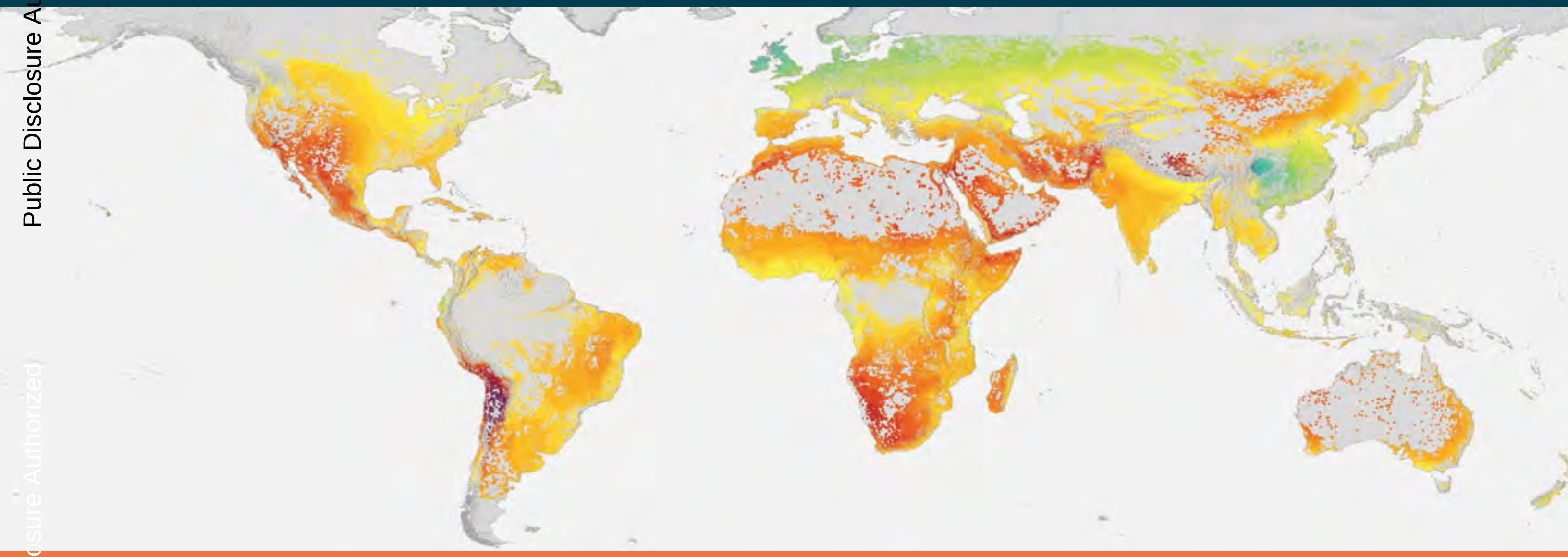
ESMAP
Energy Sector Management Assistance Program

GLOBAL PHOTOVOLTAIC POWER POTENTIAL BY COUNTRY

JUNE 2020



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ABOUT ESMAP

The Energy Sector Management Assistance Program (ESMAP) is a partnership between the World Bank and 18 partners to help low and middle-income countries reduce poverty and boost growth through sustainable energy solutions. ESMAP's analytical and advisory services are fully integrated within the World Bank's country financing and policy dialogue in the energy sector. Through the World Bank Group (WBG), ESMAP works to accelerate the energy transition required to achieve Sustainable Development Goal 7 (SDG7) to ensure access to affordable, reliable, sustainable and modern energy for all. It helps to shape WBG strategies and programs to achieve the WBG Climate Change Action Plan targets. https://esmap.org

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ABOUT SOLARGIS

Solargis is a technology company offering energy-related meteorological data, software, and consultancy services to a wide range of stakeholders in solar energy. They have supported the solar industry in site qualification, planning, financing, and the operation of solar energy systems for the past 11 years. They developed and operate a high-resolution global database and applications integrated within the Solargis® information system. Accurate, standardized, and validated data help to reduce the weather-related risks and costs in system planning, performance assessment, forecasting, and management of distributed solar power. https://solargis.com

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ACRONYMS

CAPEX	capital expenditure
EPSG	Geodetic Parameter Dataset, by European Petroleum Survey Group
GDAL	transfer library for raster and vector geospatial data
GHI	global horizontal irradiation, if integrated solar energy is assumed (global horizontal irradiance, if solar power values are discussed)
GIS	geographical information system
GRASS	Geographic Resources Analysis Support System
HDI	Human Development Index
IRENA	International Renewable Energy Agency, located in United Arab Emirates (UAE)
kWh	kilowatt hour
kWp	kilowatt peak
IUCN	International Union for Conservation of Nature
Land Cover CCI	Land Cover Climate Change Initiative, led by UCLouvain and the European Space Agency
LCOE	levelized cost of energy (electricity)
MapRE	Multi-criteria Analysis for Planning Renewable Energy
MNA	Middle East and North Africa
NREL	National Renewable Energy Laboratory, a research institute based in Colorado (USA)
OECD	Organisation for Economic Co-operation and Development
OPEX	operational expenditure
OSGeo	The Open Source Geospatial Foundation
POA	project opportunity areas
PROJ	library for performing conversions between cartographic projections
PV	photovoltaic
PVOUT	photovoltaic electricity potential (expected output from a PV system)
TEMP	air temperature measured at 2 meters
WACC	weighted average cost of capital; synonymous with "discount rate" in this publication

EXECUTIVE SUMMARY

Over the last decade, the solar power sector has seen installation costs fall dramatically and global installed capacity rise massively. The International Renewable Energy Agency (IRENA) has reported that solar photovoltaic (PV) module prices have fallen 80% in the last decade, while installed capacity has grown from 40 GW to over 600 GW in the same period. These trends are set to continue with new global solar installations of over 140 GW expected in calendar year 2020.

The reason for this is straightforward. Solar radiation is essentially a free resource available anywhere on Earth, to a greater or lesser extent. Converting solar radiation into electricity is at present dominated by PV power plants, and in the current era of global climate change, PV technology becomes an opportunity for countries and communities to transform or develop their energy infrastructure and step up their low-carbon energy transition.

But is the PV power potential in a specific country or region good enough to take advantage of solar power, and on what scale? This is a question often asked by policymakers and businesses alike, and one that this report attempts to shed further light on.

Recently, global data representing the solar resource and PV power output in every country of the world has been calculated by Solargis (Figure 3.4) and released in the form of consistent high-resolution data sets via the Global Solar Atlas, a web-based tool commissioned and funded by the Energy Sector Management Assistance Program (ESMAP), a multi-donor trust fund administered by the World Bank [1]. Based on this data, it is possible to make high-level comparisons between countries and regions on their theoretical, practical, and economic solar potential.

This report provides such information to raise awareness, stimulate investment interest, and inform public debate. Therefore, it is relevant to policymakers, project developers, financial and academic sectors, and the media and communication professionals, as well as communities and individuals.

METHODOLOGY

There are numerous methodologies for **evaluating solar energy potential** in countries or regions. Chapter 2.1 provides a brief literature review by way of background and explains the methods applied in this study. Chapter 2.2 describes the global data sets that were collected and used in this report. As a general principle, the analysis relied on the best globally available and consistent data sets in each domain to ensure a high level of comparability of the results. Some data sets were ruled out, even if superior in granularity or quality, where just part of the global or individual countries were covered.

The long-term energy content of the solar resource available at a certain location defines the **theoretical solar PV potential** (Chapter 2.3). For PV technology, the energy content is well quantified by the physical variable of **global horizontal irradiation** (GHI). It is the sum of direct and diffuse irradiation components received by a horizontal surface, measured in kWh/m^2. GHI enables a comparison of the conditions for PV technology without considering a specific power plant design and mode of operation. GHI is the first approximation of the PV power production in a particular region, but it disregards important additional factors.

The cornerstone of this report is therefore the evaluation of the **practical solar PV potential** (Chapter 2.4), which is the power output achievable by a typical PV system (PVOUT). Unlike the theoretical potential, it simulates the conversion of the available solar resource to electric power considering the impact of air temperature, terrain horizon, and albedo, as well as module tilt, configuration, shading, soiling, and other factors affecting the system performance. PVOUT is the amount of power generated per unit of installed PV capacity over the long term (the specific yield), measured in kilowatt hours per installed kilowatt peak (kWh/kWp).

The calculated practical potential can be considered as a conservative case—assuming a large-scale installation of monofacial crystalline silicon modules fixed mounted at an optimum angle, which has been the prevailing setup of PV power plants to date. This report evaluates the practical potential at three levels defined by a number of topographic and land-use constraints:

- Level 0 disregards any limitations to the development and operation of solar projects.
- Level 1 excludes land with physical or technical constraints. These include rugged terrain, extreme remoteness, built-up environment, and dense forests.
- Level 2 additionally excludes land under 'soft' constraints, such as regulations related to protection of cropland and conservation areas.

Apart from the annual average of practical potential, the seasonal variability derived from the monthly PVOUT values is summarized and compared at the country level.

The **economic PV potential**, expressed in this report via a simplified levelized cost of energy (LCOE), describes how much it would cost to produce a unit of energy. Apart from the PVOUT value, the cost of the PV technology, overall capital expenditure, operation costs, and discount rate are considered over the typical PV plant lifetime. The metric enables the comparison of solar energy to other energy generation technologies (Chapter 2.5). The presented estimate illustrates the solar economic potential from a global viewpoint, with a country as the smallest unit serving as a basis for further in-depth analysis of local intricacies.

KEY FINDINGS AND LESSONS LEARNED

The geographical variability of the solar energy yield is primarily driven by the distribution of the solar resource. The global pattern of the resource (theoretical PV potential) is determined mainly by latitude, occurrence of clouds, terrain elevation and shading, atmospheric aerosol concentration, and atmospheric moisture content. At regional to local scales, solar resource is also affected by proximity to sea and large water bodies, as well as urban and industrial areas. This creates a very diverse spatial distribution of solar resource.

Air temperature is the second most significant geographical factor, as it affects PV conversion efficiency. The power output is also variable in time: it changes over seasons and days due to astronomical and geographical factors and, in the very short term, the variability is driven by clouds. Moreover, the practical utilization of solar power plants is limited by various physical and regulatory land-use constraints. Practical PV potential assessment provides a higher added value by including all these additional factors.

Practical PV Potential Distribution

The results presented in this report show that the global range of PVOUT is not as wide as might be expected. The distribution of air temperature often counteracts the distribution of GHI (the theoretical potential). Places with below average solar radiation may benefit from cooler air temperatures year round, and conversely, high air temperatures may hinder the PV power output in regions with high solar resource.

As a result, the difference between the countries with the highest (Namibia) and the lowest (Ireland) average practical potential is only slightly higher than a factor of two. In total, 93% of the global population lives in countries where the average daily PV potential is in the range between 3.0 and 5.0 kWh/kWp.

Around 20% of the global population lives in 70 countries boasting excellent conditions for PV, where long-term daily PVOUT averages exceed 4.5 kWh/kWp. Countries in the Middle East and North Africa (MNA) region and Sub-Saharan Africa dominate this category, accompanied by Afghanistan, Argentina, Australia, Chile, Iran, Mexico, Mongolia, Pakistan, Peru, and many nations of the Pacific and Atlantic islands.

At the lower end of the ranking, 30 countries accounting for 9% of the global population score an average PVOUT below 3.5 kWh/kWp, dominated by European countries—except those in southern Europe—and also including Ecuador and Japan. Even in countries with lower solar resource availability, the potential is not dramatically lower compared to the top-performing group.

Finally, countries in the favorable middle range between 3.5 and 4.5 kWh/kWp account for 71% of the global population. These include five of the six most populous countries (China, India, the United States, Indonesia, and Brazil) and 100 others (Canada, the rest of Latin America, southern Europe, and African countries around the Gulf of Guinea, as well as central and southeast Asia).

Beyond Average Values

While knowing a single averaged value over the country's territory is useful, the indicator may not be representative enough for countries with a diversified geography. Countries that are elongated in the north-south direction (i.e., have a significant latitudinal span), as well as those located within major mountain ranges or climatic gradients, tend to have a wide PV potential range.

Where possible, PV installations tend to be concentrated in areas with the most favorable solar resource conditions, and often a minor portion of a country's area with feasible practical potential may host enough capacity to meet the country's entire energy demand. Considering this, a higher percentile instead of the average (e.g., Percentile 75, Percentile 90, or the maximum) could better illustrate the potential for installation of large PV power plants in a country. Therefore, Figures 3.8 and 3.20 provide more detailed zonal statistics in individual country factsheets.

Indeed, the availability of detailed PV power potential data enables an estimation of the country area that would be needed to cover electricity production targets. For instance, Mexico would need to dedicate only around 0.1% of its territory to utility-scale PV power plants to cover its entire yearly electricity consumption (about 270 TWh recently [2]). However, this percentage varies hugely by country. In France, due to higher electricity consumption and lower PV yield, it would be about 1.0% of the country area. In contrast, Ethiopia would need only 0.003% of its land area to be covered in solar PV to meet its annual energy needs in recent years.

PV Potential Seasonality

A single long-term yearly average of practical PV potential, summarized as PVOUT, does not tell the full story in the temporal domain, as it hides various profiles of seasonal variability. Stronger seasonal fluctuations pose economic and technological challenges to the exploitation of PV electricity. Therefore, this report includes new statistics describing the degree of seasonality at the country level (Figure 3.12).

Interestingly, there is a loose, indirect association between the PV potential and the seasonality index—defined as the ratio between the highest and the lowest monthly PVOUT. The high-potential countries tend to have low seasonality (below 2.0) and vice versa. In total, 86% of the global population lives in 150 countries where the average seasonality index is below 2.0, and PVOUT exceeds 3.5 kWh/kWp (the dense cluster of countries in the upper-left part of Figure 3.12). We suggest that it is these countries where solar PV is poised to meet a significant share of energy demand in the future.

In the remaining countries, despite higher seasonality and somewhat lower PVOUT values, solar PV may still be a profitable option playing an important role in the energy mix along with other energy sources. In many cases the seasonal variations of solar PV may be complementary to those of wind or other resources, and in countries with a high cooling demand solar PV can even be load following. While outside the scope of this report, the resources made available allow for such a high-level analysis to be carried out.

Economic PV Potential

Currently, data to accurately calculate the LCOE is available only for a fraction of the countries covered in this report. We derive a simplified version of LCOE as a proxy of the economic potential, taking generalized assumptions about costs of construction and operation of a typical PV power plant. The value, conceived as a snapshot in 2018, ranged globally from under $0.06 to over $0.26 per kWh, with over 75% of the evaluated global area scoring below $0.12 (Figure 3.9).

Comparing PVOUT with average electricity tariffs (Figure 3.18) shows why grid parity for solar PV is seen across a wide range of countries, regardless of their actual resource potential. The relative differences in electricity tariffs can far exceed the differences in practical and economic PV potential. Therefore, PV generation can be profitable in countries with some of the lowest average PV potential (such as Denmark, Japan, and the United Kingdom). Importantly, there is a group of countries with high tariffs (over $0.20) with high potential at the same time (over 4 kWh/kWp). This group includes many island nations and countries with less-developed electricity grids, where expensive and polluting small-scale diesel generators are the primary power generation source.

A comparison of the PV potential with further socioeconomic indicators provides new insights. For example, a high number of less-developed countries—in terms of the Human Development Index, reliability of electricity supply, and access to electricity—tend to have very high practical PV potential, so far untapped (as illustrated by currently installed PV capacity, Figure 3.13). There is a unique opportunity for solar PV to provide affordable, reliable, and sustainable electricity services to a large share of humanity where improved economic opportunities and quality of life are most needed. The information and insights contained in this report can help to unlock some of that investment.

Explore More

The global data presented in this report, plus individual country factsheets, are available via the Global Solar Atlas at https://globalsolaratlas.info/global-pv-potential-study. Furthermore, the interactive tools, offered via the homepage of the Global Solar Atlas, make it possible to estimate the PV potential at a specific site or any defined region, and the site provides a wealth of additional data, maps, and reports.

Solar Power Plant, Maharashtra, in state of Maharashtra, India. Photographer: Thomas Lloyd Group, Creative Commons Attribution-Share Alike 4.0 International license.

1. INTRODUCTION

Solar radiation is essentially a free resource available anywhere on Earth, to a greater or lesser extent. Solar PV power plants convert solar radiation into electricity. In the current era of global climate change, PV technology becomes an opportunity for countries and communities to transform or develop their energy infrastructure and step up their low-carbon energy transition. Some may ask whether the PV power potential in a specific country or region is good enough to take advantage of, and on what scale? This is a question often asked by policymakers and investors alike, and one that this report attempts to shed further light on.

Until now, a global and harmonized assessment of country-level PV potential has not existed. This report attempts to fill this gap by evaluating the theoretical potential (the general solar resource), the practical potential (accounting for additional factors affecting PV conversion efficiency and basic land use constraints), and the economic potential of PV power generation (considering a simplified evaluation of electricity production costs).

This work has been facilitated by detailed global data representing the solar resource and PV power output recently calculated by Solargis (Figure 3.4) and, for the first time, released in the form of consistent high-resolution data sets via the Global Solar Atlas [1]. The data make it possible to evaluate or compare virtually any site, region, or country. For example, we could state that Namibia has the highest average practical PV power potential of all countries, and it is twice as high compared to the United Kingdom, a country with one of the least generous conditions for PV (consult the ranking in Figure 3.8).

However, when we dig deeper and combine this information with other geographical and socioeconomic data, we see that the reality is more complex. Alongside solar resource, the potential for growth in the solar industry is determined by electricity needs; supportive or restrictive policies; costs and payback time; weather-related risks; stability of electricity grids; predictability of solar power supply; interconnection of grids enabling transmission and distribution; and other technical, social, and economic factors.

The value of a solar energy project depends on an appropriate and cost-effective implementation, which supports the energy independence of the communities and the transition toward cleaner electricity. Hence, there are neither 'good' nor 'bad' locations for developing solar PV power systems around the world. Rather, at different locations or regions, we can evaluate a 'higher' or 'lower' potential for PV energy yield, considering its availability, but also seasonal stability and short-term variability. This shows that solar PV is viable in most parts of the world given the right combination of environmental, economic, and regulatory factors.

1.1 OBJECTIVE

This report aims to provide an aggregated and harmonized view on solar resource and PV power potential from the perspective of countries and regions, assuming a utility-scale installation of monofacial modules fixed mounted at an optimum angle, which has been the prevailing setup of a PV power plant.

This can be considered as a conservative definition of PV potential, since nowadays technologies that are more efficient (e.g., bifacial PV modules) or can harvest solar resource in a more flexible regime (e.g., single-axis solar trackers) are becoming cost competitive. A detailed evaluation of individual PV technologies is, however, outside the scope of this study. The term 'utility-scale' is typically defined by minimum installed capacity, starting in the range from 1 MW [3] to 5 MW [4]; we consider here any plants above the lower threshold.

