial constraints has been evaluated by numerous authors for different parts of the

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Latin symbols

G	global horizontal irradiance [W/m²]
G_i	global irradiance incident on plane [W/m²]
$G_{b,n}$	beam normal irradiance [W/m²]
G_d	diffuse horizontal irradiance [W/m²]
G_{eff}	effective irradiance [W/m²]
G_n	global normal irradiance [W/m²]
$G_{toa,n}$	normal irradiance at TOA [W/m²]
H	global horizontal irradiation [J/m²]
H_n	global normal irradiation [J/m²]
I_{sc}	short circuit current of a solar cell [A]
N_c	number of solar cells per module
P_{stc}	module output power under STC [Wp]
T_a	ambient air temperature [K]
T_c	solar cell temperature [K]
v_w	wind speed [m/s]

Greek symbols

η_c	solar cell efficiency [%]
η_s	PV system efficiency [%]
θ	angle of incidence [rad]
θ_S	solar zenith angle [rad]
ϕ_S	solar azimuth angle [rad]

Subscripts

b	beam
c	solar cell
d	diffuse
eff	effective
i	incident
n	normal
S	the Sun
s	PV system
sc	short circuit
stc	standard test conditions
toa	top of the Earth's atmosphere
w	wind

Abbreviations

AC	alternating current
CdTe	cadmium telluride
CF	plant capacity factor
c-Si	crystalline silicon
DC	direct current
EP	economic potential
EPC	engineering, procurement and construction
GIS	geographic information system
LCOE	levelised cost of electricity
MBtu	million British thermal units
mc-Si	monocrystalline silicon
O&M	operation and maintenance
pc-Si	polycrystalline silicon
PV	solar photovoltaic
RP	resource potential
STC	standard test conditions
TMY	typical meteorological year
TOA	top of the Earth's atmosphere
TP	technical potential
UAE	United Arab Emirates
USD	United States Dollar

world (e.g. Beták et al., 2012; Domínguez Bravo et al., 2007; Lopez et al., 2012; Šúri et al., 2007). A widely used tool for the geospatial analysis of PV TP is PVGIS covering Europe, Africa, and Asia (European Commission, Joint Research Centre, Institute for Energy and Transport, 2014; Huld et al., 2005; Šúri et al., 2005).

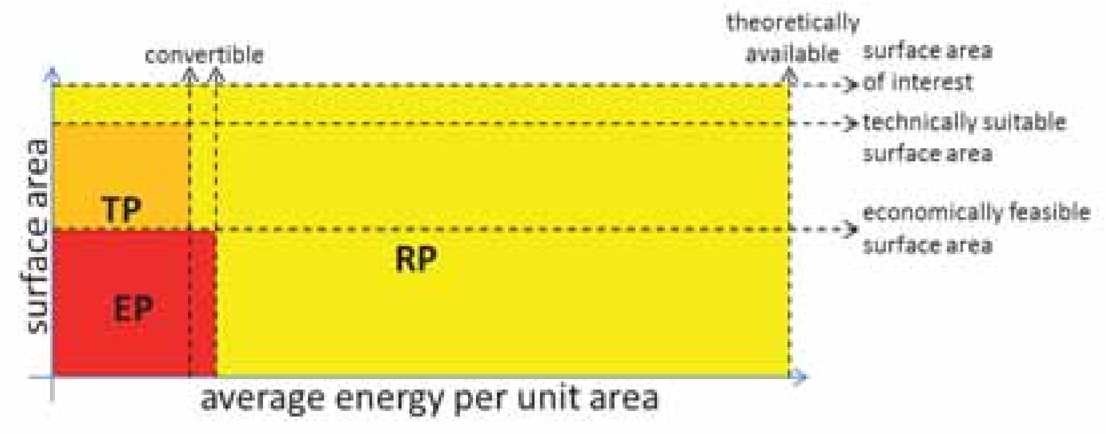

Fig. 1: The relation of renewable energy potentials to energy convertibility and site suitability

The economic viability of renewable energy-based power generation is primarily determined by its unit energy cost i.e. levelised cost of electricity (LCOE). Provided that consumers and policy makers do not have power source-specific preferences, there is no EP for a technology at a site where the competing technologies can generate electricity at a lower cost. Hence, in this paper, EP for a technology is defined as the amount of electrical energy that no other technology can supply at a lower cost in the area of interest. Due to the poor availability of component and infrastructure-related cost data, the quantification of EP is more difficult than that of TP. That is why when assessing PV EP, most authors have settled for fuzzy logic-based models which score sites based on their suitability for PV power generation rather than actually computing LCOE estimates. Suganthi et al. (2015) review studies applying fuzzy logic to PV EP assessment. While the LCOE-based EP quantification is a common topic amongst the scholars of solar thermal technologies (starting from Broesamle et al., 2001), PV EP is found to be geospatially quantified based on LCOE estimates only in three published studies – by Sun et al. (2013) in Fujian, China and by Ossenbrink et al. (2013) and by Huld et al. (2014) by means of PVGIS in Europe.

In addition to the absolute level of PV EP, the focus of PV plant site zoning studies lies on the spatial variability of site suitability. Therefore, special attention should be paid to appropriately modelling the impact of spatially variable parameters, be they ambient variables or cost components. Sun et al. (2013) base their PV EP assessment on simplistic PV TP quantification assuming horizontally fixed PV array mounting and a performance ratio, which is constant in space. In other words, they assume the spatial variability of potential PV system output to be entirely dependent on the variability of H ignoring the impact of the other spatially variable ambient factors. Also, apart from the sites located near the Equator, PV arrays with fixed mount are usually tilted and therefore, irradiance incident on the plane of arrays (G_i) is the primary performance factor rather than G. By contrast, Ossenbrink et al. (2013) and Huld et al. (2014) consider G_i and vary PR in space addressing the nonlinear effects of T_a and G_i on module output power. Their performance ratio maps are based on a model proposed by Huld et al. (2011) for crystalline silicon wafer-based (c-Si) solar modules. Since Ossenbrink et al. (2013) and Huld et al. (2014) only analyse the LCOE of building-applied PV systems, it is justifiable to use a model that has been exclusively developed for c-Si modules as other module types are rarely used in such systems. As for the EP assessment of utility-scale photovoltaics however, it is important to also consider other module types. In addition to ambient parameters, some of the engineering, procurement and construction (EPC) as well as operation and maintenance (O&M)-related costs show spatial variation. The reviewed past PV EP assessment studies, however, assume all costs to be constant in space.