The sub-objectives include:

- Propose a method to derive comparable PV statistics based on the Solargis data and a range of other globally consistent geospatial data sets;
- Provide a ranking and comparison of countries and regions according to their theoretical and practical PV potential;
- Address the spatial and seasonal variation in PV potential;
- Approach the economic PV potential estimation based on the LCOE concept; and
- Present the PV potential in the context of socioeconomic indicators relevant to PV development.

This report does not aim to advocate for or against solar energy or make policy recommendations. Instead, the findings provide high-level comparisons between countries and regions on their solar energy potential and are intended to raise awareness, stimulate investment interest, and inform public debate. The study, therefore, will be relevant to policymakers, project developers, financial and academic sectors, and the media and communication professionals, as well as communities and individuals.

Finally, the results and the underlying data presented are not intended, and should not be relied upon, to guide investment decisions. This requires more granular, site-specific data combined with expert analysis and financial modeling.

Mosaic distribution of the PV power plants (highlighted with the violet color) in the landscape of southeast Germany.
Source: Copernicus Sentinel Hub, Sentinel-2, True color, 2019–09–21 L2A. Composed by Solargis.

2. METHODOLOGY

2.1 PHOTOVOLTAIC POTENTIAL: REVIEW OF CONCEPTS

Previous Studies of Solar Energy Potential

With an increasing interest in solar power generation, the number of published studies evaluating the PV potential of various regions has been growing steadily for over a decade.

One strand of research focuses on the accurate estimation of power production by PV systems mounted on roofs or building facades [5, 6, 7]. Building-integrated PV evaluation presents a highly computational and data-intensive task and is out of the scope of this report.

The second strand of research focuses on the assessment and selection of sites for utility-scale, ground-mounted solar power plants, and is therefore more relevant to this study. The territorial scope in this group of studies varies greatly. Most studies, though, present a country or regional view, while only a few studies target more than one country (e.g., Jahangiri et al.) [8]. The study by Šúri et al., [9] evaluated Europe-wide solar energy potential in a broader perspective, without identifying particular production sites.

However, to our knowledge, no such assessment has been published so far at the global level, which indicates a significant research gap. This underlines the importance of this research to the global solar industry.

Country and regional studies typically aim at identifying or recommending project opportunity areas (POA) for solar energy development. The usual method involves a spatial analysis of several geographic data sets executed in Geographical Information System (GIS) software, following the principles of multiple-criteria decision-making (MCDM) [10, 11] or an analytic hierarchy process (AHP) [12, 13]. The quantity, quality, and appropriateness of the data sets available for such analyses varies by country and type of study, as well as on the extent of the study area.

Regional studies allow for the implementation of more sophisticated approaches, often involving information on local land-use regulations, power grid elements, transmission lines, accessibility, and costs. While the additional complexity may increase the accuracy of the work, it also means the study is less replicable and comparable with other regions and countries, where the input data are insufficient or unavailable.

Beyond the data inputs, the exact settings of the methods used cause further divergence of the results (Boolean vs. fuzzy logic, arbitrary weights, thresholds, or classifications applied to each data set). Finally, each country/regional study may pursue different objectives, siting criteria and exclusion zones, stemming from specific regulatory regimes.

The lack of harmonization in solar (and wind) energy potential assessments has been partly addressed by the Multi-criteria Analysis for Planning Renewable Energy (MapRE) approach of Berkeley Labs. It provides a common analytical framework, GIS tools, and geodata requirements, while the choice of suitable data sets is up to the user.

So far, the concept has been applied in eastern and southern Africa [14] and India [15]. While MapRE helps reduce the methodological discrepancies between various countries and regions, the results are not always comparable, as they are affected by the particular choice of data sets made by the user. The decision is driven by the data availability, which is region-specific, and individual study objectives (i.e., identification of POAs according to different criteria).

Concepts Applied

Contrary to approaches used in the previous country and regional studies, in a global assessment it is desirable to avoid the use of region-specific data and criteria. It is tempting to use the best available data sets, even if they cover only an individual country or region. Nonetheless, we preferred a conservative approach, selecting only the best and globally consistent data sets in each domain, even if they might not be the optimum from the local perspective. Such selection of input data, as well as a uniform methodology using common criteria and thresholds, ensures the highest level of comparability of the outcomes.

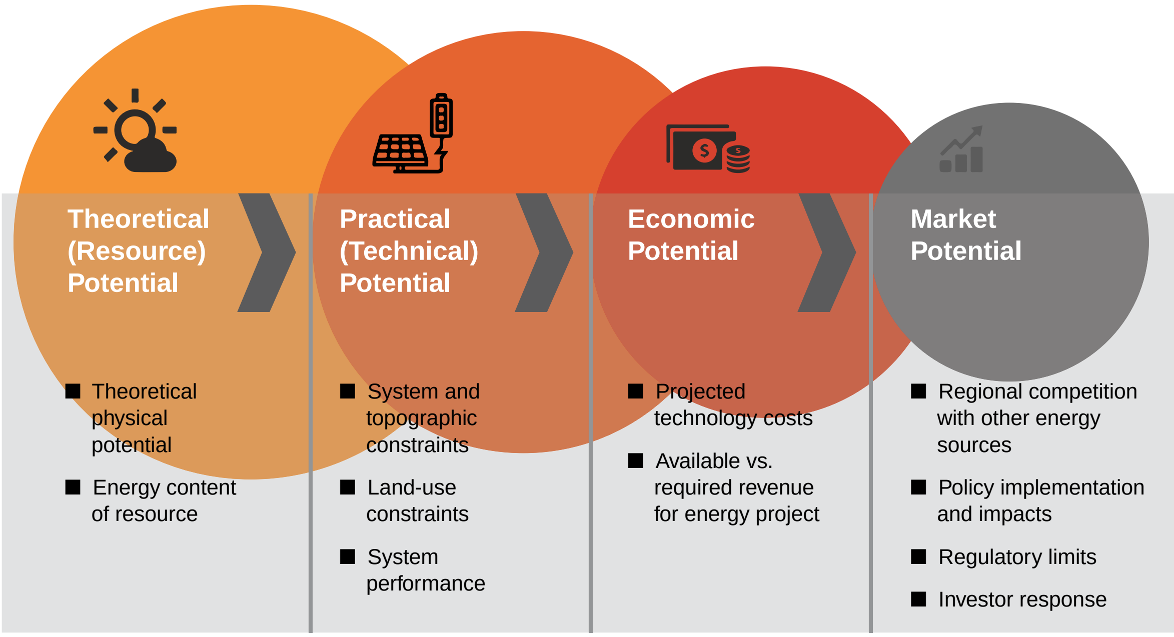
Importantly, this study does not intend to identify POAs. Rather, it gives an overview of the PV power potential for each country in a global context. The results should, however, assist the stakeholders in the identification of POAs in their regions as a follow-up action, and we would be happy to engage with them further.

We employ the concept of renewable energy potential proposed by the U.S. National Renewable Energy Laboratory (NREL) [16] and adapted, as shown in Figure 2.1. Our focus is on international consistency, but a lack of suitable and comparable data prevented the global evaluation of the market potential. Instead, we focus on mapping of the preceding three types of photovoltaic power potential:

- **Theoretical** (resource) potential is characterized by the amount of energy physically available, without considering any constraints or a particular PV system.
- **Practical** (technical) potential is characterized by the annual average of PV power production, taking into account the theoretical potential, real-world PV system performance, and configuration, as well as topographic and land-use constraints.
- **Economic** potential. We assess the costs of PV power generation at the country level based on the practical potential and the concept of LCOE.

By using geospatial analysis of key factors, we identified the theoretical, practical, and economic potential of PV in each country in the form of maps and summary tables.

FIGURE 2.1: TYPOLOGY OF POTENTIALS FOR RENEWABLE ENERGIES



Note: The grey item in the diagram [market potential] is not covered here.
Source: Adapted from NREL Technical Report [16].

We used multi-source overlay analyses to create a basis for a more realistic assessment of practical PV potential. The input data layers come from different sources. Therefore, their integration and harmonization were necessary. We used GDAL, GRASS GIS software, PROJ, and related OSGeo libraries to achieve:

- Unification of the coordinate system (EPSG:4326)
- Unification of resolution with appropriate down-sampling methods (target pixel size: 30 arcsec)
- Inspection and conversion of administrative borders, used as zones in the statistics

Raster map algebra is applied on a set of input data to identify the areas that are unsuitable for large PV projects. Input and derived raster data layers are available for download via the Global Solar Atlas: https://globalsolaratlas.info/global-pv-potential-study.

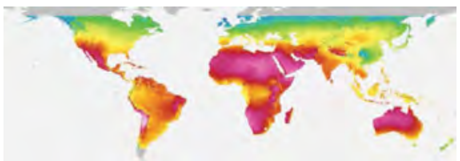
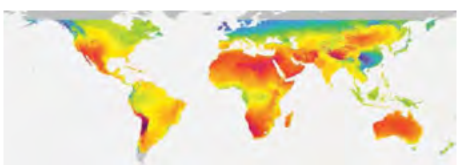
2.2 INPUT DATA

The main inputs to assess theoretical and practical PV potential are global gridded data (i.e., two-dimensional matrices of values computed per each pixel). Standard GIS operations, such as raster algebra, are performed on the data to calculate the resulting final layers. The custom-developed tools are used to calculate zonal statistics. Tables 2.1 and 2.2 show the key characteristics and sources of the data layers used in this study.

Primary data layers, necessary for statistical evaluation of the potential in countries/regions (Table 2.1):

- Global horizontal irradiance (GHI)
- Updated air temperature at 2 meters (TEMP)
- PV power production potential (PVOUT)
- Index of seasonal variability (SEASONALITY) derived from monthly PVOUT values
- Simplified levelized cost of electricity (LCOE) derived from PVOUT and economic data
- Administrative boundaries (country borders)

TABLE 2.1: PRIMARY GLOBAL DATA LAYERS APPLIED IN THIS STUDY

Preview	Name	Source	Spatial Resolution[1]
	Global horizontal irradiance (GHI)	Solargis	30 arcsec (approx. 1 km)
	Air temperature at 2 meters (TEMP)	ECMWF, NASA, and Solargis	30 arcsec (approx. 1 km)
	Photovoltaic power potential (PVOUT)	Solargis	30 arcsec (approx. 1 km)
	PVOUT seasonality index (SEASONALITY)	Solargis	30 arcsec (approx. 1 km)
	Simplified levelized cost of electricity (LCOE)	Solargis, based on inputs from IRENA [17]	30 arcsec (approx. 1 km)
	Administrative boundaries	Cartography Unit, GSDPM, World Bank Group, 2016.	Vector polygon layer

[1]The nominal pixel size of the data used in this study.
Source: Authors.

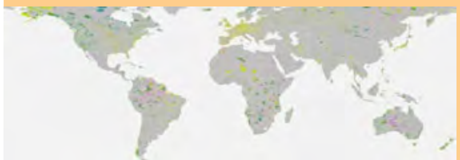
Auxiliary data, required for the identification of unsuitable areas in the practical potential evaluation (Table 2.2):

- Terrain elevation and slope
- Built-up areas
- Population clusters
- Tree cover density
- Land cover
- Water bodies
- Protected areas

TABLE 2.2: AUXILIARY GLOBAL DATA LAYERS APPLIED IN THIS STUDY

Preview	Name	Source	Spatial Resolution[1]
	Terrain elevation	Merged data sources, post-processed by Solargis. SRTMv4.1 (Jarvis, et al., 2008), viewfinderpanoramas.org by Jonathan de Ferranti, ASTER GDEM v2 (ASTER Science Team, 2009)	3 arcsec (approx. 90 m)
	Terrain slope	Derived from terrain elevation by Solargis	3 arcsec (approx. 90 m)
	Built-up area density	GHS BUILT-UP, EC JRC (Pesaresi, et al., 2015)	1 km
	Population clusters	GHS S-MOD, EC JRC (Pesaresi, et al., 2016)	1 km
	Tree cover density	MOD44B Version 6 Vegetation Continuous Fields (Dimiceli, et al., 2015)	250 m

TABLE 2.2: *continued*

Preview	Name	Source	Spatial Resolution[1]
	Land cover	Land Cover CCI, v2.0.7 © ESA Climate Change Initiative—Land Cover led by UCLouvain (2017)	10 arcsec (approx. 330 m)
	Water bodies	Global Surface Water, Source: Source: EC JRC/Google (Pekel, et al., 2016)	1 arcsec (approx. 30 m)
	Protected areas	World Database on Protected Areas (UNEP-WCMC, 2016)	Vector polygon layer

[1]The nominal pixel size of the data used in this study.
Source: Authors.

Primary Data Layers

The first detailed global overview of PV power potential has been calculated by Solargis, in 2016, and released within the Global Solar Atlas [1]. The data was further updated in 2019. The calculation of such a high-resolution data layer requires harmonized input data, accurate algorithms, robust computing infrastructure, and multidisciplinary knowledge. Generated power output from a PV power plant is related to several factors. Besides the technical settings of the PV system and local geography, two input parameters are the most influential: solar resource and air temperature.

Solar resource

The solar resource, or solar radiation, is quantified by a set of data layers calculated by the Solargis model, based on satellite images and atmospheric data. The model uses data from five geostationary satellites to calculate the attenuation effect of clouds and additional variables characterizing the state of the atmosphere (such as aerosols/atmospheric pollution and water vapor). The solar resource is represented by GHI and direct normal irradiation (DNI), which are both explained below. The solar model also computes diffuse irradiation and global tilted irradiation received at the plane of PV modules. The historical time series of solar irradiance data is aggregated into monthly and yearly averages.

The data on the solar resource is available for a land surface between 60°N and 45°S parallels (up to 55°S in New Zealand), covering over 99% of the world's population. Regions in the far north and far south are excluded due to unavailability or insufficient quality of the data from geostationary meteorological satellites. Therefore, countries located in these regions are evaluated only partially in this study (Argentina, Canada, Chile, Norway, Russia, Sweden, and the U.S. state of Alaska) or are entirely excluded from the evaluation process (Finland and Iceland).

In the solar energy industry, the two primary parameters of the solar resource are:

- **Global horizontal irradiation (GHI):** This refers to the shortwave solar radiation received by a horizontal surface This is the most important parameter for energy yield calculation and performance assessment of flat-plate photovoltaic modules, which is presently the most widely spread technology. Therefore, in this study, we further analyze GHI in relation to PV power potential
- **Direct normal irradiation (DNI):** This refers to the shortwave solar radiation received by a surface normal to the sun. This is the most important parameter in the assessment of concentrating solar power and for accurate calculation of global irradiation received by tilted and sun-tracking PV modules

GHI and DNI data parameters are used to calculate global tilted irradiation (GTI), i.e., solar radiation received by the surface of PV modules.

Air temperature

Air temperature is the second most important natural factor affecting PV power production. It is calculated by post-processing of the data from the European Centre for Medium-Range Weather Forecasts' (ECMWF) ERA-5 reanalysis meteorological data set and a high-resolution digital terrain model that was derived from multiple sources by Solargis.

Photovoltaic power potential

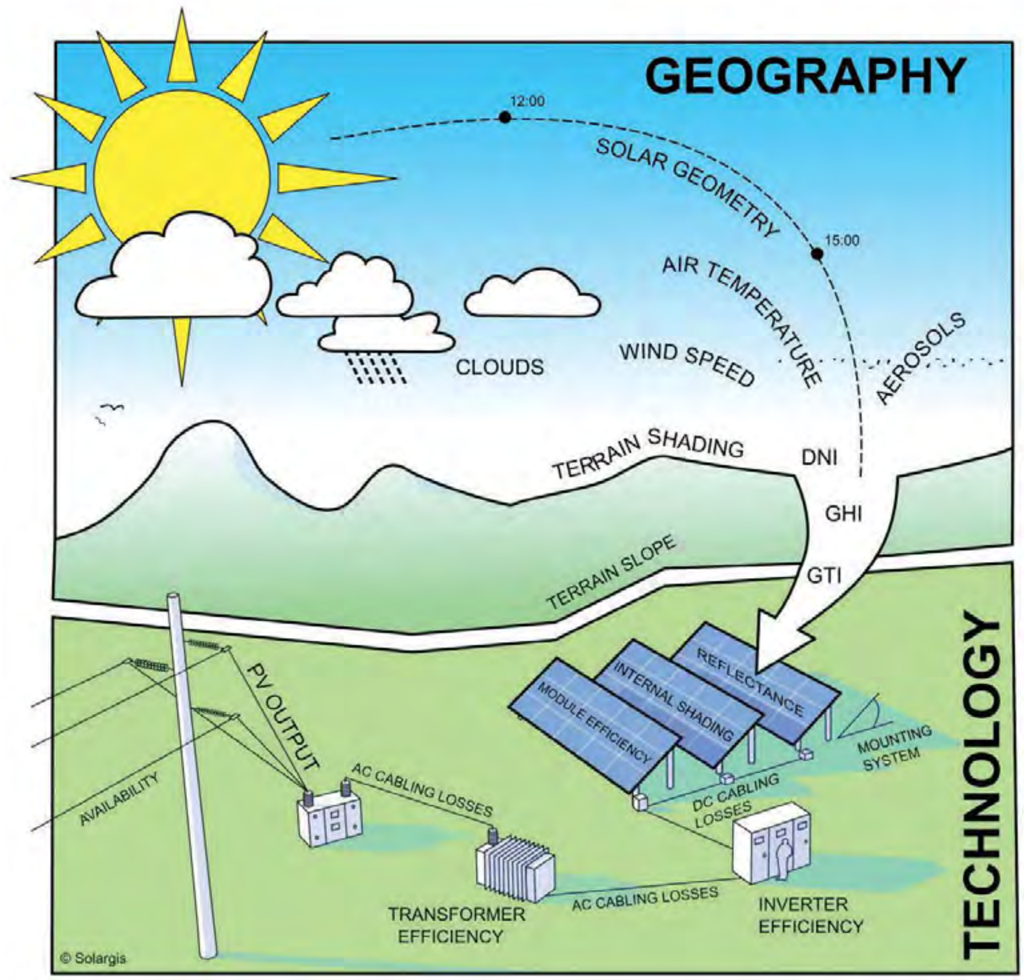
The primary input is a global raster data layer, representing the long-term average of **photovoltaic power potential** (PVOUT), calculated by the Solargis approach. We consider a typical large-scale PV power plant. More precisely, the PV system configuration consists of free-standing structures with monofacial crystalline silicon PV modules fixed mounted at an optimum tilt to maximize the yearly energy yield. The use of high-efficiency inverters is also assumed. For a simplified scheme of PVOUT calculation, consult Figure 2.2.

The calculation takes into account the solar radiation, air temperature, and terrain to simulate the energy conversion and losses in the PV modules and other components of a PV power plant. The simulation assumes a loss of 3.5% due to dirt and soiling. The cumulative effect of other conversion losses—including interrow shading, mismatch, inverters, cables, and transformers—is assumed to be 7.5%. The power plant availability is considered to be 100%.

The simulation uses primary data with 10-, 15-, or 30-minute time steps, depending on the satellite region, and the aggregated data represent yearly and monthly long-term averages of PVOUT daily totals, calculated for a period from 1994, 1999, or 2007 (depending on the satellite region) to 2018 in spatial resolution of 30 arcsec (nominally 1 km). More details about PVOUT calculation can be found in the Methodology section on Global Solar Atlas documentation pages [1].

Typical uncertainty of the input solar radiation data is estimated to ±4% to ±8%, and up to ±10% in the regions with complex geography.

FIGURE 2.2: SOLARGIS CALCULATION SCHEME FOR PHOTOVOLTAIC POWER POTENTIAL



Seasonality index

Although the annual solar yield is often the most indicative value for project evaluation, its seasonal distribution is also quite important. We introduce the 'seasonality index', which is calculated as a ratio between the highest and the lowest average monthly potential values in an average year:

$$PVOUT_{SEASON} = MAX[m01, m02 \ldots, m12] / MIN[m01, m02 \ldots, m12]$$

Key:

$PVOUT_{SEASON}$ = Seasonality index
MAX[m01, m02 . . . , m12] = Highest monthly average yield of PVOUT for the country/region
MIN[m01, m02 . . . , m12] = Lowest monthly average yield of PVOUT for the country/region.

The seasonality index provides an elementary indication of the seasonal variability. For example, the PVOUT seasonality index in South Africa reaches the value 1.2, which represents very stable electricity production through the year. In India, it exceeds 1.6, which shows there are minor and major seasons for production. In Germany, the average value of the seasonality index is around 4.4, meaning that there is less than a quarter of electricity generation in the lowest winter month compared to the best-performing summer month.

Apart from the single seasonality index value, individual monthly statistics provide more detailed information about the seasonal effect. These are published online per country in dedicated factsheets (see Chapter 3.4 for an example of the downloadable material).

Auxiliary Data Layers

We use several data layers to create exclusion zones for practical potential evaluation so that we can identify areas where large PV installations are physically/technically restricted, or where regulatory restrictions might apply. We selected suitable data sets in terms of relevance, global consistency, and sufficient spatial resolution. These criteria filtered out some of the domains that could be considered as exclusion criteria in the ideal case of a more localized study. The selected auxiliary data layers are listed in Table 2.2, and the procedure to obtain the exclusion masks is detailed in Chapter 2.4.

2.3 THEORETICAL PV POWER POTENTIAL

Theoretical potential for PV power generation is best characterized by the long-term distribution of solar resource, in other words, the 'amount of fuel' available for PV electricity generation at a given location. The theoretical potential allows for the comparison of the conditions between different sites without considering any particular PV system configuration. The amount of solar resource can be measured using several physical variables, two of which are of prime concern to the solar industry, as explained in Chapter 2.2: GHI and DNI.

2.4 PRACTICAL PV POWER POTENTIAL

Identifying Practical Potential Areas

The base data set used for practical potential analysis is PVOUT at **Level 0,** which assumes that each country or region could reach their full PV potential with no technical obstructions.

Next we assume two sets of restrictions to calculate practical potential assuming also various limiting factors. Based on the multiple-criteria decision-making (MCDM) concept and auxiliary data (Chapter 2.2), we consider a two-level categorization (Levels 1 and 2).

First, at **Level 1,** we identify 'exclusion zones', where utility-scale PV development is not practical due to physical or technical land-use constraints. The exclusion zones comprise areas, which meet the following criteria, considering the data spatial resolution (pixel size) 30 arcsec (nominally 1 km^2):

- **Complex terrain** includes the areas where the intra-pixel elevation range exceeds 300 m or intra-pixel standard deviation is higher than 60 m.
- **Large water bodies** involve any permanent surface waters, with the exception of a 1 km buffer zone adjacent to the coastline of continental water bodies, where floating PV technologies could be developed.

- **Compact forests,** which include forest areas where the density of tree cover is 50% and more. This criterion prevents the planning and developments of large-scale PV plants in the forested areas.
- **Uninhabited areas,** which include remote land with no or extremely sparse settlements, defined as any area located further than 25 km from the nearest population cluster of a minimum of 50 inhabitants per km^2. These areas are unsuitable due to lack of infrastructure, workforce, and power consumption.
- **Intra-urban areas** where the density of urbanization is higher than 50%. These include most of the areas with existing urbanization or high stress for further urban development. Additionally, non-built enclaves fully enclosed by an urbanized area (such as urban parks) are excluded too.

We have set the exclusion thresholds bearing in mind the technical requirements of a utility-scale PV installation. Additionally, we empirically tested the correctness of the abovementioned thresholds by location analyses of the 10,000+ existing utility-scale PV projects, sourced from Global Power Plant Database and OpenStreetMap data.

Second, at **Level 2,** we identify and exclude zones that may be unsuitable due to regulatory land-use restrictions possibly imposed by national authorities. We considered two criteria:

- **Protected areas** with any status, as characterized by the International Union for Conservation of Nature (IUCN) categories system.
- **Cropland,** defined by categories and subcategories "cropland rainfed, irrigated, or post-flooded" in Land Cover CCI, v2.0.7 data set (categories coded from 10 to 20).

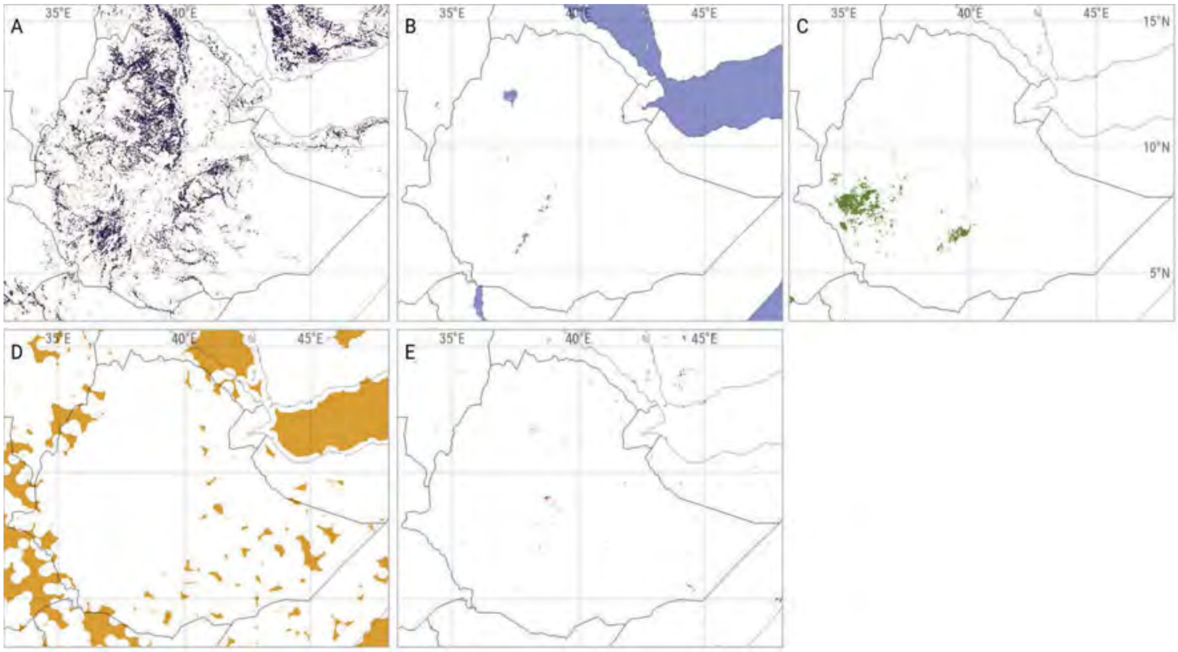
Component layers of both masks (Level 1 and Level 2) are shown in Figures 2.3 and 2.4 using Ethiopia as an example. The resulting masks are shown at the global scale in Figures 2.5 and 2.6.

The level of restrictions or regulations may vary by country or region. For instance, some countries take measures toward agricultural land conservation to ensure food self-sufficiency. Indeed, agriculture and utility-scale solar PV projects may compete for the same land.

However, with thorough planning, the construction of PV power plants is still possible in agricultural regions without affecting the agricultural yield significantly. It can also provide electricity for crop irrigation as well as for processing and refrigeration of agricultural produce. Here, we provide several reasons why we include the agricultural areas in the practical PV potential assessment:

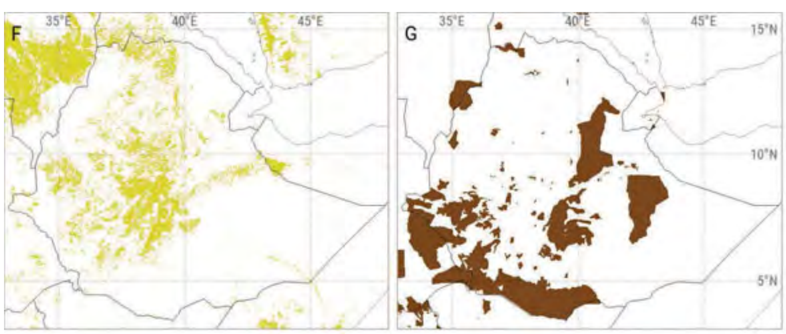
- Agrivoltaic systems can successfully combine agricultural production with PV electricity generation, and even boost agricultural production in some climate zones [18].
- A PV installation can be considered as a long-term, but still temporary, land use. In agricultural areas not actively farmed due to economic or social circumstances, the PV might be a welcome substitute that can be easily removed after some time, unlike construction works.
- Land classified as "agricultural" often contains heavily degraded, contaminated, or in other ways unproductive parcels. PV power plants might be considered as an additional use of land requiring long-term recovery as fallow land or pasture.
- Due to climate change, some irrigated croplands will become unsustainable due to water shortages. An alternative source of income could be obtained via PV development, as arid areas typically offer an excellent solar resource.

FIGURE 2.3: DATA LAYERS DEFINING PRIMARY EXCLUSION ZONES (LEVEL 1), USING ETHIOPIA AS THE EXAMPLE. (A: Complex terrain, B: Large water bodies, C: Compact forests, D: Uninhabited areas, E: Intra-urban areas)



Source: Authors.

FIGURE 2.4: DATA LAYERS DEFINING SECONDARY EXCLUSION ZONES (LEVEL 2), USING ETHIOPIA AS THE EXAMPLE. (F: Cropland, G: IUCN protected areas)

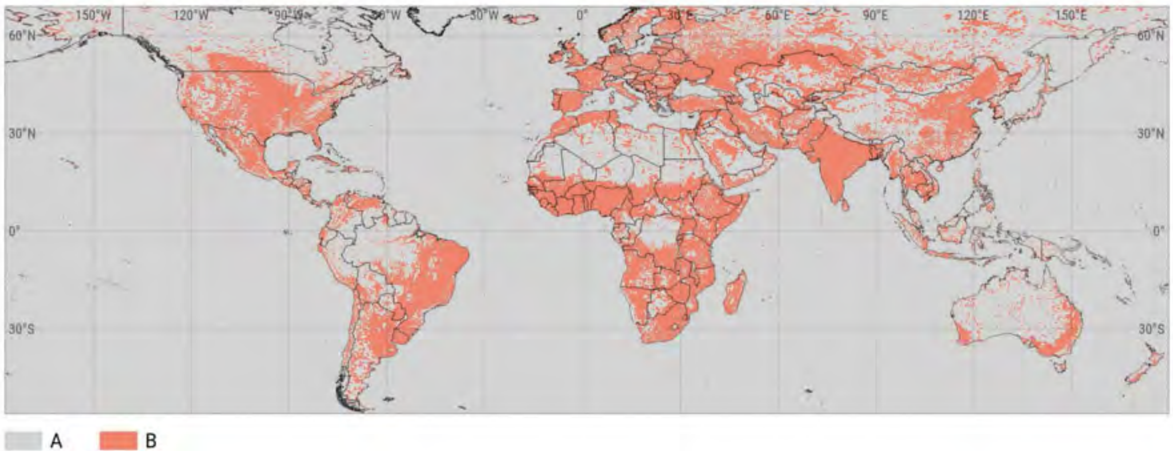


Source: Authors.

For a precise analysis, more granular data on the cropland would be required, but this is still not available globally.

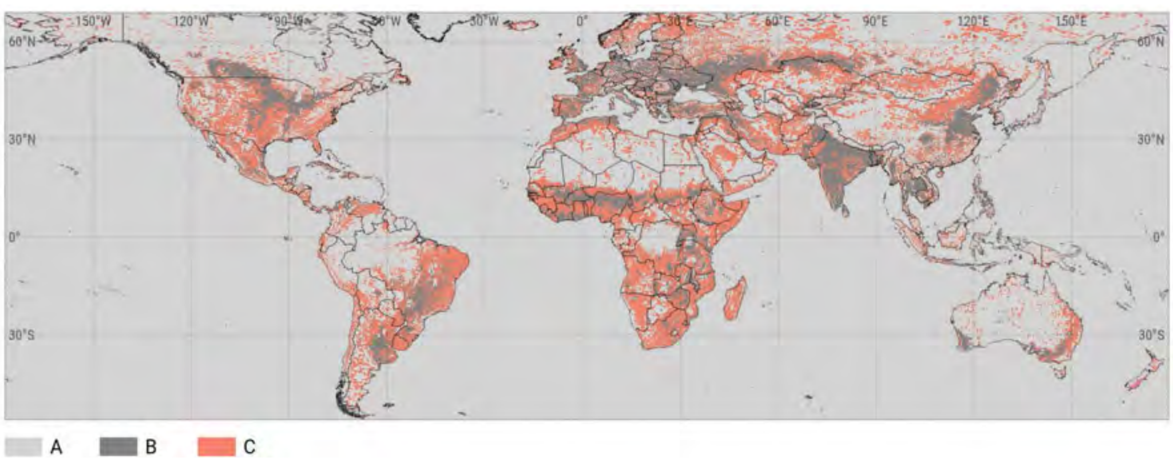
There might also be a question about why the forested areas in our study are not considered at the same level as croplands. Our reasoning for this is that, unlike cropland conversion, we consider deforestation as a more significant transformation process, from natural or semi-natural to cultural land. Hence, the replacement of forest by PV is not as readily reversible as is the case with croplands, and so would represent a greater barrier to development.

FIGURE 2.5: MASK SHOWING COMBINED PRIMARY EXCLUSION ZONES FOR PRACTICAL POTENTIAL AT LEVEL 1. (A: Exclusion zones composed of individual masks, B: Areas that could be developed at Level 1)



Source: Authors.

FIGURE 2.6: MASK SHOWING COMBINED PRIMARY AND SECONDARY EXCLUSION ZONES FOR PRACTICAL POTENTIAL AT LEVEL 2. (A: Exclusion zones composed of individual primary masks for the potential at Level 1, B: Additional exclusion zones composed of secondary masks for the potential at Level 2, C: Areas that could be developed at Level 2)



Source: Authors.

Additionally, from an environmental standpoint, replacing forests with a PV power plant is a counter-productive process because the deforestation would negate the positive effect of renewable power generation.

There is also an overlap between the forested areas we considered and the protected areas in the Level 2 analysis. A considerable part of the protected areas overlaps with the physical factors considered at Level 1 (forests, mountains, and remote areas). Moreover, the IUCN data set contains areas with some degree of sustainable land management, as well as settled areas, such as the indigenous reserves in North and South America. The installation of a large utility-scale PV plant would not be recommended in a strictly protected area. At the same time we cannot completely rule out, for example, a 1 MWp plant, depending on the country and the level of local protection.

In conclusion, we believe that the Level 2 restriction does not pose a substantial barrier for ground-based installations of PV power systems. Therefore, discussion in Chapter 3 focuses on the results of the statistical analysis at Level 1.

Representing Practical PV Potential

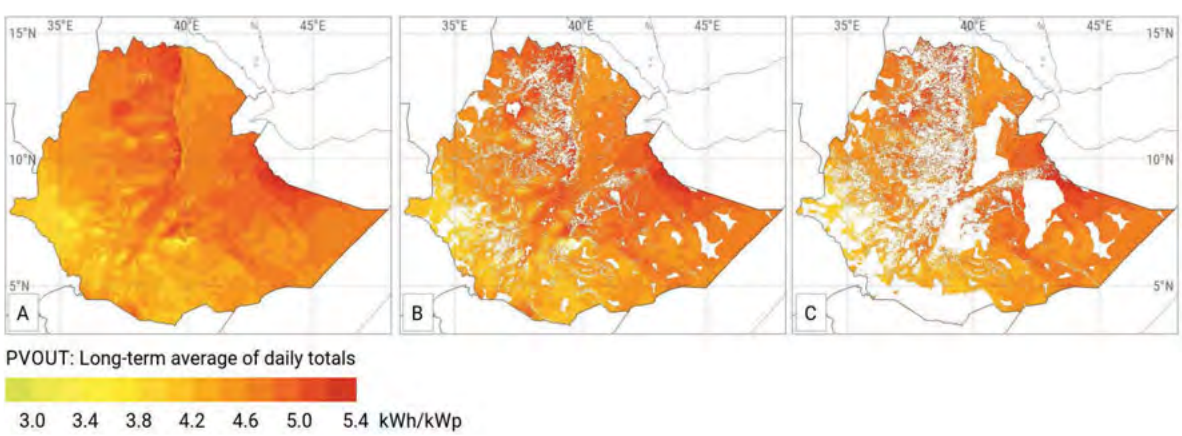
The source layers representing the theoretical potential (GHI) and practical potential (PVOUT) are gridded geographic data, while the country boundaries are represented as polygons. To summarize the values occurring in each country, we used the zonal statistics algorithm. The algorithm evaluates the spatial relationship between the polygons and grid values, and summarizes all values overlapping individual polygons (countries/regions). While the zonal statistics are part of the toolbox in any standard GIS software, we have developed a tailored solution that considers the imperfections of map projections and accounts for the actual pixel area that decreases with increasing latitude.

We calculate the practical potential statistics at three different levels (Figure 2.7):

- The complete territory of the country/region identifying **Level 0 practical potential**
- With primary exclusion mask applied to identify **Level 1 practical potential** (considering physical/technical land-use constraints)
- With primary and secondary exclusion masks applied to identify **Level 2 practical potential** (considering possible regulatory land-use constraints)

For each country or region and level, we calculate MEAN, MIN, MAX, and percentile values. Note that MIN and MAX statistics in this study are defined as percentiles P0.5 and P99.5 respectively, to filter out local extremes or artifacts. Based on the statistics, we have composed factsheets on the theoretical and practical PV power potential in a country or region; see examples in Chapter 3.4.