Previous work by Sun et al. (2013), Ossenbrink et al. (2013), and Huld et al. (2014) is enhanced by complementing PV EP quantification methodologies with more comprehensive PV performance modelling tools as well as more detailed and spatially variable cost data. This paper describes the modified methodology and presents the results of its application using five different PV plant configurations in the United Arab Emirates (UAE). Utility-scale photovoltaics in the UAE is an interesting subject for the case study due to the large potential indicated by previous studies (e.g. Beták et al., 2012; Mokri et al., 2013; Sgouridis et al., 2015) against the relatively modest installed capacity of 23 MWp (Abu Dhabi Future Energy Company PJSC, 2015; First Solar, Inc., 2015) and 340 MWp under development (Dubai Electricity & Water Authority, 2015; Middle East Solar Industry Association, 2015). In addition to proposing novel methods for PV EP assessment, this study aims to serve the various actors working on PV plant siting and zoning in the UAE by creating up-to-date high-resolution information about the spatial variability of PV EP in the country.

The proposed methodology is demonstrated at the hourly scale based on a database of irradiance and meteorological parameters for the year 2013. Spatial referencing is performed through an equal-area map projection with a resolution of 1000 metres. As each considered map pixel is assumed to be covered by the largest possible PV plant that can be fitted in the pixel, plant surface area does not show systematic spatial variability. However, due to the significance of latitude in optimal array inclination and row spacing, plant capacity does. Thus, capacity cannot be specified as a fixed PV plant configuration parameter.

The parameters of the five fixed plant configurations are specified in Tab. 1. The three commercially dominant PV materials are considered: monocrystalline silicon (mc-Si), polycrystalline silicon (pc-Si), and cadmium telluride (CdTe). The first three configurations are equipped with each of the three module types with fixed polar-aligned mounting. The two remaining configurations involve high-efficiency mc-Si wafer-based modules mounted on horizontal single axis or dual axis trackers. Inverters are sized based on an array-to-inverter loading ratio. The loading ratios given in Tab. 1 are approximate optimal loading ratios derived through plant design optimisation based on irradiance and meteorological observations made at a coastal (24.42 °N, 54.61 °E) and an inland site (23.90 °N, 55.50 °E) in the UAE over a three-year period from 2009 until 2011. The design optimisation is performed through maximising the simulated yield of each configuration in both locations by varying the loading ratio from 50 to 150 per cent at intervals of five per cent.

In the UAE, electricity is mostly generated by combined cycle power plants that use natural gas as the primary fuel. Therefore, PV EP is calculated based on the price of natural gas under different market conditions. Drawing on the analysis of Sgouridis et al. (2015), resale prices at 6, 10, and 14 United States Dollars (USD) per million British thermal units (MBtu) are considered.

Tab. 1: PV power station configurations considered

Configuration identifier	Module type	Mounting method	Inclination	Array-to-inverter loading ratio
mc-Si-fm	mc-Si, N_c: 72, P_{stc}: 340 Wp	fixed mount	polar-aligned	115%
pc-Si-fm	pc-Si, N_c: 72, P_{stc}: 310 Wp	fixed mount	polar-aligned	115%
CdTe-fm	CdTe, N_c: 146, P_{stc}: 100 Wp	fixed mount	polar-aligned	110%
mc-Si-1t	mc-Si, N_c: 128, P_{stc}: 455 Wp	single axis tracking	horizontal	110%
mc-Si-2t	mc-Si, N_c: 128, P_{stc}: 455 Wp	tip-tilt dual axis tracking	-	105%

N_c: number of individual cells, P_{stc}: output power under standard test conditions (STC)

Sections 2-4 discuss each of the three levels of PV potential. All the three sections consist of two subsections. The first subsection describes the proposed methods while the second one specifies the case-specific inputs and shows the outcome of their application to utility-scale photovoltaics in the UAE. The case study follows the proposed methodology but due to limited data availability, simplifying assumptions are deployed.

2. Assessment of Resource Potential

2.1. Proposed Methodology

As explained in section 1, PV RP is defined as H_n in the territory of interest over a TMY. A TMY dataset is constructed instead of using the entire spatiotemporal database in order to reduce the computational requirements. Yearly average datasets are easier to generate but their usage is not recommended because they smoothen out natural variability and do not preserve persistence of temporal patterns and information related to the consistency and coevolution of different variables. This is problematic from the viewpoint of PV performance modelling as PV plant output is nonlinearly dependent on multiple ambient parameters. More information is preserved when using TMY dataset construction methods that are based on the concatenation of continuous multivariate time series spanning those individual months that are found to provide the best agreement with long-term monthly statistics (e.g. Cebecauer and Šúri, 2015; Kalogirou, 2003; Marion and Urban, 1995). How different variables are weighted when quantifying monthly representativeness depends on the application. Cebecauer and Šúri's (2015) proposal for the PV power generation-specific set of TMY variables is G, diffuse horizontal irradiance (G_d), and ambient air i.e. dry bulb temperature (T_a) with the respective weights of 0.75, 0.20, and 0.05. Thereby, T_a indirectly influences PV RP estimation. As for the source data, Cebecauer and Šúri (2015) recommend using time series of 15 years or more to establish a good representativeness of the long-term solar climate.

As H_n is an extensive physical property, an equal-area map projection (e.g. Mollweide projection or Lambert cylindrical equal-area projection) has to be applied to the TMY maps in order to avoid map pixel size-related bias in the pixel-specific H_n estimates. For example, when using the reference coordinate system of the Global Positioning System (WGS 84) with a spatial resolution of 0.02° and without an equal-area map projection, the pixel surface areas at 20 °N are approximately nine per cent greater than those at 30 °N.