FIGURE 2.7: THREE LEVELS OF PRACTICAL POTENTIAL (DATA MASKING FOR ZONAL STATISTICS CALCULATION) IN ETHIOPIA (A: Level 0, B: Level 1 [physical/technical land-use constraints], C: Level 2: [possible regulatory land-use constraints])



Source: Authors.

2.5 ECONOMIC PV POWER POTENTIAL

At the start of 2010, the main selling point of the solar PV industry was its small environmental footprint, but only a minority believed that it could economically compete with traditional energy sources in the near future.

However, as a result of many advances in the intervening decade, solar PV has achieved grid parity in many regions of the world and is forecast by institutions, including IRENA, to become even cheaper [17]. With other technological advances—such as energy storage, efficiency improvements, and solar power forecasting—solar PV has the capacity to strengthen its position in the energy mix of almost all countries.

In section 2.5, we assess the costs of PV power generation from the utility-scale power plants at the country level, without considering any subsidy-related factors. We also select multiple relevant socio-economic indicators and portray the PV power potential in a broader context of the various economies.

LCOE Calculation

As seen earlier (Figure 2.1), the economic potential of solar PV power does not consider the market potential, which is site specific due to land costs, grid infrastructure, logistics, legal, and political framework.

There are various ways of assessing economic potential, including the payback period; the return on investment for the owner or operator; and the LCOE. We have chosen to focus on the concept of LCOE because it allows us to compare various power generation technologies, including a wide range of renewables and fossil fuels. Each technology might have slightly different inputs to encompass its specific requirements but, in general, LCOE is the product of all of the lifetime costs associated with construction and operation of the power plant, divided by the electricity produced during this lifetime. It can be interpreted by the following formula:

$$LCOE = \frac{\sum_{n=0}^{N} \frac{C_n}{(1+d)^n}}{\sum_{n=1}^{N} \frac{Q_n}{(1+d)^n}}$$

Key:

- N = Analysis period in years
- C_n = Annual project costs in the year n ($), which include capital expenditure (CAPEX), operational expenditure (OPEX), loan financing, taxes, and incentives (if applicable)
- Q_n = Electricity generated by the system in the year n (kWh)
- d = Discount rate (real or nominal)

Over the years, more complex and descriptive methods of calculating LCOE have been introduced in solar energy to better encompass the specific needs of developers, engineering firms, and financial institutions. One example is given by the financial advisory and asset management company Lazard, which devised a way of calculating LCOE by focusing on the developer's internal rate of return (IRR) and working backward to calculate the resulting LCOE from the point of view of a developer or equity investor [19].

Another common way to calculate LCOE is the expanded general formula of LCOE developed by IRENA [17] and used in its reporting on the state of the sector:

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+d)^t}}{\sum_{t=1}^{n} \frac{E_n}{(1+d)^t}}$$

Key:

$LCOE$ = Average lifetime levelized cost of electricity generation

I_t = Investment expenditures in the year t

M_t = Operations and maintenance expenditures in the year t

F_t = Fuel expenditures in the year t (if applicable)

E_t = Electricity generation in the year t

d = Discount rate

n = Lifetime of the PV system in years

The calculation by IRENA expands on the capital costs associated with the construction and operation of a PV power plant. In its methodology, the LCOE of renewable energy varies by technology, country, and project, based on the renewable energy resource, capital, and operating costs, and the efficiency/performance of the technology.

The approach in the IRENA analysis is based on a discounted cash flow (DCF) analysis, which is used to estimate the present value of an investment based on future cashflows. This method of calculating the cost of renewable energy technologies is based on discounting financial flows (annual, quarterly, or monthly) to a common starting point.

Given the capital-intensive nature of renewable power generation technologies and the fact that fuel costs are low or zero, the discount rate also has a critical impact on the LCOE. Funding arrangements agreed in the initial phases of a project play a key role in determining financial performance through its life cycle.

We chose to use the IRENA LCOE equation in this research for its ease of use and replicability.

Calculating Economic PV Potential

By defining LCOE and calculating PVOUT, we can indicatively calculate the LCOE value of solar PV in a particular geographical reference point. However, the LCOE presented here may not reflect specific local market conditions as it is only a rough estimate due to input values being averaged and associated at the country/regional level.

Regional and country-level estimates of cost (CAPEX and OPEX) are available in various solar industry publications (e.g., [20], [21]), but they are not representative enough for this work as they can be specific to regional conditions at the time of compilation and calculated by different methodologies. We use the most harmonized data set available, to give indicative cost estimates for CAPEX as a primary input into the LCOE calculation:

$$LCOE = \frac{\sum_{t=1}^{n} \frac{CAPEX_t + OPEX_t}{(1+d)^t}}{\sum_{t=1}^{n} \frac{PVOUT_t}{(1+d)^t}}$$

Key:

$LCOE$ = Average lifetime levelized cost of electricity generation
$CAPEX_t$ = Investment expenditures in the year t
$OPEX_t$ = Operations and maintenance expenditures in the year t
$PVOUT_t$ = Electricity generation in the year t
d = Discount rate (WACC)
n = Lifetime of the PV system in years

Capital expenditure

The most comprehensive information on capital investment cost estimates (CAPEX) is available in the *Renewable Power Generation Cost Report 2018* by IRENA [17]. This report analyzes the CAPEX of PV power plants in 19 countries. Table 2.3 represents data for the countries with a high share of PV installed power worldwide, as reported by IRENA, as well as the global weighted average.

The countries listed below have the average cost harmonized for the year 2018, including inflation and excluding local incentives. Local incentives in many countries have helped the growth of the PV sector in recent years, but they have recently been phased out. The global weighted average value of $1,210/kWp was calculated by IRENA using IRENA's Renewable Cost Database. The calculated value is used as an indicative estimate for all other countries.

TABLE 2.3: CAPEX FOR A UTILITY-SCALE PV POWER PLANT VALUE FOR 19 SELECTED COUNTRIES IN 2018

Country Name	CAPEX [$/kWp]	Country Name	CAPEX [$/kWp]
Canada	2,427	Republic of Korea	1,326
Russia	2,302	Saudi Arabia	1,267
Japan	2,101	Turkey	1,206
South Africa	1,671	Indonesia	1,192
Australia	1,554	Germany	1,113
United States	1,549	France	1,074
Brazil	1,519	China	879
Mexico	1,541	Italy	870
Argentina	1,433	India	794
United Kingdom	1,362	Global Weighted Average	1,210

Source: IRENA [17].

However, this value is affected to a large extent by installed solar PV capacity in countries such as China and India, which have low installation costs in addition to being key manufacturing hubs for most balance of systems hardware.

Operational expenditure

Operational and maintenance spending (OPEX) makes up the second-largest portion of the lifetime cost of a PV power plant. Factors including climate conditions, local geography, and levels of industrialization and urbanization determine the soiling rate of PV modules, as well as the general upkeep of power plants. A well-designed PV power plant that has been built diligently, uses quality components, and has proactive risk mitigation strategies in place will correlate with lower OPEX over the lifetime of the project. Many developers and engineering companies work with a value of around $15/kWp/yr for utility-scale projects [22] to assess the lifetime costs of the PV power plant.

Discount rate

To estimate the annualized future fixed cost and future PVOUT we use the "discount rate," which is a term used interchangeably with weighted average cost of capital (WACC).

For PV investments, WACC is calculated with both share and cost of equity and debt. Cost of capital is used for discounting as it represents the "opportunity cost" of the money that is invested in building the power plant. Cost of equity reflects the foregone return that an investor could have earned on alternative investment, and cost of debt is the interest rate paid. For global studies involving diverse countries with different financial and market conditions, a simplified approach exists: WACC of 7.5% is used for OECD countries and China, and WACC of 10.0% is used for the rest of the world [17].

Lifetime energy production

In the PVOUT calculation (Chapter 2.2), the energy output is shown as the one generated for the year 0 of plant operation, with the components performing at their manufactured peak. Therefore, we have applied a linear PV performance degradation of 0.8% for the first year, and 0.5% for every following year to better illustrate the energy generated during the operational lifetime and various hardware performance degradation for a typical operational lifetime of 25 years.

Interpreting LCOE calculated in this study

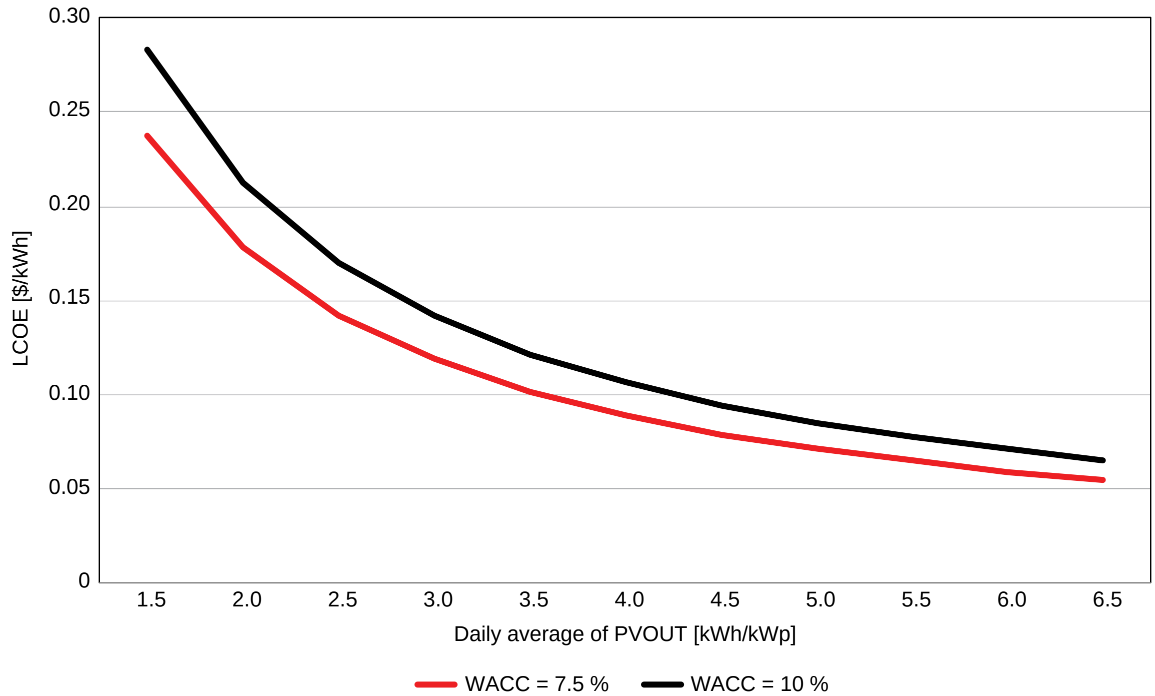
The resulting LCOE in this study is a simplified calculation that disregards local market conditions but gives a rough idea of the local potential for further analysis. It is a way of translating PVOUT results into a financial indicator.

We should note that very rough input values disregard local intricacies, which are impossible to assess at this global perspective. The actual LCOE at the real PV power plant might vary considerably from our calculations due to various reasons, including local costs of land, grid infrastructure, and soft costs such as installation/construction, permits, and design. Furthermore, each can differ substantially even within the country itself.

Another value to consider is the WACC. Figure 2.8 illustrates its considerable effect, particularly at low PVOUT values. This figure is addressed on a per-project basis by financing organizations.

The cost of PV power has dropped quickly over the last decade as a result of increased commercial utilization. As this fall is likely to continue, the estimates here can only represent a snapshot of the current

FIGURE 2.8: LCOE FOR DIFFERENT PVOUT CALCULATED FOR CAPEX GLOBAL WEIGHTED AVERAGE OF $1,210/kWp



Source: Authors.

time. In addition, while the decline in CAPEX and OPEX is likely to continue, we will also see other less predictable factors that influence the overall value of solar. These include advances in storage technology, solar power forecasting, electricity demand management, and ability of the grid to effectively manage and transfer energy within regions and over long distances.

Selected Indicators Related to Economic PV Potential

We have been able to access a number of socioeconomic indicators, which are monitored by the World Bank [23] and other respected organizations, for multi-criteria analyses. We selected socioeconomic indicators relevant to PV development status (Table 2.4) and correlated them with countries' average of practical PV power potential.

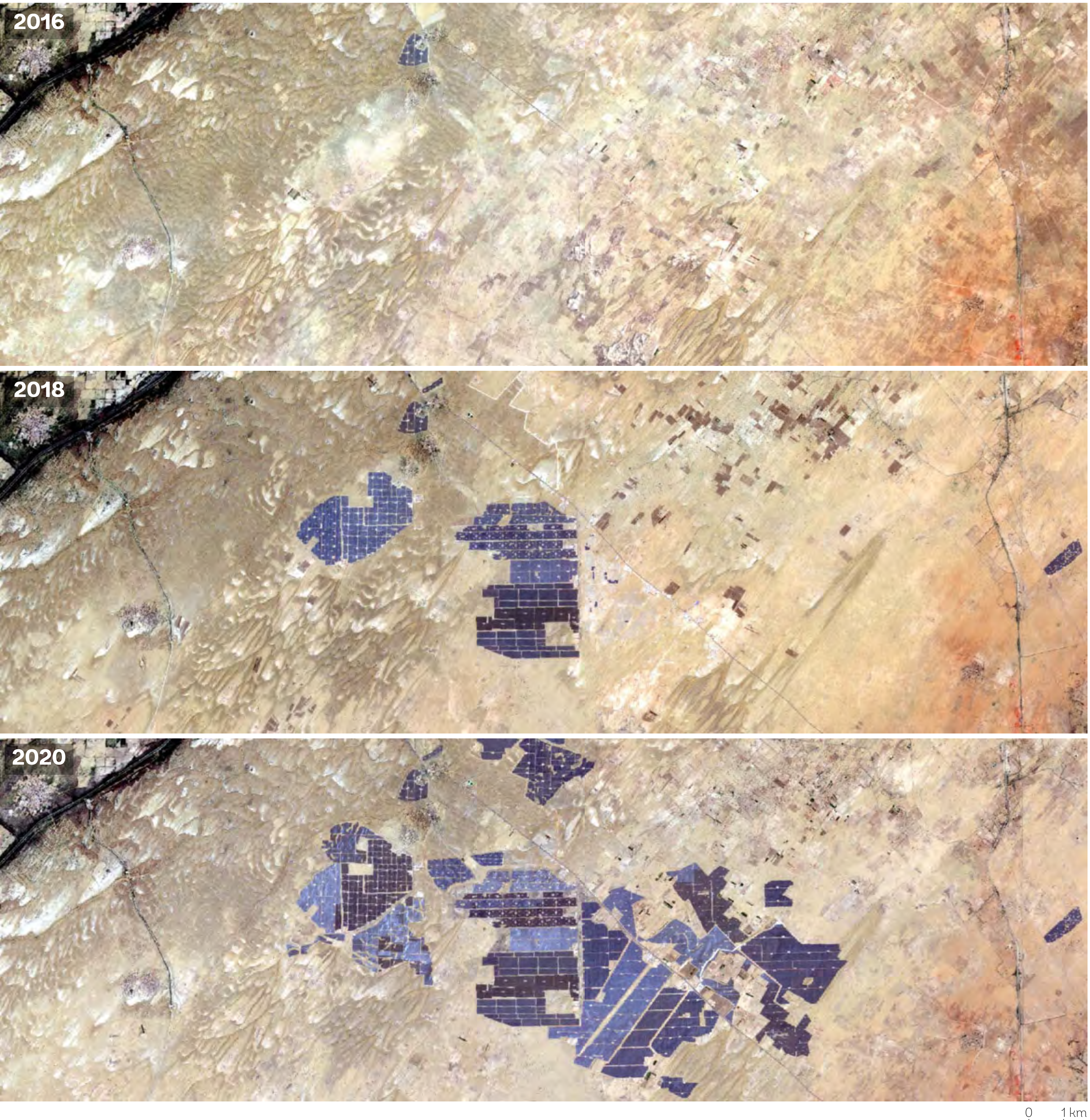
We picked a "bubble chart" style for data visualization where, besides the country PVOUT (x-axis) and the selected indicator (y-axis), we emphasized the other two characteristics: country population (bubble size), and regional reference (color).

As a result, we have been able to combine four features in each chart, providing a unique interpretation base for the reader. Consequently, we comment on some notable phenomena (Chapter 3.4). A closer look at the position of individual countries is included in the *country factsheets*.

TABLE 2.4: SOCIOECONOMIC INDICATORS, SELECTED FOR COMPARISON TO PV POWER PRODUCTION

Indicator	Description
Population	Total population is based on the de facto definition of population, which counts all residents regardless of legal status or citizenship. The values shown are mid-year estimates [24].
PV Installed Capacity	PV installed capacity shows the country's exposure to the PV technology deployed within its borders. The installed capacity is calculated as the maximum output of electricity that a generator can produce under optimal conditions. Capacity levels are normally determined as a result of performance tests and allow utilities to project the maximum electricity load that a generator can support. Capacity is generally measured in megawatts or kilowatts [25]. The data from the study [26] are used.
Human Development Index	The Human Development Index (HDI) is a summary measure of human development. It measures the average achievements in a country in three basic dimensions of human development: a long and healthy life, access to knowledge, and a decent standard of living. The HDI is the geometric mean of normalized indices measuring achievements in each of the three dimensions and embodies imperfect substitutability across all HDI dimensions. Thus, it addresses one of the most serious criticisms of the linear aggregation formula, which allowed for perfect substitution across dimensions. Some substitutability is inherent in the definition of any index that increases with the values of its components [27].
Access to Electricity	This refers to the percentage of the population with access to electricity. Electrification data are collected from industry, national surveys, and international sources [28]. In countries where access to electricity is difficult and infrastructure underdeveloped, PV provides an outstanding opportunity for growth of energy usage.
Electricity Power Consumption	Electricity power consumption (in kWh per capita) measures the production of power plants and combined heat and power plants, after stripping out transmission, distribution, and transformation losses and own use by heat and power plants [2].
Reliability of Electricity Supply and Transparency of Tariffs	The reliability of supply and transparency of tariffs index measures supply reliability, transparency of tariffs, and the price of electricity. The most recent round of data collection for this project was completed in May 2018 [29].
Energy Use	Energy use (kg of oil equivalent per capita) refers to the use of primary energy before transformation to other end-use fuels. This is equal to indigenous production plus imports and stock changes, and minus exports and fuels supplied to ships and aircraft engaged in international transport [30].
Electricity Tariffs	Electricity tariffs for the end-users [31] vary significantly across the globe. In most regions, PV is already cheaper than any of the conventional power generation options. More solar electricity may stabilize, and in some cases, also reduce the electricity costs in the future.