H_n estimates are computed based on the equal-area projected TMY time series of maps of G, G_d, beam normal irradiance ($G_{b,n}$), solar zenith angle (θ_S), and solar azimuth angle (ϕ_S). In addition, a spatially constant time series of normal irradiance at the top of the Earth's atmosphere ($G_{toa,n}$) is required. An irradiance transposition model (e.g. Hay, 1979; Muneer, 1990; Perez et al., 1990; Reindl et al., 1990a) enables the conversion of these data into G_n maps. If not readily available, $G_{b,n}$ and G_d estimates can be derived from G

data by means of an irradiance separation i.e. decomposition model (e.g. Erbs et al., 1982; Perez et al., 1992; Reindl et al., 1990b). θ_S, ϕ_S, and $G_{toa,n}$, in turn, can be computed through a solar geometric algorithm (e.g. Blanc and Wald, 2012; Duffie and Beckman, 2006, pp. 12–16; Reda and Andreas, 2008). Finally, the resulting G_n maps are integrated over time into a single H_n map, which is further integrated over space to obtain a PV RP estimate for the territory of interest.

2.2. Resource Potential in the UAE

The spatiotemporal database of irradiance (G, $G_{b,n}$, and G_d) for the UAE is created by means of an artificial neural network-based model proposed by Eissa et al. (2013). The model uses satellite-based SEVIRI images as input data and has been developed based on ground observations from five monitoring stations in the UAE. The resulting irradiance maps cover the year 2013 with a temporal resolution of 15 minutes and a spatial resolution of 0.02° (in WGS 84). Minor discrepancies in the spatial resolutions of the source data are removed by resampling the anomalous maps through nearest-neighbour interpolation. Irradiance data gaps are filled by interpolating and extrapolating clear-sky indices calculated based on the McClear algorithm (Lefèvre et al., 2013). As the timeframe of the data used in this case study spans only one year, no TMY dataset is constructed. Hence, the results of the study cannot be generalised to other years.

The Mollweide equal-area projection is applied to the input data maps. When reprojecting the maps, their spatial resolution is converted from 0.02° to 1000 metres. As explained in section 2.1, solar position (θ_S, ϕ_S, and $G_{toa,n}$) has to be known in order to estimate G_n. The solar geometric parameters are computed by means of the Solar Geometry 2 (SG2) algorithm developed by Blanc and Wald (2012). The SG2 algorithm is selected because it is computationally efficient with an accuracy only slightly surpassed by Reda and Andreas's (2008) Sun Position Algorithm, which is commonly considered as the state of the art in terms of accuracy.

Transposition models, which convert G, $G_{b,n}$, G_d, and solar geometric data into G_i estimates, comprise transposition processes for $G_{b,n}$, diffuse sky irradiance, and ground-reflected irradiance. In the case of G_n, $G_{b,n}$ is not transposed as it is always normal to the receiving surface. Tuomiranta and Ghedira (2015) evaluate 18 sky diffuse and four ground-reflected irradiance transposition models under the conditions of the UAE. They find the best agreement with ground observations with the model proposed by Perez et al. (1990) for sky diffuse irradiance and the model proposed by Badescu (2002) for ground-reflected irradiance. Accordingly, the two models are used to generate the G_n maps in the present study.

Fig. 2 presents the findings of the PV RP assessment. The resulting H_n estimates translate into a PV RP of 872 EJ for the UAE. At the sites with the most abundant solar resource, H_n is estimated to be 17 per cent higher than at the least sunny sites, which are concentrated in the coastal areas.

3. Assessment of Technical Potential

3.1. Proposed Methodology

As discussed in section 1, PV TP is defined as the maximum amount of electrical energy that can be supplied from PV power stations to consumers in the territory of interest over a TMY. The geographic area considered in PV TP assessment is limited by technical suitability. In other words, any site whose utilisation is possible when cost-related criteria are not taken into consideration is assumed to have nonzero PV TP. The excluded sites include all areas that cannot be used for reasons other than economic, e.g. areas protected for their natural, cultural, or other public welfare-related value such as nature reserves, historical monuments, and areas under a restrictive urban planning code.

Prior to the actual plant performance simulation, PV plant system architecture needs to be determined for every site. Due to the definition of PV TP, the maximum surface area of each plant is the pixel area. Based on the desired loading ratio and row spacing requirements as well as the maximum number of modules in a string, the plant capacity and the other system configuration-related parameters are computed. In order to enable detailed PV EP assessment, it is recommended to calculate the numbers of at least those components, for which there are cost data available. The components, whose number is directly dependent on plant sizing, include solar modules, mounting structures, inverters, transformers, junction boxes, and cables.

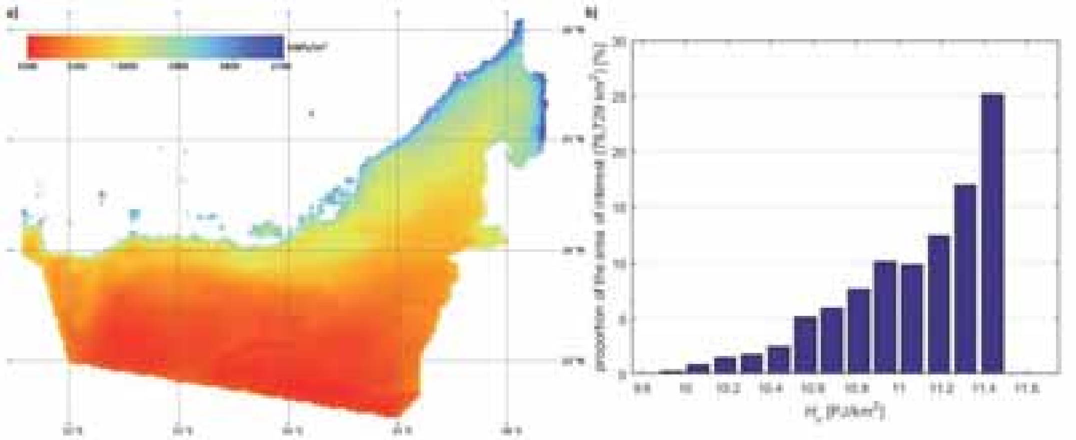

Fig. 2: PV RP in the UAE; a) map of H_n per m^2, b) histogram of H_n per km^2

The proportion of PV RP that can be converted into electricity depends on the ratio of G_i to G_n and PV system efficiency (η_s). While G_n stands for the theoretical maximum irradiance capable of being received by a solar module mounted on the Earth's surface, G_i refers to the irradiance actually incident on the module considering the mounting method and shading conditions. Geometric models (e.g. Duffie and Beckman, 2006, pp. 20–23; Marion and Dobos, 2013; Narvarte and Lorenzo, 2008) are used to compute the incidence angle of incoming irradiance (θ), which is input to a transposition model in order to obtain G_i in different plant configurations. Theoretically, a plant with dual axis tracking installed on a flat terrain with a very low ground coverage ratio can reach a unity G_i-G_n ratio.

By contrast, η_s cannot reach 100 per cent due to losses fundamentally associated with the operation of semiconductor-based solar cells: spectral mismatch and charge carrier recombination. In addition, utility-scale PV power conversion involves extrinsic optical losses, recombination via impurities, and parasitic losses. Each loss process is determined by both ambient and technological parameters. The ambient parameters of relevance include level, spectral distribution, and θ of incoming irradiance, T_a, sky temperature, wind speed (v_w), wind direction, and dust deposition. The technological parameters are subject to the selected module type and system architecture of each plant. Finally, the amount of electrical energy actually supplied to consumers is dependent on the losses of power transmission.

As illustrated in Fig. 3, the simulation of η_s is divided into three components: optical, thermal, and electrical modelling. Most of the models following this approach make use of the STC parameters that are commonly measured and available in module datasheets. Based on its STC parameters, a solar module's performance is known under a set of standard conditions to which the operating conditions can be compared.

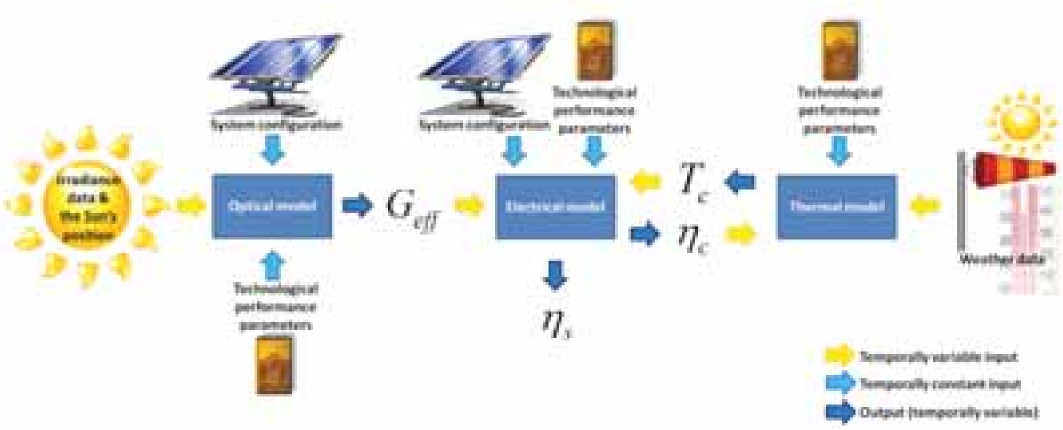

Fig. 3: Steps involved in modelling η_s

Under STC, a solar module receives irradiance that is normal to its surface and whose spectral distribution follows the standard spectrum at an air mass coefficient of 1.5 (G03 Committee, 2012). The purpose of an optical model is to address the performance effects of the deviations of the spectrum and θ from STC. The additional attenuation due to dust deposition should be quantified. For this purpose, an optical model converts G_i and θ as well as dust deposition and spectral distribution-related data into effective irradiance (G_{eff}). G_{eff} is adapted from G_i such that a solar cell's short circuit current (I_{sc}) is always linearly dependent on it. In G_{eff}, the effects of changing spectrum, angular reflection losses, and dust deposition are isolated by normalising $G_{i,stc}$ (1000 W/m^2) by the ratio of I_{sc} to $I_{sc,stc}$. Thus, $G_{eff,stc}$ is equal to $G_{i,stc}$. I_{sc} is estimated by means of modifier equations for θ (e.g. Davis et al., 2002; Duffie and Beckman, 2006, p. 234; Souka and Safwat, 1966) and spectral distribution (e.g. Betts et al., 2004; King et al., 1998; Martín and Ruiz, 1999). The impact of dust deposition should be considered on its own (e.g. Kimber et al., 2006) as well as in association with θ and spectral modifiers (e.g. Martín and Ruiz, 2005).

The purpose of a thermal model is to simulate the temperature of a solar cell's photoactive layers (T_c), which is the primary effective variable involved in η_s modelling. The fundamental basis of the simulation of T_c is the heat transfer energy exchange of a solar cell's active components with the surrounding layers and ambient air. Therefore, T_c can be obtained through transient heat transfer modelling or by means of one of the numerous empirical and semi-empirical models and correlations (see e.g. Skoplaki and Palyvos, 2009a). The most significant ambient parameters are T_a, G_i, and v_w. Since the internal heating process within a solar cell depends on the efficiency at which the cell is converting radiation into electricity, most of the T_c modelling formulations also include cell efficiency (η_c) as an input variable.

The effective variables, G_{eff} and T_c, are converted into η_s by an electrical model with three components addressing power generation (e.g. De Soto et al., 2006; King et al., 2004; Mermoud and Lejeune, 2010; Sutterlueti et al., 2011), transmission, and conversion (e.g. Baumgartner et al., 2007; Driesse et al., 2008; King et al., 2007). A power generation model simulates all losses occurring inside solar cells. If T_c is simulated by means of a thermal model which is dependent on η_c, the thermal model and the electrical model for generation are coupled and, therefore, comprise a thermoelectrical model. The numerous empirical relationships (see e.g. Skoplaki and Palyvos, 2009b) between η_c and ambient and technological parameters are not recommended due to their weak generalizability across different locations and technologies. Nevertheless, the effects of time-dependent degradation (see e.g. Jordan et al., 2012) and performance mismatch between modules and arrays are generally considered through empirically determined, fixed loss percentages. Models for transmission and conversion address the losses occurring in conductors and power conditioning equipment, respectively. Power transmission losses are due to Joule heating and power conversion losses due to the conversion of direct current (DC) into alternating current (AC) in inverters and stepping up plant output voltage in transformers.