Source: Authors.



Timeline of the PV power plants development near Bhadia (Rajasthan, India).
Source: Copernicus Sentinel Hub, Sentinel-2, True color, a) 2016–05–21, L1C product, b) 2018–07–10, L2A product, c) 2020–05–10, L2A product. Composed by Solargis.

3. RESULTS AND DISCUSSION

Based on the methods presented in Chapter 2, we have evaluated and mapped three types of PV power potential per each country or region: theoretical, practical, and economic potential. We present the results here in a variety of forms and outputs:

- This report presents aggregated information for all countries within the global perspective
- Data for each country or region are also accessible online via the Global Solar Atlas [1]
  - Separate from this report, we publish country factsheets with a complete set of summary statistics
  - An interactive map tool provides access to solar potential data for any site, country, or custom area
  - Poster maps show a detailed look at the theoretical potential
  - Raw data on primary variables can be downloaded in standard GIS formats and used for further spatial analysis

3.1 THEORETICAL POTENTIAL

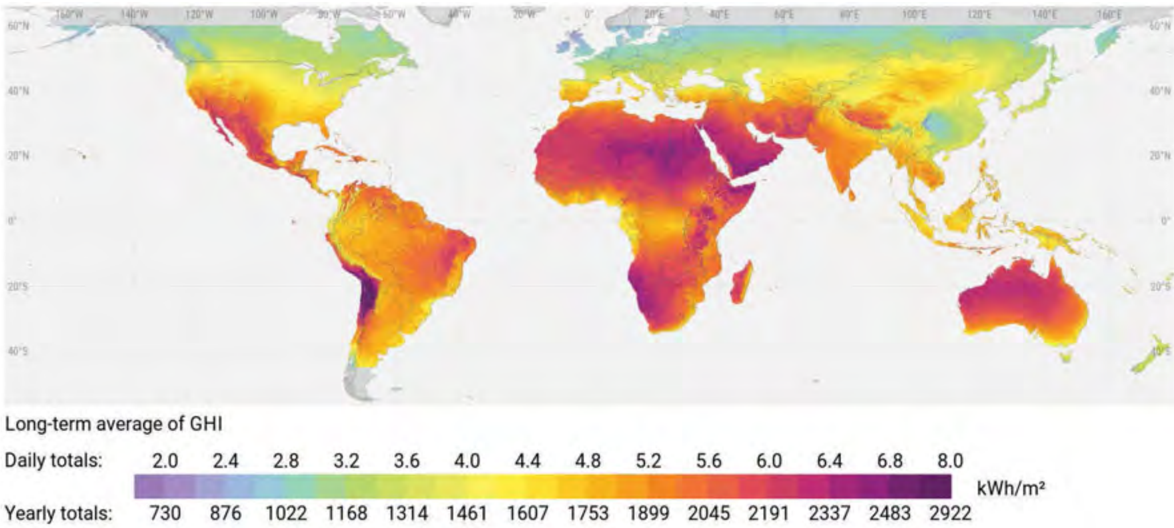
The global maps in this chapter show the **theoretical potential** for PV power that is characterized by the long-term distribution of solar resource: global horizontal irradiation (GHI) and direct normal irradiation (DNI).

As discussed earlier, GHI allows for comparison of the natural conditions for implementing a PV system without considering any particular technical design or mode of operation. We evaluate the theoretical potential by estimating GHI (Figure 3.1), as it is the most relevant variable for the fixed mounted PV systems assessed in this study. Power performance for any PV design is also determined by availability of DNI (Figure 3.2); therefore, we present also its geographical distribution.

The global pattern of GHI is determined mainly by geographic latitude, abundance of clouds, atmospheric aerosol concentration, and moisture content. In general, the highest theoretical potential is seen in arid tropics and subtropics (north and south Africa, the Middle East and Arabian Peninsula, Australia, Mexico, parts of Brazil and the United States, the Caribbean, and Mediterranean regions). The potential is often amplified by higher altitude due to thinner and more transparent atmosphere, especially in the Andean region, but also in east Africa, the Himalayan region, and elsewhere. The equatorial belt has less potential due to the frequent occurrence of clouds. A lower potential is typical for the temperate zone due to a lower sun angle, as well as in India and the parts of China with a higher concentration of aerosols.

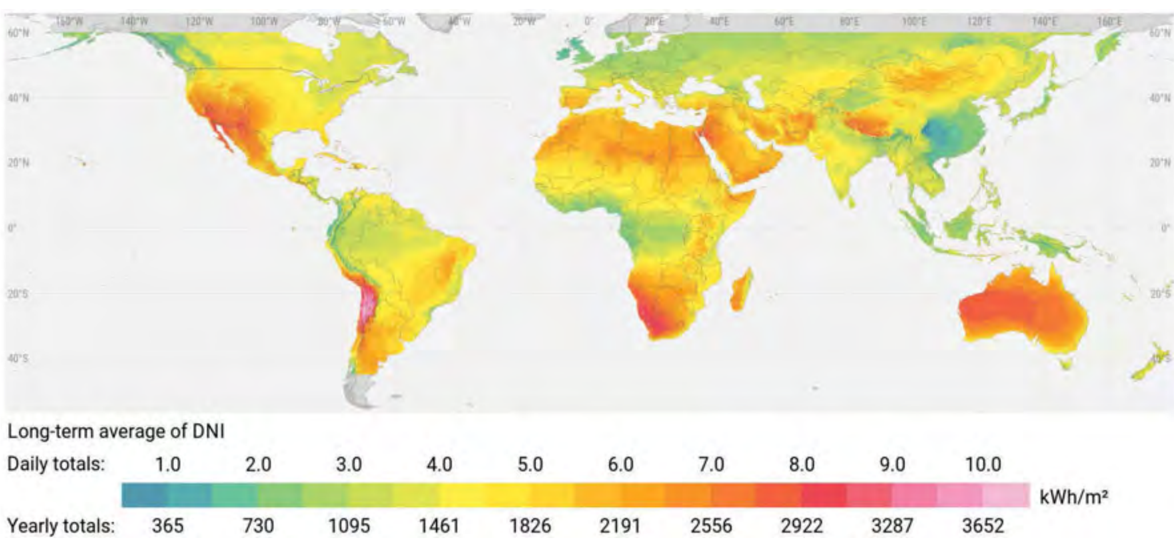
At a given site, solar resource (GHI and DNI) is modulated by local terrain, clouds, atmospheric pollution, dust, and some other geographical factors.

FIGURE 3.1: GLOBAL HORIZONTAL IRRADIATION: LONG-TERM YEARLY AVERAGE OF DAILY/YEARLY SUMMARIES



Source: Authors.

FIGURE 3.2: DIRECT NORMAL IRRADIATION: LONG-TERM YEARLY AVERAGE OF DAILY/YEARLY SUMMARIES



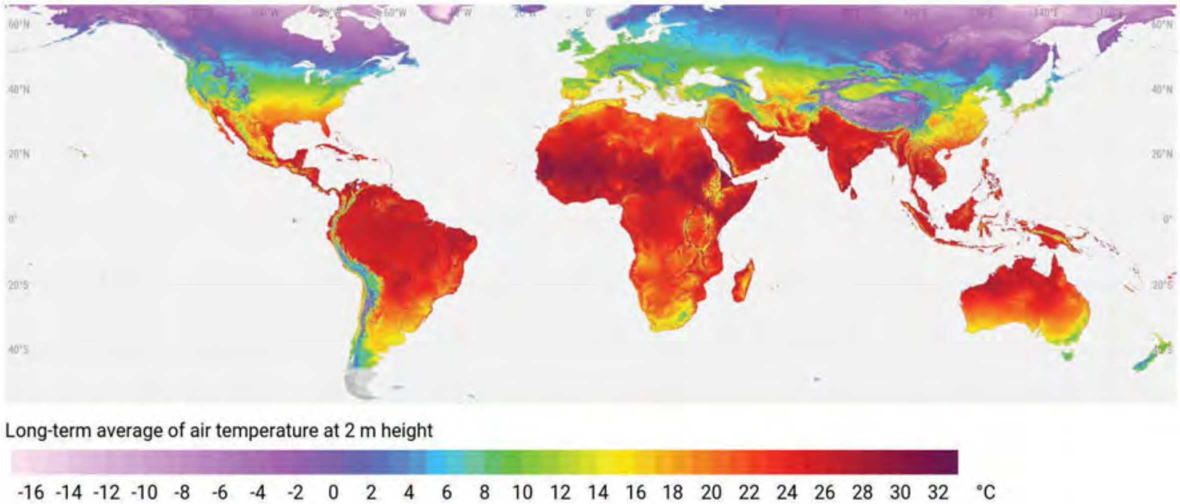
Source: Authors.

As can be seen in Chapter 3.2, GHI (and DNI as complementary information) can be considered only as a simplified approximation of PV power potential, and it does not fully describe the real potential for PV power production. After solar resource, **air temperature** (TEMP, Figure 3.3) is the leading natural factor that affects PV generation.

3.2 PRACTICAL POTENTIAL

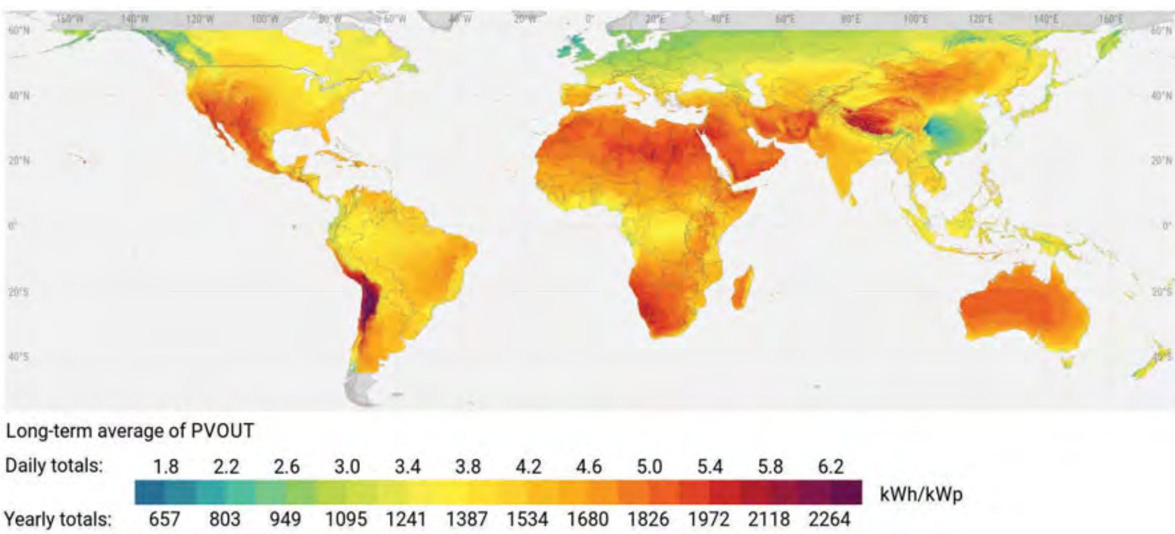
The practical PV potential is illustrated by the estimated power output produced per unit capacity of the assumed PV system configuration: the **PVOUT** variable, measured in kWh/kWp. We evaluate the long-term average of yearly production totals (Figure 3.4), derived using the previously explained calculation method (Chapter 2.2).

FIGURE 3.3: AIR TEMPERATURE: LONG-TERM YEARLY AVERAGE



Source: Authors.

FIGURE 3.4: PRACTICAL SOLAR PV POWER POTENTIAL: LONG-TERM YEARLY AVERAGE OF DAILY/YEARLY SUMMARIES (LEVEL 0)



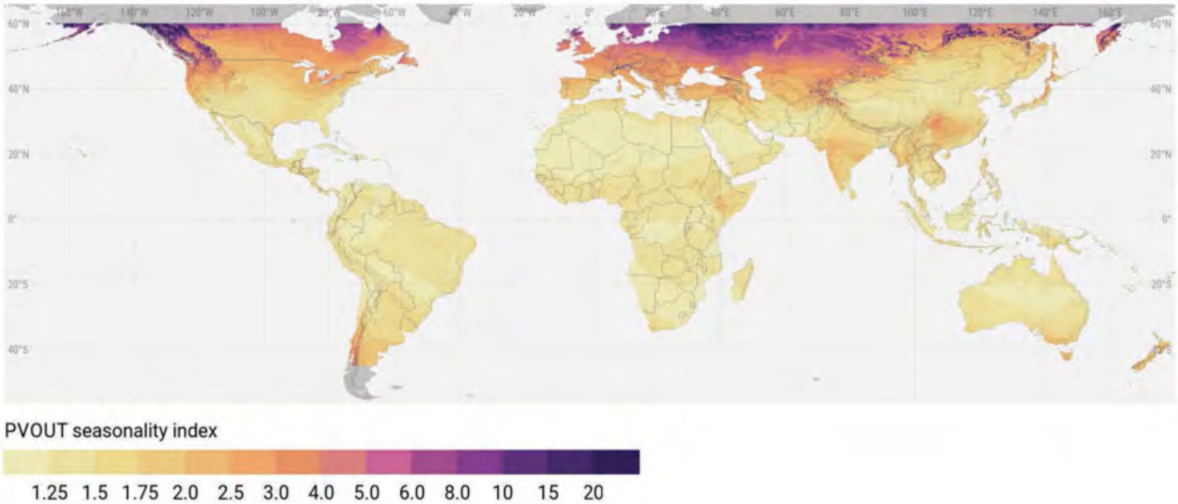
Source: Authors.

No PV technology can exploit the full theoretical potential of the solar resource: the output is determined by factors, including the configuration of the PV system, the conversion efficiency of PV modules, and the shading and soiling of the modules. Moreover, the PV conversion efficiency decreases at higher temperatures. This is why air temperature is so important when we are seeking to calculate PVOUT.

Figure 3.4 displays PVOUT distribution regardless of any limitations to the development and operation of solar PV power. Therefore, this can be considered the Level 0 practical potential.

A map of the **seasonality index** complements the practical potential evaluation, as it characterizes the PVOUT variability throughout the year (Figure 3.5).

FIGURE 3.5: PRACTICAL SOLAR PV POWER POTENTIAL: SEASONALITY INDEX (LEVEL 0)



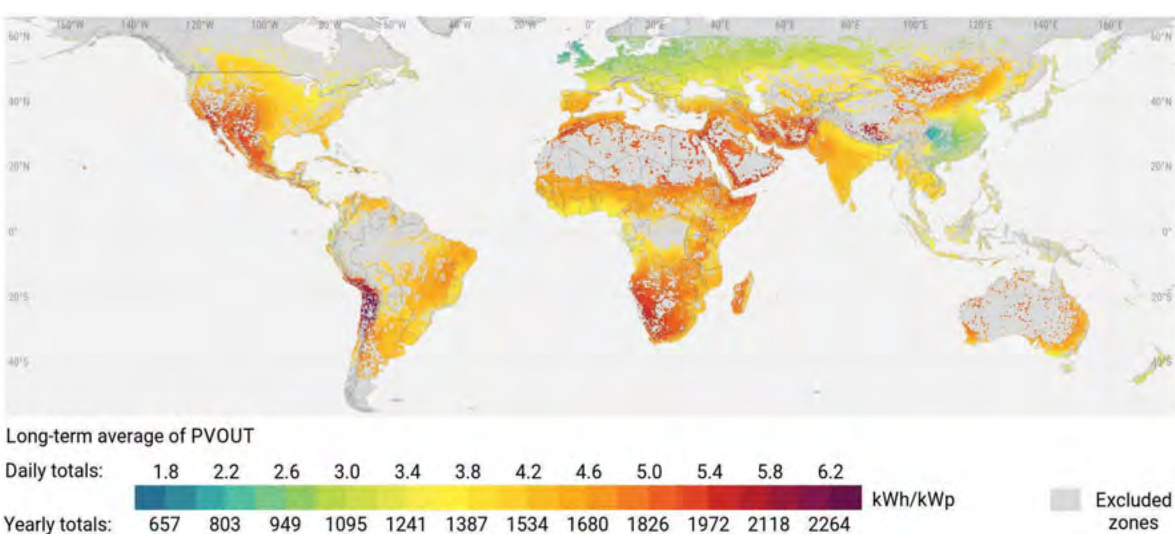
Source: Authors.

However, to realistically examine the practical potential and to derive figures representative for the territory of individual countries or regions, we have to also consider the topographic and land-use constraints. We excluded areas with physical limitations due to complex terrain and other natural features described earlier (Chapter 2.3). Even though the localization of the utility-scale PV power plants might be possible, the project establishment would require excessive costs or efforts.

Level 1 practical potential (Figure 3.6) describes areas without identifiable physical or technical obstacles. **Level 2** practical potential (Figure 3.7) shows a further restricted distribution, as it excludes additional areas potentially unsuitable due to nature protection or cropland conservation regulations.

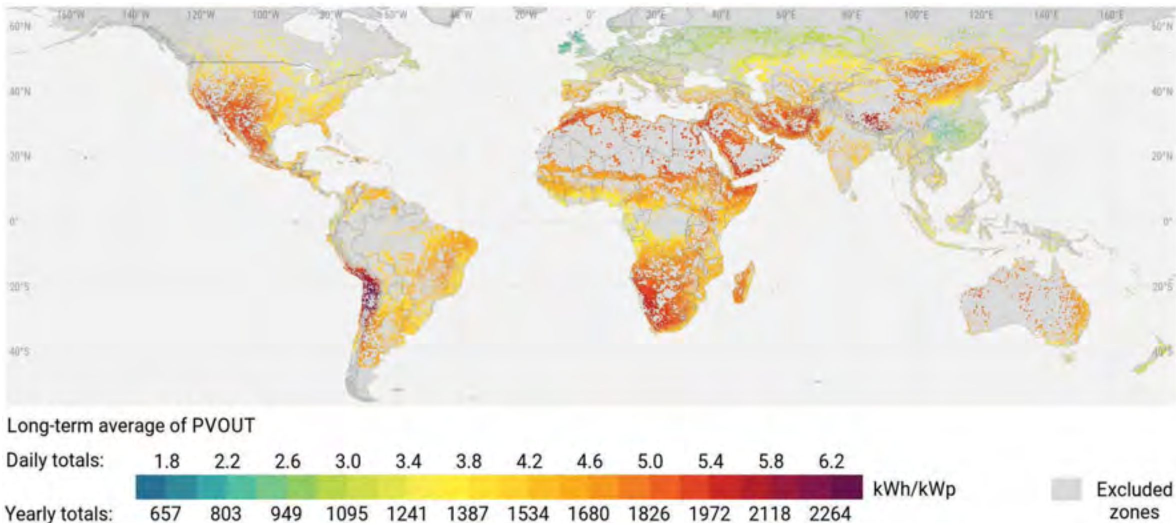
Using administrative boundaries, we calculated zonal statistics to summarize the distribution of solar power potential in each country or region. Figure 3.8 shows ranking by country-averaged practical

FIGURE 3.6: PRACTICAL PHOTOVOLTAIC POWER POTENTIAL AT LEVEL 1 (LONG-TERM AVERAGE)



Source: Authors.