Furthermore, η_s is affected by a power station's auxiliary consumption. While inverter self-consumption during power conversion is considered by most inverter performance models, power losses due the consumption of trackers, air conditioning units, lighting, plant management equipment, and inverters' nocturnal standby operation have to be additionally quantified. The consumption levels of trackers and inverters are available in product datasheets. Air conditioning-related losses can be estimated by heat transfer modelling (e.g. International Organization for Standardization, 2008), which is also enabled by various software packages used for sizing air conditioning units.

The instantaneous PV plant output power can be computed as a product of G_i and η_s. As PV TP represents the amount of electricity supplied to consumers, the final step is the estimation of transmission losses for each site. Apart from the plants' own power consumption, all power demand is assumed to be concentrated on the urban areas excluded from the assessment. Transmission losses are computed for each site based on the weighted average distance to the nearest demand concentration areas using a reference high-voltage transmission line and increasing quadratically with plant output power. The transmitted power, when integrated over time and space, provides the PV TP of the territory of interest.

3.2. Technical Potential in the UAE

Area-wise, we exclude areas with conservation status as specified in the World Database on Protected Areas (International Union for Conservation of Nature and United Nations Environment Programme World Conservation Monitoring Centre, 2015) and urban status classified manually using open access geographical information software. The excluded areas represent 21 and 2 per cent of the entire area of interest, respectively.

As explained above, PV TP assessment requires data on meteorological parameters in addition to irradiance – most importantly T_a and v_w. A locally calibrated global atmospheric model is used to retrieve the relevant data. Due to the optical and thermal models of choice, spectral data as well as data on sky temperature and wind direction are not needed.

Both the plant's system architecture and performance are simulated by means of a PV plant performance simulator (Tuomiranta, 2014). The simulator incorporates locally validated optical and thermal models and Sandia's electrical models for generation and conversion (King et al., 2007, 2004). The impact of soiling is addressed by a fixed loss percentage together with the dust deposition-dependent θ modifier model proposed by Martín and Ruiz (2005). This simplified approach is justified as PV arrays installed in the UAE can be assumed to be regularly cleaned. Therefore, dust deposition can be primarily considered as an O&M cost factor. Spectral correction is not applied due to the lack of models appropriately validated for desert climates characterised by severe aerosol loading. The thermal model found to provide the best agreement with local measurements is the one proposed by Schott (1985) (Tuomiranta et al., 2014). This semiempirical model predicts T_c based on T_a, G_{eff}, v_w, and η_c and is calibrated based on measurements made in Abu Dhabi (Tuomiranta et al., 2014).

As PV TP represents the maximum amount of electrical energy that can be supplied in a territory of interest, a single power station can be assumed to serve the entire territory rather than the areas in its proximity. Accordingly, transmission losses are estimated by means of an approximated power demand-weighted average distance to all urban areas where the country's entire demand for electricity is assumed to be concentrated. The electrical properties of transmission lines are based on the parameters published by Abu Dhabi Transmission & Despatch Company (2013).

The results of the PV TP assessment are illustrated in Fig. 4. Due to its comparatively high ground coverage ratio and average η_s, configuration mc-Si-fm provides the highest TP at all sites in the UAE. Therefore, the PV TP histogram presented in Fig. 4b is solely based on the transmitted yields of mc-Si-fm type of power stations. Out of the total PV TP of 51 EJ, 11 EJ (22 per cent) is represented by the protected areas and 94 PJ (2 per cent) by the urban areas. The maximum plant yield (mc-Si-fm, 23.22 °N, 52.60 °E, 681 TJ) is 183 per cent higher than the minimum yield (mc-Si-2t, 25.29 °N, 56.37 °E, 240 TJ).

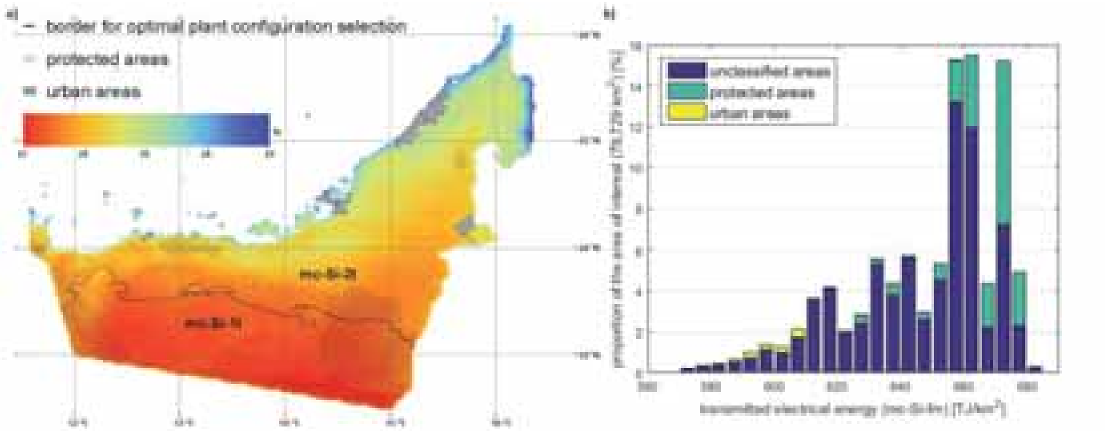

Fig. 4: PV TP in the UAE; a) map of CF and technically optimal plant configurations, b) histogram of transmitted electrical energy per km^2 separating the contributions of urban and protected areas

The map of Fig. 4a shows the spatial distribution of the highest simulated plant capacity factors (CF) considering transmitted electrical energy. Due to the high G_i-G_n ratio enabled by tracking, configurations mc-Si-1t and mc-Si-2t provide the highest CFs everywhere in the UAE. The G_i-weighted average T_c is lower in the case of configuration mc-Si-1t. Hence, configuration mc-Si-1t is the technically optimal choice for the southern part of the country, which experiences the highest G_i-weighted average T_a. The technically most appropriate site-configuration combination (mc-Si-1t, 23.69 °N, 53.23 °E, CF: 26.7%) provides 42 per cent higher CF than the technically poorest combination (pc-Si-fm, 25.90 °N, 56.12 °E, CF: 18.9%). Amongst the fixed mount configurations, CdTe-fm power plants operate at the highest capacity factor (21% on average) at all sites.

4. Assessment of Energy Economic Potential

4.1. Proposed Methodology

PV EP assessment mainly involves the estimation of the level and spatial distribution of different cost components in order to appropriately capture the spatial dynamics of PV LCOE. In the present paper, PV LCOE refers to the cost of electricity supplied to consumers by a PV power station when considering the entire lifetime of the power project. LCOE is sensitive to numerous cost factors, some of which are difficult to be quantified accurately. Due to site-specific plant configuration and other spatial cost factors, most costs show spatial variability.

PV project-related cost data are often given in price per Wp of module capacity. When comparing different sites and technologies, this highly case-specific cost indicator can be regarded as excessively simplified. Therefore, Wp-based cost data are recommended to be converted into more appropriate cost component-tailored indicators, which enable the allocation of spatial cost factors more accurately to the components actually affected. Such a set of indicators is proposed in Tab. 2. In addition to cost categorisation, the table specifies the spatial factors influencing each of the cost components. These factors do not include plant configuration-related parameters (e.g. capacity, array area, cable volume), which are also varied spatially in the present analysis.

Accurate quantification of the cost factors specified in Tab. 2 requires access to data that are often non-existent or unavailable free of charge. However, through publicly accessible industry review studies and interviewing local industry experts, many of the factors can be approximated without costly data acquisition. Land values can be estimated by correlating point data from real estate market with relevant spatial data such as land use and population density. Earthworks cost can be estimated by multiplying publicly available cost estimates by cut and fill volumes calculated based on a digital elevation model. PV system design software can be used to convert Wp-based EPC costs to component unit-based costs. Estimates of the effects of land cover, wind load, and slope as well as project development, O&M, and road and grid connection costs for land and sea can be obtained from experts. A critical component of O&M is array cleaning if the area of interest is under severe dust loading. A three-dimensional chemistry transport model such as CHIMERE can be used to estimate the spatial variability of dust deposition. By means of published average soiling loss percentages, the dust deposition estimates can be correlated to the desired cleaning frequency.

4.2. Energy Economic Potential in the UAE

A detailed listing of the different cost data is presented in Appendix A. As shown in Fig. 5a, the spatial variability of LCOE is significantly higher than that of PV RP or TP. In fact, the LCOE levels in the country's mountainous areas are far higher than the maximum specified in the legend. The two most significant cost factors that can be identified based on Fig. 5a are cut and fill volume contributing to earthworks cost and soil consistency affecting the foundation EPC cost. The areas with LCOE levels higher than 0.10 USD per kWh are characterised by highly variable terrain elevation and consequently high earthworks costs. Most of the areas with LCOE levels ranging from 0.08 to 0.10 USD per kWh are either covered by loose sand causing inconsistency in the surface soil or located on islands with a poor access to supporting infrastructure. The minimum LCOE of 0.0657 USD per kWh is reached by configuration mc-Si-fm at the site coordinates of 24.00 °N and 52.50 °E.

The natural gas prices of 6, 10, and 14 USD per MBtu correspond to conventional power LCOE estimates of 0.06, 0.08, and 0.11 USD per kWh. As can be seen from the histogram of Fig. 5b, there is no PV EP anywhere in the UAE if natural gas price is 6 USD per MBtu. At the price of 10 USD per MBtu, 32 % (16 EJ) of the country's surface area provides conditions for economically feasible PV power generation. The proportion becomes as high as 96% (49 EJ) at the price of 14 USD per MBtu. Fig. 6 illustrates PV EP in the

UAE in case the LCOE of conventional power generation is 7 USD per kWh (natural gas at 8.1 USD per MBtu). The resulting entire PV EP is 11 EJ, out of which protected areas represent 10%.

Tab. 2: Proposed cost categorisation and the spatial cost factors under consideration

Cost category	Cost component	Cost unit	Spatial cost factors
Land	Land acquisition	USD/ha (plant area)	• land value
	Earthworks	USD/m^3	• cut and fill volume
EPC	Foundation	USD/m^2 (array area with fixed mount and single axis tracking) / USD/tracker (dual axis tracking)	• land cover • road distance to a cement factory/industrial area • slope
	Mounting structures	USD/m^2 (array area) / USD/tracker	• wind load • slope
	Solar modules	USD/Wp	
	Module cables	USD/module	• slope
	Solar cables / DC main cables	USD/m^3 (cable volume)	• slope
	Junction boxes	USD/junction box	• slope
	AC BOS	USD/MVA	• slope
	Civil works	USD/ha (plant area)	• slope
	Auxiliary systems	USD/Wp	• slope
Supporting infrastructure	Road connection	USD/km	• Euclidean distance to a road • slope
	Grid connection	USD/km	• Euclidean distance to a transmission line • land/marine connection • slope
	Substation	USD/substation	• slope
Intra-country transportation		USD/m^3/km	• road/Euclidean marine distance to a primary port
Project development		USD (% of total EPC)	
O&M	Arrays	USD/m^2/year (array area)	• dust deposition • slope
	Civil works	USD/ha/year (plant area)	• slope
	Power block	USD/power block/year	
	Plant management	USD/MWp/year	
	Utilities	USD/MWp/year	
	Road connection	USD/km/year	• Euclidean distance to a road • slope
	Grid connection	% of transmission line cost	