FIGURE 3.7: PRACTICAL PHOTOVOLTAIC POWER POTENTIAL AT LEVEL 2 (LONG-TERM AVERAGE)



Source: Authors.

potential, based on the PVOUT data masked at Level 1. The colored bar symbolizes the minimum, first quartile, median, third quartile, and maximum (represented by Percentile 0.5, Percentile 25, Percentile 50, Percentile 75, and Percentile 99.5, respectively). The black line-bars show the full range of the practical potential at Level 0.

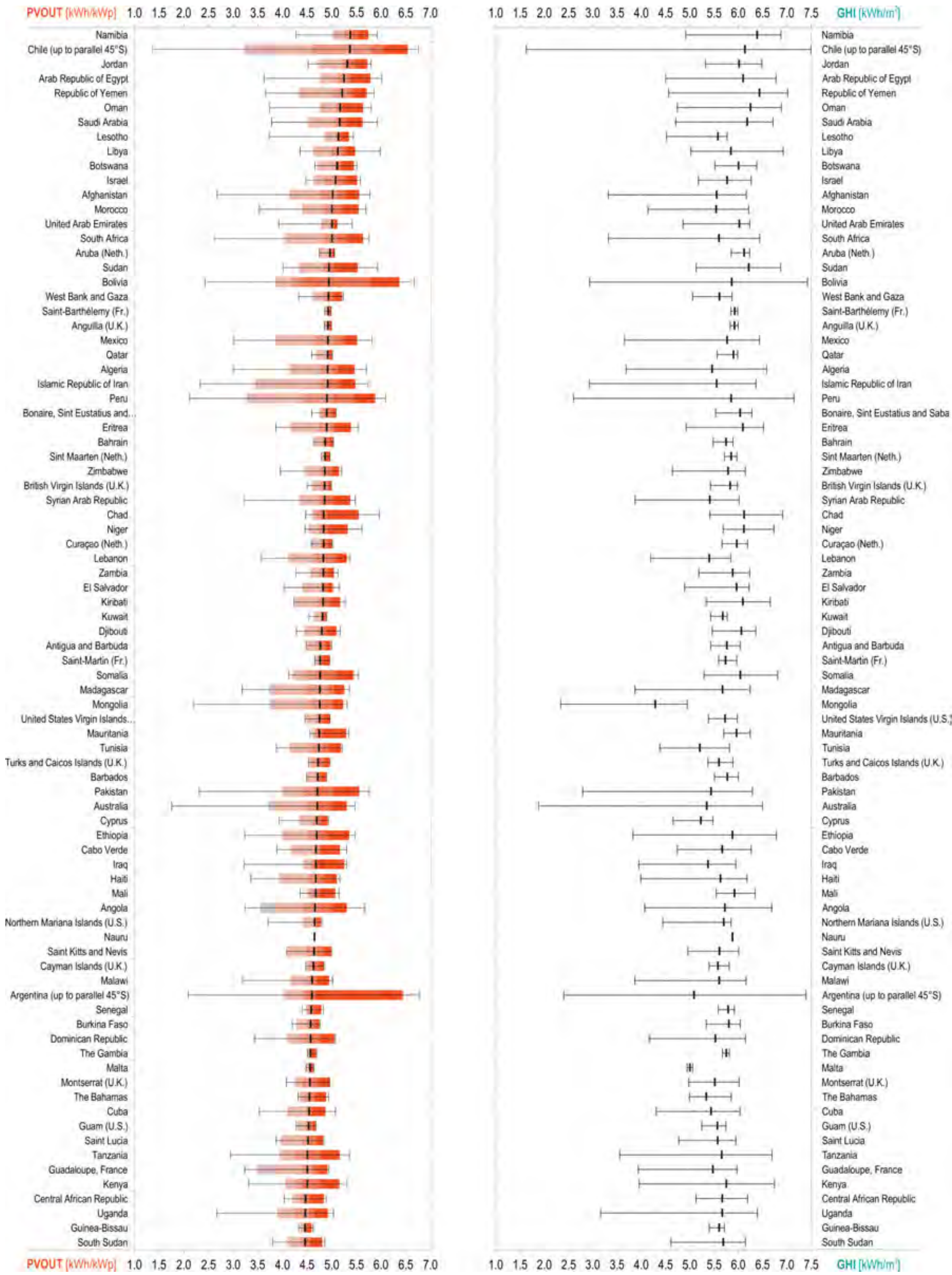
For comparison, we show the theoretical potential (GHI) in the right half of Figure 3.8. GHI is the essential parameter as it indicates the solar resource available to PV technology. Nonetheless, the relation between the two variables is less pronounced and less proportional than one could expect. The notable cases include Chad, Lesotho, Malta, Mongolia, and others (see also Figure 3.11 for more explanation). A ranking based on the theoretical potential would differ considerably.

The ranking enables country-based comparisons, benchmarking, or groupings based on the average practical PV potential. However, the order could also be based on other statistics, which would create a slightly different story. Thus, the position of a particular country in this ranking is not absolute, and it should be considered within the context of other countries.

For example, policymakers or project developers would prefer to locate PV power plants in the areas providing higher PV yield. For such a purpose, the order by PVOUT Percentile 75 value or even Percentile 90 value can give a more appropriate ranking of the countries. All source data for the graphics are available for download from the Global Solar Atlas website [1].

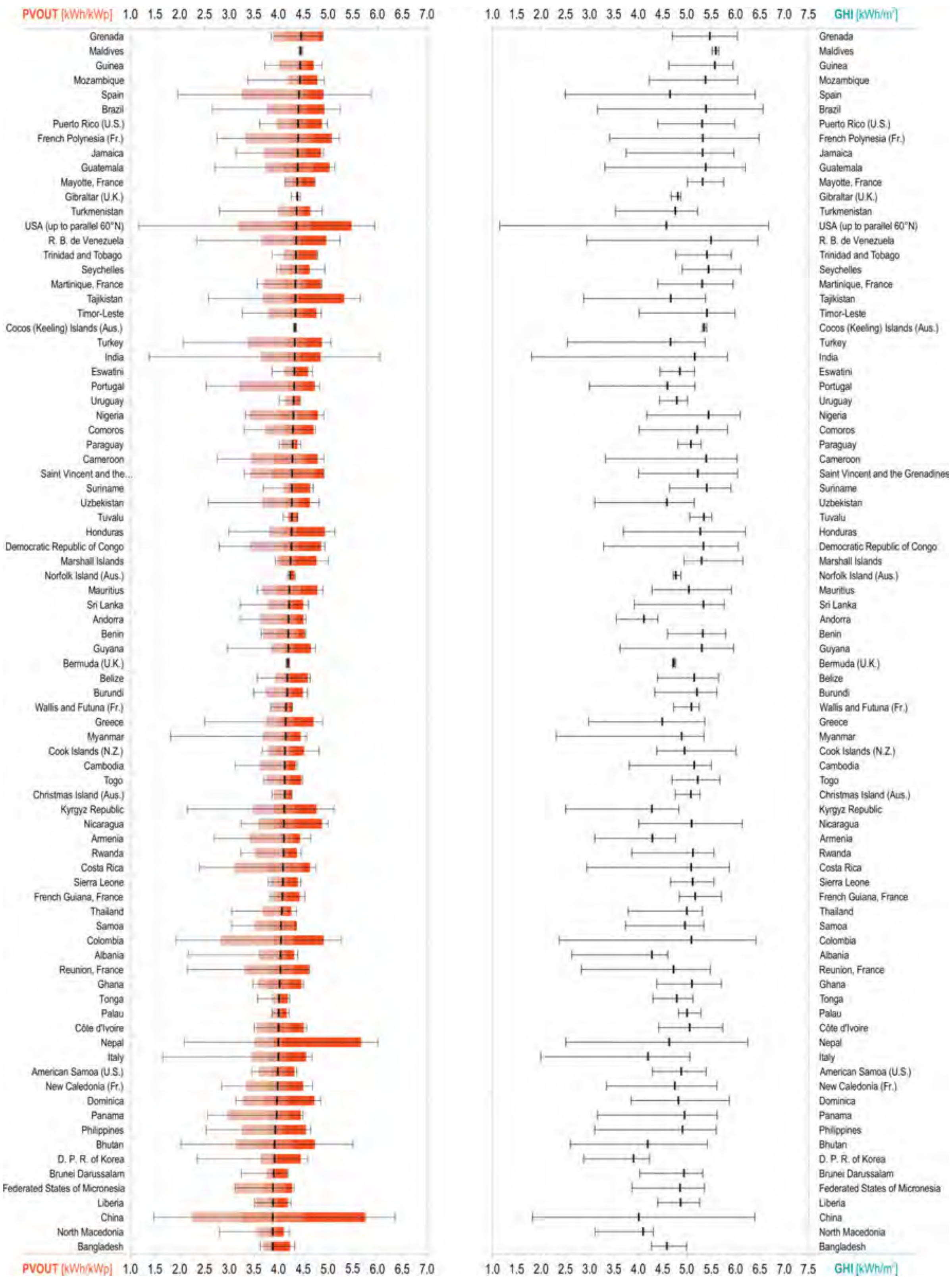
Notable geographical relations are documented in Figure 3.8, supported by Figure 3.4. These disrupt the common myth that latitude is the main determining factor of the PV power potential. Traditionally, lower PV yield used to be expected when moving from equatorial zones toward the higher latitudes. This pattern works well in the European climate. However, it is inverted elsewhere, for instance, in southeast and east Asia. In North America we see a diagonal correlation, where PV power potential generally increases from northeast to southwest. All such features have various climatological and geographical reasons, which are considered by the Solargis model in order to provide the most realistic results.

FIGURE 3.8 (PART 1 OF 3): RANKING OF SELECTED COUNTRIES, BASED ON ZONAL STATISTICS OF PRACTICAL PV POWER POTENTIAL



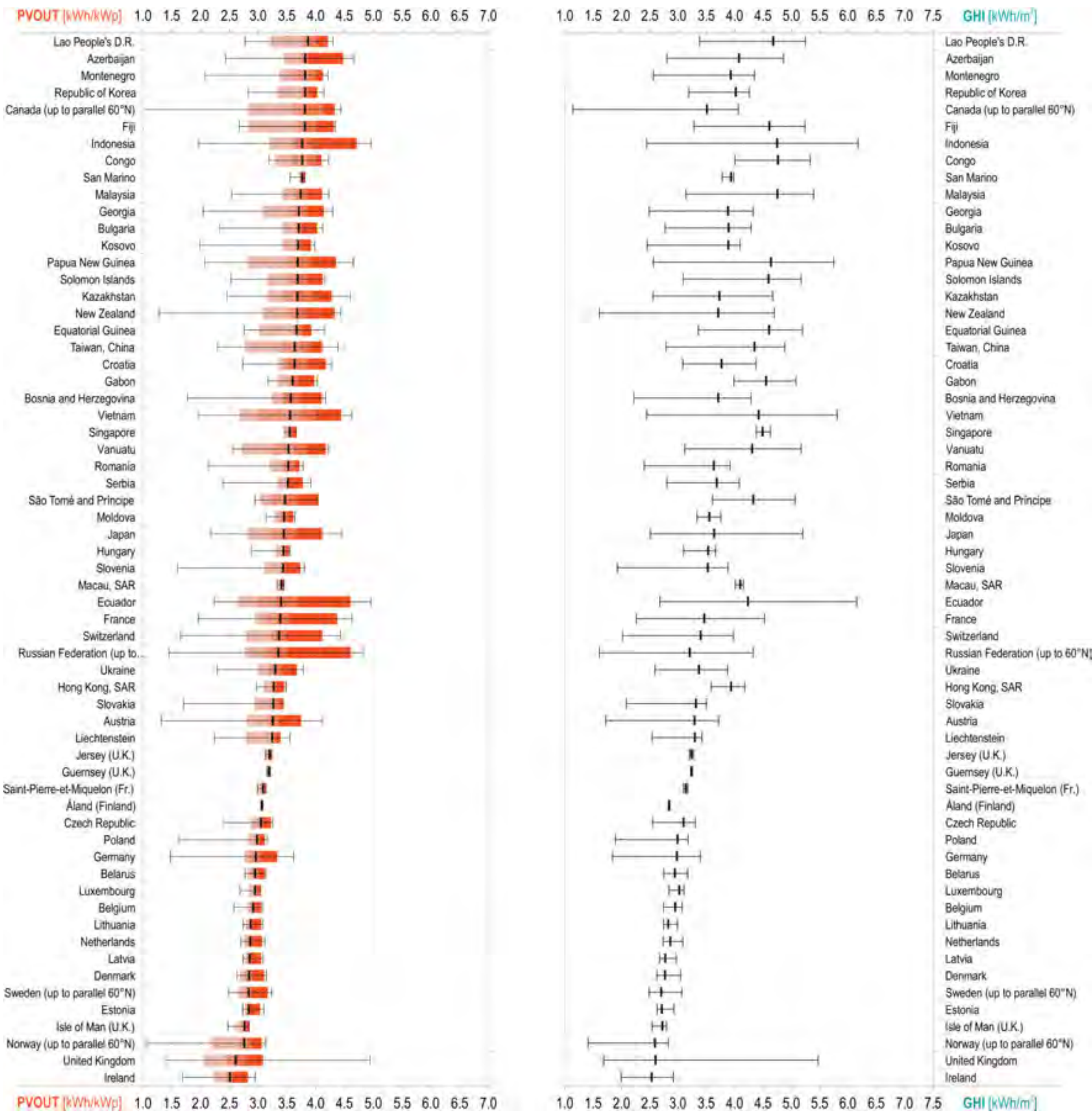
Source: Authors.

FIGURE 3.8 (PART 2 OF 3): RANKING OF SELECTED COUNTRIES, BASED ON ZONAL STATISTICS OF PRACTICAL PV POWER POTENTIAL

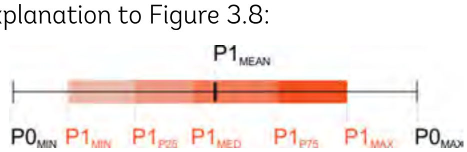


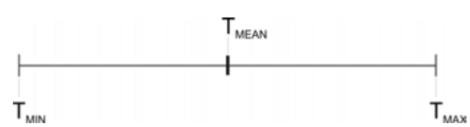
Source: Authors.

FIGURE 3.8 (PART 3 OF 3): RANKING OF SELECTED COUNTRIES, BASED ON ZONAL STATISTICS OF PRACTICAL PV POWER POTENTIAL



Explanation to Figure 3.8:





Countries' statistics of the practical PV power potential
$P0_{MIN}$ = Level 0: Minimum value
$P1_{MIN}$ = Level 1: Percentile 0.5 value
$P1_{P25}$ = Level 1: Percentile 25 value
$P1_{MED}$ = Level 1: Percentile 50 (median) value
$P1_{MEAN}$ = Level 1: Mean value; countries/regions are sorted based on this value
$P1_{P75}$ = Level 1: Percentile 75 value
$P1_{MAX}$ = Level 1: Percentile 99.5 value
$P0_{MAX}$ = Level 0: Maximum value

Countries' statistics of the theorectical solar resource (GHI):
T_{MIN} = Minimum value
T_{MEAN} = Mean value
T_{MAX} = Maximum value

Source: Authors.

The largest range of PVOUT values is typically seen in north-south elongated countries that cross several climate zones, such as Argentina and Chile. However, high variability also occurs in the regions that span across diverse climate zones (Ecuador, Iran, Peru, and China's Sichuan province). The variability is often related to factors such as the presence of high mountains, and prevailing or seasonal atmospheric circulation.

Of the many remarkable patterns displayed by the maps, we want to highlight two of them.

First, the highest PV power potential is observed in the Andes region in South America. In absolute values, the PV power potential is 15%–20% higher compared to other similar climate regions of the world, such as the Arabian Peninsula or north Africa. This is a result of a unique combination of factors that is not found elsewhere: persisting clear sky conditions, clean air, low air temperature, and high altitude, which causes the atmosphere to be thinner compared to lower-altitude areas. Therefore, the top values of solar resource and PV power potential are found in northwest Argentina, Bolivia, northern Chile, and southern Peru.

Second, the opposite extreme is observed in the central Chinese provinces Chongqing and East Sichuan. In this area, located around the 30°N latitude, one would not expect such low solar resource and PV power potential. Low solar irradiance is explained by the combination of several peculiar atmospheric and geographic factors. The high concentration of aerosols in the atmosphere migrating from the periglacial zones of the Himalaya-Karakoram-Tibet region is accompanied with human-induced air pollution. Weak ventilation of the basin caused by the enclosed barrier of the mountain ranges results in heavy haziness of the atmosphere during most of the year, which reduces the available solar resource. In comparison with regions in similar latitudes, the PV power potential in north India and California is 200% higher, and in the Middle East and North Africa (MNA) region 250% higher [1].

Around 20% of the global population lives in 70 countries boasting excellent conditions for PV, where long-term daily PVOUT averages exceed 4.5 kWh/kWp. Countries in the MNA region and Sub-Saharan Africa dominate this category, accompanied by Afghanistan, Argentina, Australia, Chile, Iran, Mexico, Mongolia, Pakistan, Peru and many nations of the Pacific and Atlantic islands.

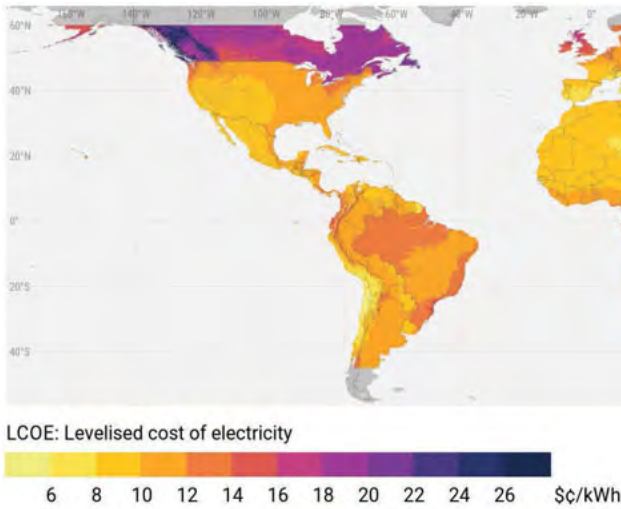
At the lower end of the ranking, 30 countries accounting for 9% of the global population score an average PVOUT below 3.5 kWh/kWp, dominated by European countries—except those in southern Europe—and also including Ecuador and Japan. Even in countries with lower solar resource availability, the potential is not dramatically lower compared to the top-performing group.