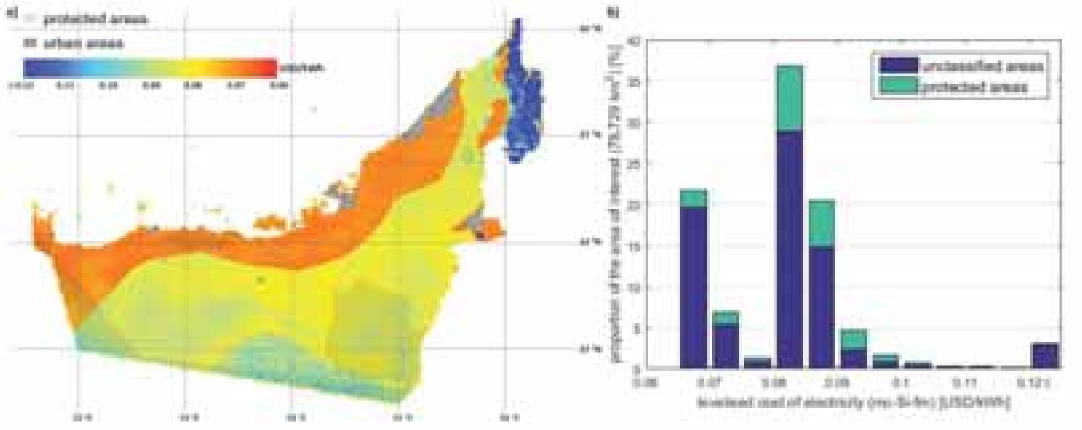

Fig. 5: PV LCOE in the UAE; a) map of minimum LCOE, b) histogram of the minimum LCOE estimates

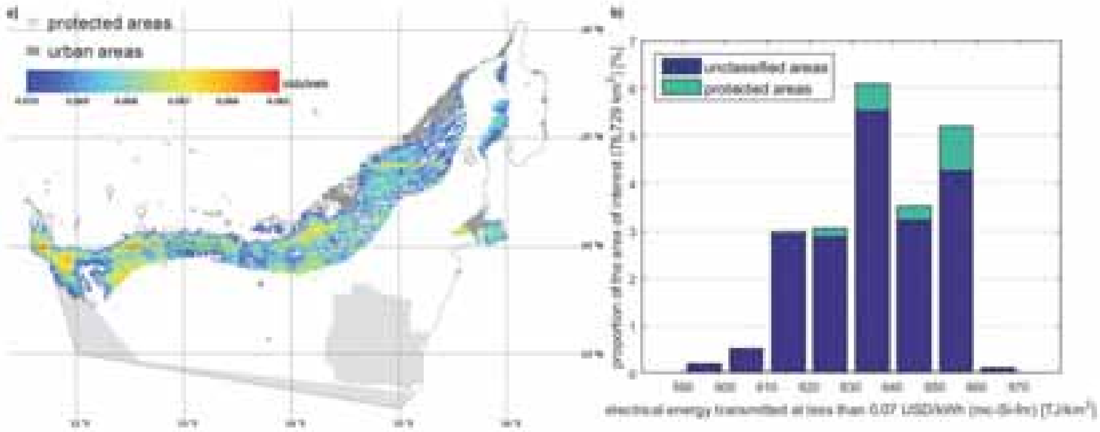

Fig. 6: PV EP in the UAE; a) map of LCOE in areas where PV competitive against natural gas at 8.1 USD/MBtu, b) histogram of transmitted electrical energy per km^2 from the highlighted area

In 2015, Dubai Electricity and Water Authority (DEWA) reached a financial close for a PV project of 200 MWp at a historically low price of 0.0598 USD per kWh (Dubai Electricity & Water Authority, 2015). This price is significantly less than the lowest LCOE level estimated in this study. It should be noted, however, that in this paper, PV potential is analysed from the governmental perspective. Thus, some cost components irrelevant for the companies bidding for DEWA’s project need to be considered. These components are mainly related to land and supporting infrastructure. In addition, financial parameters such as debt-to-equity ratio have a great impact on LCOE but are highly company-specific. The presented analysis is based on financial parameter values typical of the industry.

5. Conclusion

This paper presents an enhanced methodology for the assessment of energy economic potential for utility-scale photovoltaics. It is shown that by only using publicly accessible literature and expert interviews, high-resolution information about the spatial variability of PV potential can be generated. The methodology can be further improved by using optical models that capture local spectral and dust deposition-related particularities and more refined cost parameters e.g. for foundation construction. Also, the power demand-driven cost factors should be taken into consideration when taking the high-level, systemic approach in future studies.

The presented case study confirms the UAE’s tremendous PV potential indicated by previous studies by actually quantifying it for the entire country for the first time. Tab. 3 aggregates the findings and compares them to the annual power demand in the UAE in 2013. As can be seen from the table, the PV EP is 26-fold the country's electricity demand when considering an electricity price of 0.07 USD/kWh. These findings together with the recent advances in further capacity building indicate a bright future for PV power generation in the UAE.

Tab. 3: Comparison of the different levels of PV potential to the UAE's annual electricity demand in 2013

Potential	Entire territory	% of annual electricity demand (0.4 EJ, 2013)	Unclassified territory	% of annual electricity demand (0.4 EJ, 2013)
PV RP	872 EJ	231,000%	670 EJ	177,000%
PV TP	51 EJ	13,500%	39 EJ	10,300%
PV EP (≤ 0.11 USD/kWh)	49 EJ	13,000%	37 EJ	9,900%
PV EP (≤ 0.08 USD/kWh)	16 EJ	4,200%	13 EJ	3,400%
PV EP (≤ 0.07 USD/kWh)	11 EJ	2,900%	10 EJ	2,600%