Finally, countries in the favorable mid-range between 3.5 and 4.5 kWh/kWp account for 71% of the global population. These include five of the six most populous countries (China, India, the United States, Indonesia, and Brazil) and 100 others (Canada, the rest of Latin America, southern Europe, and African countries around the Gulf of Guinea, as well as central and southeast Asia).

3.3 ECONOMIC POTENTIAL

The **economic potential** describes how much it costs to produce a unit of energy compared to other energy generation sources. Figure 3.9 shows the potential via a simplified LCOE calculated according to the method described in Chapter 2.4. This estimate takes a global viewpoint to illustrate the economic potential.

FIGURE 3.9: A SIMPLIFIED LCOE ESTIMATED FOR LARGE-SCALE GROUND-MOUNTED PV POWER PLANTS WITH EXPECTED LIFETIME OF 25 YEARS



Source: Authors.

In the last decade, the LCOE reduction in the PV industry has been dramatic [17], and further reductions over the following decade are expected. Therefore, the results presented here should be interpreted only as a snapshot for 2018, estimated from the available data.

The map shows that CAPEX plays an important role in the distribution of LCOE across the globe. It is relatively high in Russia, Canada, and Japan, causing the LCOE to rise to over $0.15/kWh even in the regions with favorable PV potential, and over $0.20/kWh with less promising PV potential.

On the other hand, low CAPEX dramatically influences the LCOE, including in China, India, and Italy, where most of the area in the countries reach the level of $0.06/kWh or less. LCOE for particularly large PV projects drops even lower in countries such as in the United Arab Emirates and Saudi Arabia, according to publicly available data [17].

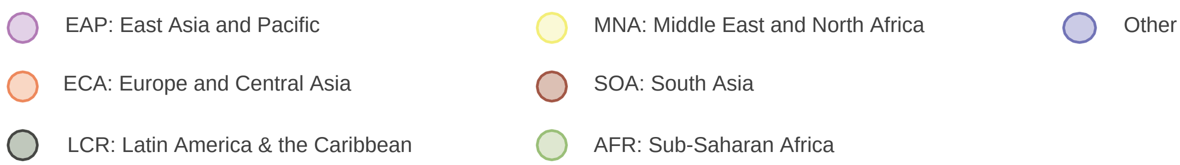
Nevertheless, the economic potential varies between $0.06/kWh and $0.14/kWh in most countries and over 75% of the evaluated global area scores below $0.12, which makes solar PV competitive with conventional power-generating sources.

In addition to LCOE, we compare practical solar PV potential to a set of other **socioeconomic indicators** to show the solar power generation potential in the context of economic, human, and social development.

The selected indicators are described in Table 2.3 and shown in the form of bubble charts. The y-axis in all charts represents the country's or region's practical potential at Level 1, represented by the mean value of the long-term average of daily totals. The color of a bubble refers to a group of countries, or world regions, defined by the World Bank (Table 2.1, Figure 3.10). The size of the bubble represents the population. Bubbles of the largest economies in each group or the extremes are tagged with a two-letter country code (ISO-3166-1 alpha-2).

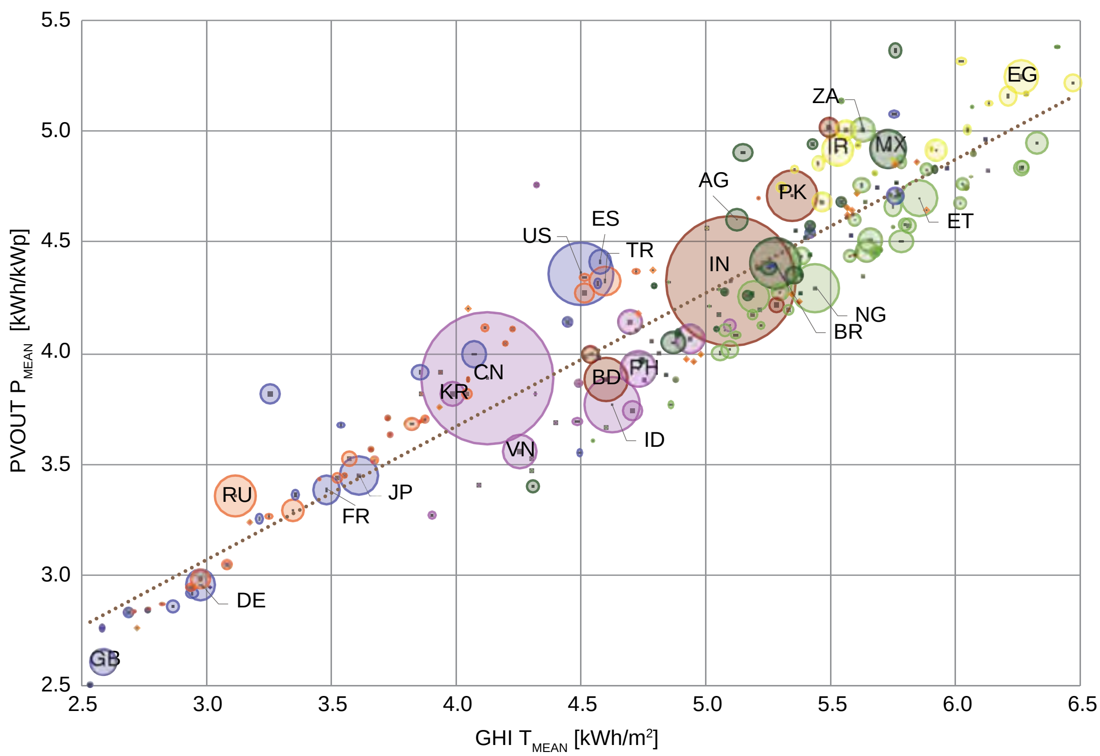
The data and graphs available in this report are also available for interactive viewing and may be downloaded from the Global Solar Atlas.

FIGURE 3.10: COUNTRY GROUPS, ACCORDING TO THE WORLD BANK, USED IN FIGURES 3.11 TO 3.19



Source: Authors.

FIGURE 3.11: AVERAGE PRACTICAL PV POWER POTENTIAL AT LEVEL 1 (PVOUT) COMPARED TO THEORETICAL POTENTIAL (GHI)

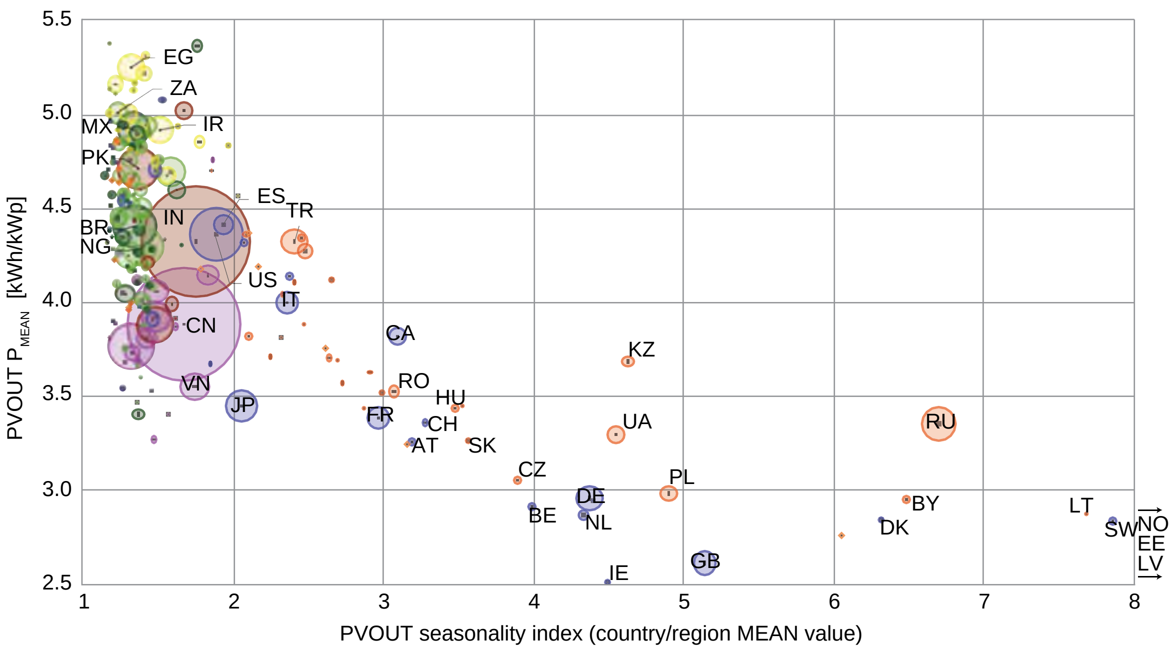


Source: Authors.

Figure 3.11 is an alternative view of the P_{mean} values presented in Figure 3.8. It shows that the theoretical potential, represented by GHI, is not fully proportional to practical PV power potential PVOUT. The main reason for this is that air temperature influences the performance of PV power plants. For the same GHI values, the specific PV power generation is higher in regions with a colder air temperature, and lower in regions with a higher air temperature.

Indonesia and Turkey are both striking examples: the mean GHI value is similar, 4.75 and 4.66 kWh/m^2, respectively. Although Turkey has slightly lower GHI, the country's mean value of PVOUT is almost 15% higher compared to Indonesia (4.32 and 3.77 kWh/kWp, respectively). Other notable cases are Nigeria

FIGURE 3.12: ABSOLUTE VALUES OF PRACTICAL PV POWER POTENTIAL COMPARED TO PV SEASONALITY INDEX



Source: Authors.

and Pakistan, Tanzania and South Africa, Kenya and Mexico, and Eritrea and Egypt. In each of the pairs, both countries have similar theoretical potential, but PVOUT is superior in the latter country.

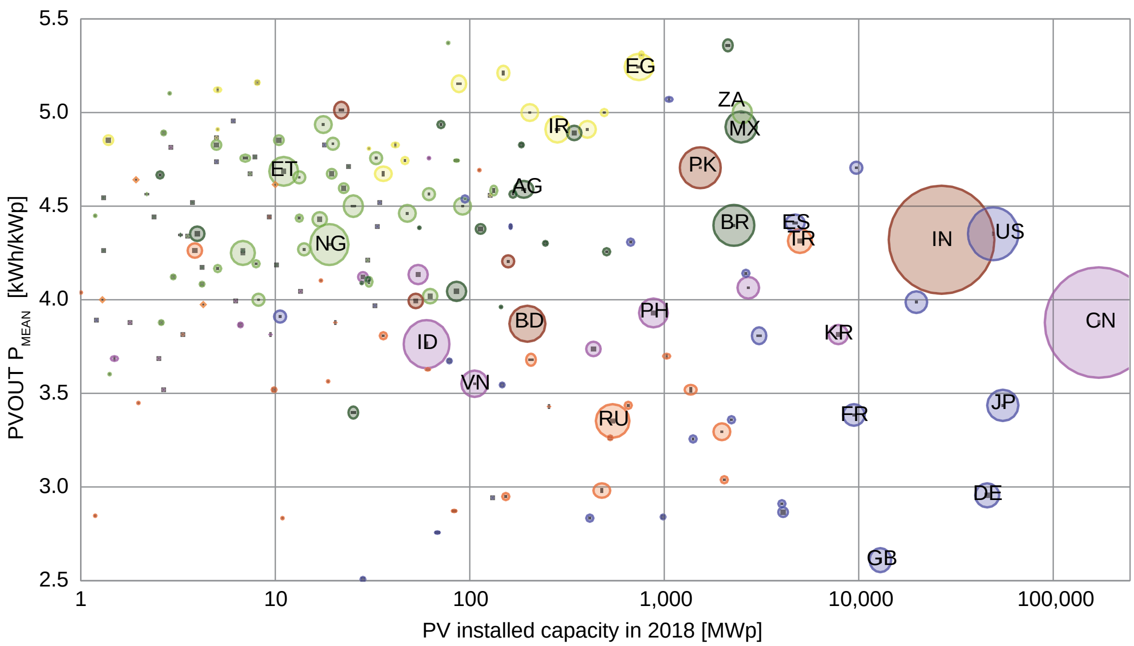
Other than the absolute value of PV potential, the stability of power generation throughout the year is another important factor (Chapter 2.2). Regular weather cycles, or seasons, determine the yearly pattern of PV power generation. A seasonality index close to 1.0 indicates no seasonal effect in PV power generation, while higher values indicate the occurrence of seasons with lower and higher power production during a year. In general, seasonality increases from the sub-equatorial zone, through higher latitudes, up to the Arctic Circle.

More than 85% of the global population lives in 150 countries where the average seasonality index is less than 2.0 and PVOUT exceeds 3.5 kWh/kWp (Figure 3.12). Almost half of the population lives in countries where the seasonality index is around 1.5 or less. Furthermore, approximately 80% of the population lives in countries that comprise at least some area with a negligible seasonality effect (up to 1.3).

Low seasonality increases the value of solar power, but a moderate seasonal effect of PV power generation can be in natural synergy with seasonal demand in areas where cooling is the primary energy challenge. This applies in most of the countries with tropical, subtropical, and temperate climates.

On the contrary, high seasonality challenges the countries in the higher latitudes, where the highest demand for energy is during cold winters. At the same time, short daylight periods and low sun angle limit the PVOUT generation. Countries in the northern part of Europe are the typical examples—and, perhaps paradoxically, this includes Germany, which is one of cradles of the PV industry.

FIGURE 3.13: PRACTICAL PV POWER POTENTIAL VERSUS INSTALLED CUMULATIVE PV CAPACITY IN 2018



Note: x-axis has a logarithmic scale.
Source: Authors.

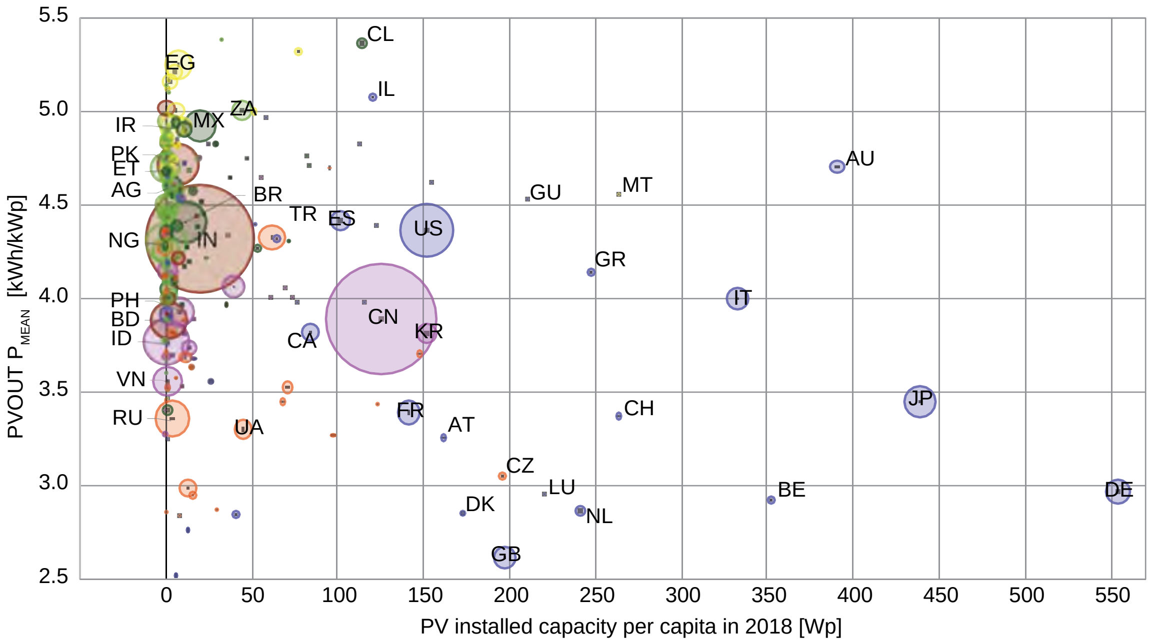
The existence of extreme seasonal cycles is a challenge for the smart technical optimization of PV power plants as owners seek to smooth the PV power generation curve during the year. These practical challenges include the tilt of the modules and the involvement of the tracking systems, as well as the fact that other energy sources are likely dominant during the seasons with very low PV power output. However, this does not disqualify PV from being a significant part of the regional energy mix (see Figure 3.13).

Indeed, achieving synergy with other renewable and nonrenewable energy sources may play an important role in the energy mix. Hydro-connected PV power plants are an excellent example of such synergy [32, 33], especially in monsoon-affected countries such as India and Vietnam, as well as Africa. Hydro plants only have enough water during the rainy season, during which the cloudy conditions will also reduce PV electricity generation. However, the opposite effect occurs during the dry season, and indicates the technologies could complement each other well.

In 2018, a cumulative capacity of more than 480 GWp of PV power was installed worldwide [26]. Over one-third of the global capacity was installed in China, while the second third was made up of a combination of Japan, the United States, and Germany. In total, the top 15 countries accounted for 90% of all PV capacity (Figure 3.13). The uneven distribution of installed capacities in that year is a typical sign of a young and developing industry.

In terms of installed PV capacity per capita (Figure 3.14), the top three positions belong to Germany (554 Wp per capita), Japan (438 Wp), and Australia (390 Wp). At the same time, the top three countries represent very different regions in terms of PV potential: low, moderate, and high.

FIGURE 3.14: PRACTICAL PV POWER POTENTIAL VERSUS INSTALLED CUMULATIVE PV CAPACITY PER CAPITA IN 2018



Source: Authors.