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Appendix A

Cost component	Reference value	Modelling approach	Reference
Land acquisition		Spatial interpolation of point data on land value	dubizzle.com, 2015. Land for Sale [WWW Document]. URL https://abudhabi.dubizzle.com/property-for-sale/land/ (accessed 9.10.15)
Earthworks	3.27 USD/m^3 (sand) 49 USD/ m^3 (rock)	Averaging publicly available cost data; a multiplier of 15 for moving rock from expert interviews; cut and fill volumes from a digital elevation model; not deployed with dual axis tracking systems	Ghantoot Group, 2015. Major Projects [WWW Document]. URL http://ghantootgroup.com/marine.html (accessed 1.10.15) Industry expert interviews
Foundation	6.36 USD/m^2 of arrays (ramming for fixed mount and single axis tracking with noncorrosive soil types) 9.54 USD/m^2 of arrays (ramming for fixed mount and single axis tracking with corrosive soil types) 462.65 USD/tracker (ramming for dual axis tracking with noncorrosive soil types) 800.75 USD/tracker (ramming for dual axis tracking with corrosive soil types) 19.08-39.76 USD/m^2 of arrays (concrete for fixed mount and single axis tracking) 1388-2892 USD/tracker (concrete for dual axis tracking)	Concrete foundation used with inconsistent terrains (loose sand); manual territorial classification; varying concrete foundation cost with a distance to an industrial area; linear slope dependence starting from a slope of 15% with dual axis tracking systems	Industry expert interviews United States Geological Survey, United States Department of the Interior Google Inc, 2015. Google Maps [WWW Document]. URL https://www.google.ae/maps (accessed 1.10.15)
Mounting structures	22.26 USD/m^2 of arrays (fixed mount with a maximum wind gust of 30 m/s and below) 26.72 USD/m^2 of arrays (fixed mount with a maximum wind gust of more than 30 m/s) 809.65 USD/tracker (single axis tracking with a maximum wind gust of 30 m/s and below) 971.58 USD/tracker (single axis tracking with a maximum wind gust of more than 30 m/s) 2344.42 USD/tracker (dual axis tracking with a maximum wind gust of 30 m/s and below) 2813.30 USD/tracker (dual axis tracking with a maximum wind gust of more than 30 m/s)	Linear slope dependence starting from a slope of 8.5° with dual axis tracking systems	Industry expert interviews
Solar modules	0.57 USD/Wp (mc-Si, 340 Wp) 0.50 USD/Wp (pc-Si, 310 Wp) 0.53 USD/Wp (CdTe, 100 Wp) 0.66 USD/Wp (mc-Si, 455 Wp)		pvXchange Trading GmbH, 2015. Price Index [WWW Document]. URL http://www.pvxchange.com/priceindex/default.aspx?langTag=en-GB (accessed 9.10.15) Industry expert interviews
Module cables	4.65 USD/module	Linear slope dependence (see mounting structures)	Industry expert interviews
Solar cables / DC main cables	27637.99 USD/m^3 of cables	Linear slope dependence (see mounting structures)	Industry expert interviews
Junction boxes	5981.27 USD/junction box	Linear slope dependence (see mounting structures)	Industry expert interviews
AC BOS	232,605 USD/MVA	Linear slope dependence (see mounting structures)	Industry expert interviews
Civil works	2.7 USD/m^2 of plant (consistent terrain)	Linear slope dependence (see mounting structures)	Industry expert interviews
Auxiliary systems	0.04 USD/Wp	Linear slope dependence (see mounting structures)	Industry expert interviews
Road connection	255,000 USD/km (gravel road)	Linear slope dependence (see mounting structures)	Archondo-Callao, R., 2000. Roads Works Costs per Km. World Bank Reports.
Grid connection	732,919 USD/km (HV transmission, land)	Linear slope dependence (see mounting structures);	Industry expert interviews

	7,273,552 $/km (HV transmission, marine)	plant-specific share: plant capacity/800 MWp	Winfield and Sterling. 2012. Electricity Transmission Costing Study. Parsons Brinckerhoff.
Substation	14,658,381 USD/substation	Linear slope dependence (see mounting structures)	Industry expert interviews
Intra-country transportation	0.06 USD/m^3/km (truck transportation) 0.03 USD/ m^3/km (barge transportation)	Island sites connected through barge transportation	Kariniemi, A. 2006. Puunkorjuu ja kaukokuljetus vuonna 2009. Metsätehon katsaus 19.
Project development	500,000 USD + 3% of the total EPC cost		Industry expert interviews
Array cleaning and maintenance	0.57 USD/m^2 of arrays/year (fixed mount, cleaning every four days) 0.62 USD/m^2 of arrays/year (single axis tracking, cleaning every four days) 0.74 USD/ m^2 of arrays/year (dual axis tracking, cleaning every four days)	Average dust deposition-dependent multiplier for array cleaning and maintenance cost; linear slope dependence (see mounting structures)	Industry expert interviews
Module and civil works maintenance	0.27 USD/m^2 of plant/year (fixed mount) 0.29 USD/m^2 of plant/year (single axis tracking) 0.35 USD/ m^2 of plant/year (dual axis tracking)	Linear slope dependence (see mounting structures)	Industry expert interviews
Power block maintenance	3349.51 USD/power block/year		Industry expert interviews
Plant management	4466.02 USD/MWp/year (fixed mount) 4846.62 USD/MWp/year (single axis tracking) 5739.82 USD/MWp/year (dual axis tracking)		Industry expert interviews
Utilities	2233.01 USD/MWp/year		Industry expert interviews
Road maintenance	4680 $/km/year	Linear slope dependence (see mounting structures)	Archondo-Callao, R., 2000. Roads Works Costs per Km. World Bank Reports.
Transmission line maintenance	3.7% of HV transmission line cost (land) 19.6% of HV transmission line cost (marine)		Winfield and Sterling. 2012. Electricity Transmission Costing Study. Parsons Brinckerhoff.
Interest rate	5%		
Rate of return	10%		
Debt-to-equity ratio	80:20		
Insurance cost	0.4% of capital cost		Speer, B., Mendelsohn, M., Cory, K., 2010. Insuring Solar Photovoltaics: Challenges and Possible Solutions (No. NREL/TP-6A2-46932).
Salvage value	10% of capital cost		Harder, E., Gibson, J.M., 2011. The costs and benefits of large-scale solar photovoltaic power production in Abu Dhabi, United Arab Emirates. Renew. Energy 36, 789–796.
Inverter replacement	50%	Occurring after 16 years of operation	Industry expert interviews
Tracker replacement	15%	Distributed over the entire lifetime	Industry expert interviews
Module replacement	6%	Distributed over the entire lifetime	Industry expert interviews
Module performance degradation	-0.7%/year (mc-Si-fm, mc-Si-1t, mc-Si-2t) -0.9%/year (pc-Si-fm) -0.6%/year (CdTe-fm)		Jordan, D. C., Wohlgemuth, J. H., Kurtz, S. R. 2012. Technology and Climate Trends in PV Module Degradation (No. NREL/CP-5200-56485)