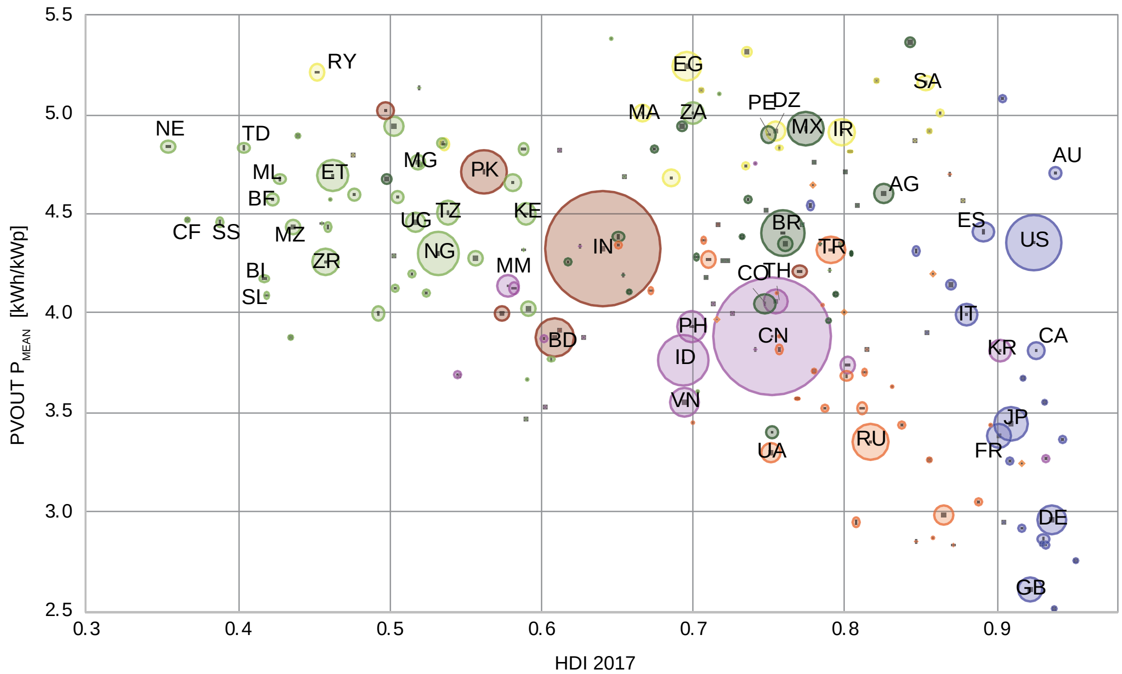
The margin of 100 Wp per capita is exceeded in 28 countries. On the contrary, around 120 countries had PV installed capacity lower than 10 Wp per capita. Approximately half of those had minimum or no installed PV capacities (below 1 Wp per capita). It is striking that this includes many countries with exceptional PV potential, including almost all African countries except South Africa, as well as Bangladesh and Indonesia. This shows that the rollout of solar PV in many countries with high PV potential has been lagging [26].

The top benefits of solar PV are scalability, versatility, and short project construction times. These are crucial factors that would support the acceleration of the growth of solar PV among users in energy-dependent sectors, especially in developing countries with low electricity generation capacities.

Almost all nations with lower Human Development Index (HDI) rankings show outstanding PV potential (Figure 3.15). Most of the countries from Sub-Saharan Africa, followed by countries from the south Asia region, are characterized by low HDI and high PVOUT (upper-left quadrant of the chart). In contrast, many countries with high HDI and lower PV power potential systematically support the growth of solar renewable energy (compare with Figure 3.14).

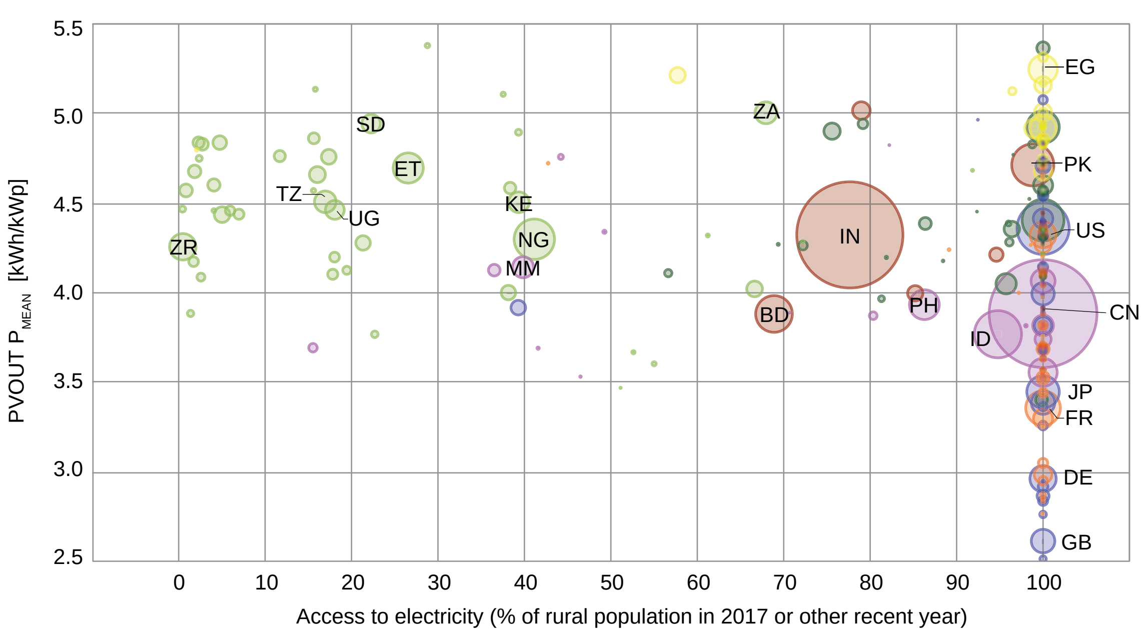
We see a similar pattern of the distribution of countries/regions in the graph that shows access of the rural population to electricity (Figure 3.16). Most countries with limited rural access to electricity show practical PV potential over 4 kWh per day. In parallel to HDI, this includes countries in Sub-Saharan Africa, followed by South Africa. Some countries in Latin America and southeast Asia also have not reached universal electricity access, especially in more remote locations. In such cases, implementation of off-grid, micro-grid, or hybrid PV solutions is likely to be a high priority.

FIGURE 3.15: PRACTICAL PV POWER POTENTIAL VERSUS HUMAN DEVELOPMENT INDEX



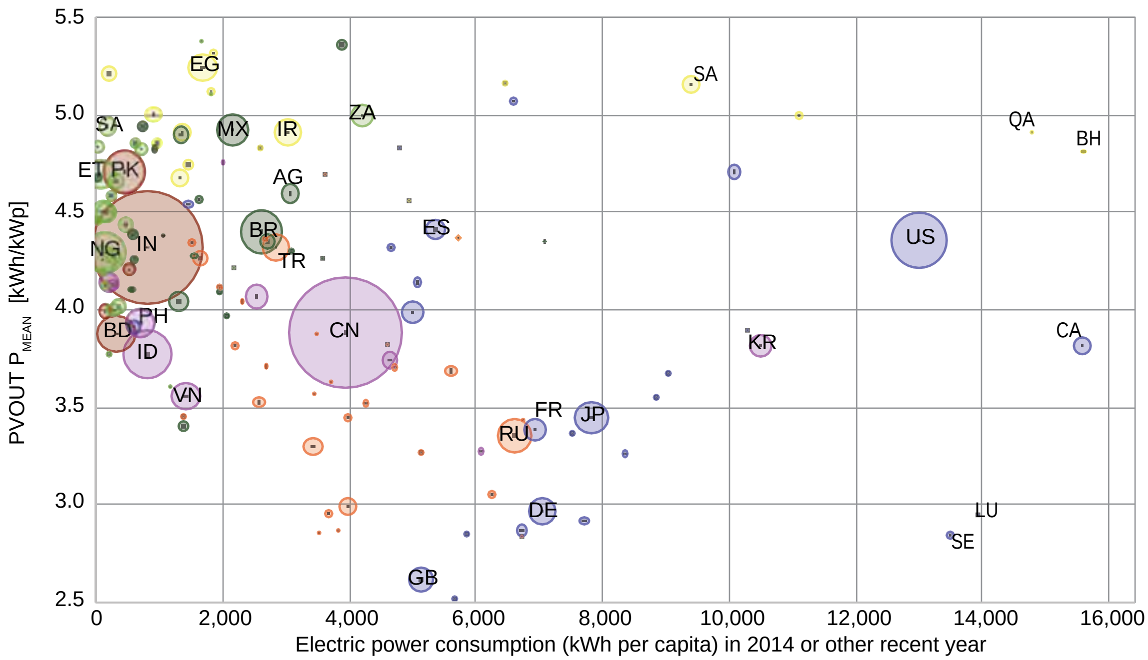
Source: Authors.

FIGURE 3.16: PRACTICAL PV POWER POTENTIAL VERSUS ACCESS TO ELECTRICITY BY THE RURAL POPULATION



Source: Authors.

FIGURE 3.17: PRACTICAL PV POWER POTENTIAL VERSUS ELECTRIC POWER CONSUMPTION



Source: Authors.

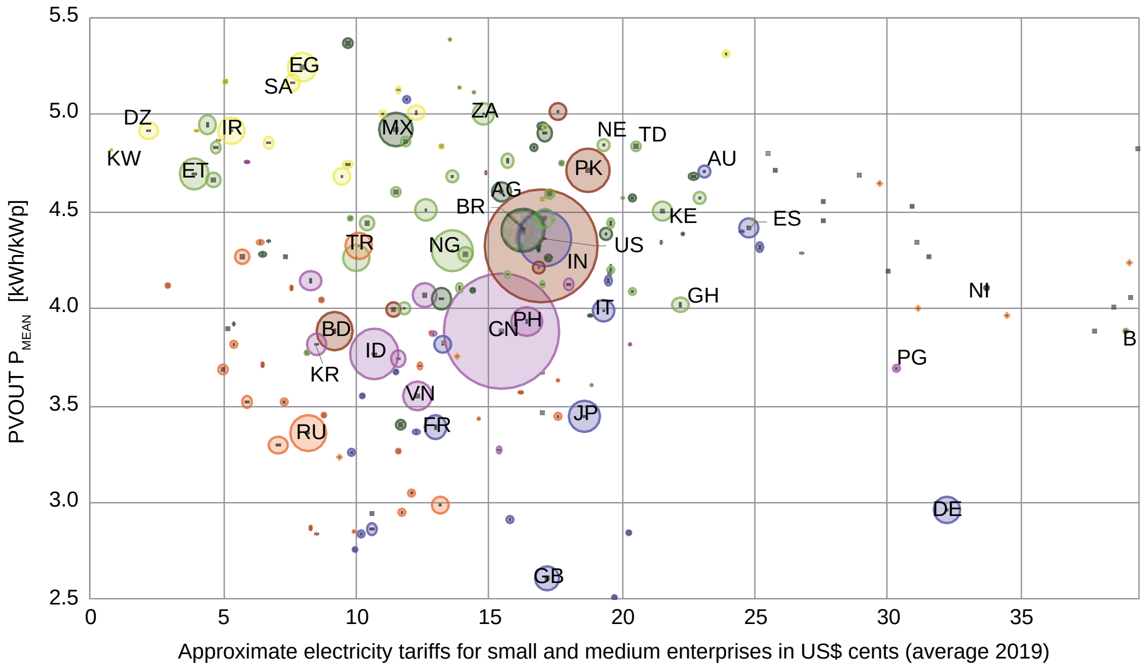
Electricity consumption per capita varies enormously across the world (Figure 3.17). In some economies, the figure exceeds 10,000 kWh per capita per year. On the other hand, around 40% of people in the world live in countries with annual electric power consumption below 1,000 kWh per capita. Many factors determine this inequality, but perhaps the most significant one is access to electricity.

Electricity demand has been rising globally in recent years. It was driven especially by low- to middle-income economies where population growth was often coupled with an increasing power consumption per capita. In the last decade, many countries in the left part of the chart (below 2,000 kWh per capita) have already doubled (Bangladesh, China, Ethiopia, Guatemala, India, Indonesia, Senegal, Tanzania) or tripled (Angola, Myanmar, Vietnam) their consumption per capita. As seen in Figure 3.17, almost all these countries have good or excellent PV power potential. The growing demand combined with high potential presents a great opportunity for PV power development.

High-income economies already have a high level of electric power consumption per capita that has been stagnating compared to developing countries. However, accelerated efforts to decarbonize economies are likely to encourage increased "electrification" in areas such as residential heating, personal mobility, and industrial processes, which could further increase consumption levels. Furthermore, policies promoting renewable energy and the need to replace retiring thermal plants are likely to lead to an increased contribution from solar power to the overall energy mix in these countries.

We have discussed how the cost of solar PV, and some other renewables technologies, has been decreasing in the last decade [17]. Comparing PV potential with end-user electricity tariffs (Figure 3.18) offers another useful insight. Electricity tariff models in some countries may be quite complex and dynamic. For example, large economies tend to have regionally diverse tariff structures, while other economies

FIGURE 3.18: PRACTICAL PV POWER POTENTIAL VERSUS TYPICAL AVERAGE ELECTRICITY TARIFFS FOR SMALL AND MEDIUM ENTERPRISES



Source: Authors.

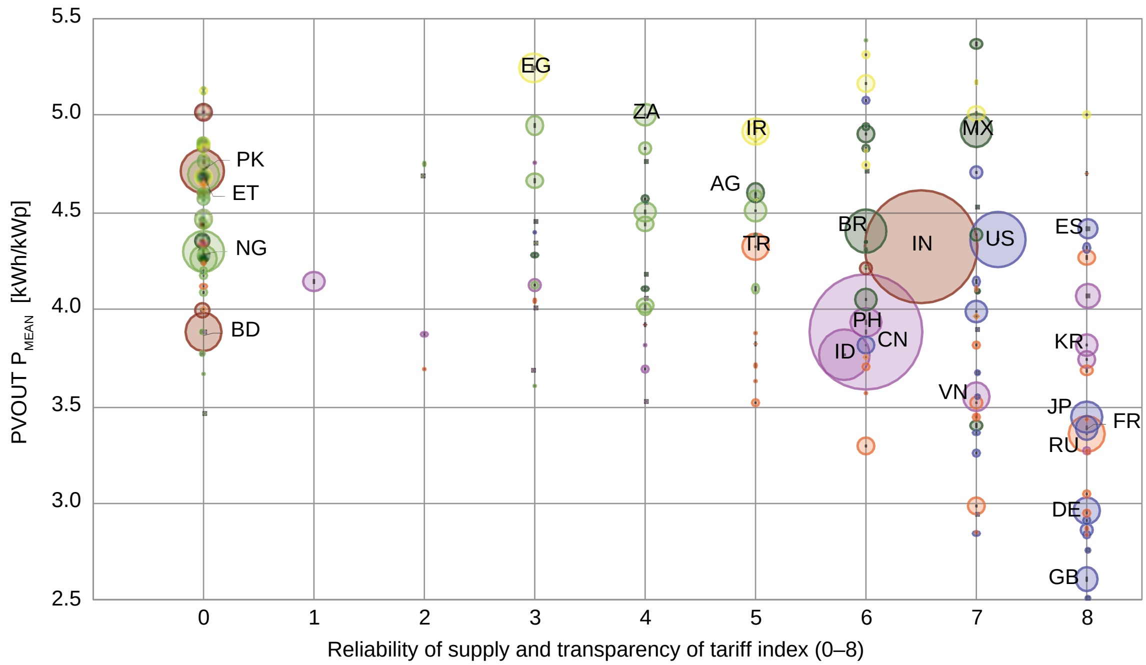
may have a uniform and straightforward structure. For the sake of comparison, we consider the average electricity tariff for small- and medium-sized enterprises [31].

At present, solar PV is cost competitive in most countries. Moreover, PV has become the most economic option in high-potential and high-tariff countries (located in the top-right segment of Figure 3.18), including Australia, Kenya, and Spain. In the case of many remote islands or isolated nations, electricity production is dominated by polluting diesel generators. In such cases, the tariffs can be extremely high due to the expensive import and transport of fuels, making PV and storage technologies an attractive alternative.

Economically, PV is competitive even in countries with lower practical PV potential. This is because of high end-user electricity prices, but also reasonable policies supporting clean energy such as net metering. These and other factors have made investment in PV technologies a rational and secure long-term decision in the private sector. This is the case in a few high-income countries with modest PV power potential, including Denmark, Germany, and Japan.

Persistent low end-user electricity tariffs in some countries with high PV power potential (located in the top-left quadrant of Figure 3.18, such as Kuwait, Qatar, Saudi Arabia) indicate why the investments in the PV sector stagnated until recently. Even so, the dramatic fall of LCOE from solar has opened the market in these regions.

FIGURE 3.19: PRACTICAL PV POWER POTENTIAL VERSUS RELIABILITY OF ELECTRICITY SUPPLY AND TRANSPARENCY OF TARIFFS



Source: Authors.

As shown in Figure 3.19, the electricity supply is not reliable in many countries. Dedicated studies [29] give the lowest score (0 out of 8) to about 50 of 183 analyzed countries/regions. Half of those are located in Sub-Saharan Africa and the other half are spread across the world, involving mainly low-income countries. About 100 countries scored up to 5, including almost all Sub-Saharan countries (except Mauritius and Namibia). The scoring encompasses quantitative data on the duration and frequency of power outages, as well as additional qualitative information.

All analyzed countries with a score of 5.0 and less have good or excellent practical PV power potential (the country average exceeds 3.5 and, in most cases, 4.0 kWh/kWp). In these countries, PV combined with storage technologies could provide an affordable way to boost the availability and reliability of electricity services.

3.4 COUNTRY FACTSHEETS

This study is accompanied by comprehensive country factsheets, which include information about theoretical, practical, and economic potential, and the position of the country in the global context of the abovementioned indicators.

Each factsheet consists of the following numerical and graphical components:

- Photovoltaic power potential map of the country with a unified color legend for all countries worldwide. Minima and maxima color intervals for the country are marked in the legend. The map also shows actual coverage of data (for some countries, the data is missing in high latitudes).

- Country zonation map, showing how the country area is split into practical potential Levels 0, 1, and 2.
- Indicators section presents basic country facts and statistics relevant to PV status in the country.
- PV equivalent area value, which presumes country area proportion to be covered by PV plants producing the equivalent of yearly electricity consumption. It includes both the active area of PV modules and the area between the module rows.
- Summary statistics provide selected results of country-based evaluation of theoretical (GHI) and practical potential on Level 1 (PVOUT). The average is considered as a representative value for each country (the countries are sorted according to this value in the ranking). Other statistics (minima, maxima, percentiles) describe the country solar power potential in better detail.
- Distribution of a photovoltaic power output histogram communicates how much land in the country is available in practical potential Levels 0, 1, and 2, and various PVOUT ranges. It helps to understand what might be the approximate area for PV development available in the best or moderate parts of the country.
- Monthly variation of the photovoltaic power potential details the seasonal PV electricity generation throughout a typical year; it is an important supplement to the seasonality index.
- The bubble charts portray the position of the country in the global context of nine socioeconomic and energy-related indicators (these are analogous to the charts in section 3.3 of this report). The bubble representing the current country is highlighted, the others are in grey. The bubble size is proportional to the population of the country. Axis x represents the given indicator while axis y represents the average practical PV potential at Level 1.

The examples of the country factsheets are presented in Figures 3.20 and 3.21. Altogether, the country factsheets for 210 countries and regions are prepared for download at Global Solar Atlas: https://globalsolaratlas.info/global-pv-potential-study.

FIGURE 3.20: AN EXAMPLE OF COUNTRY FACTSHEET (ETHIOPIA)

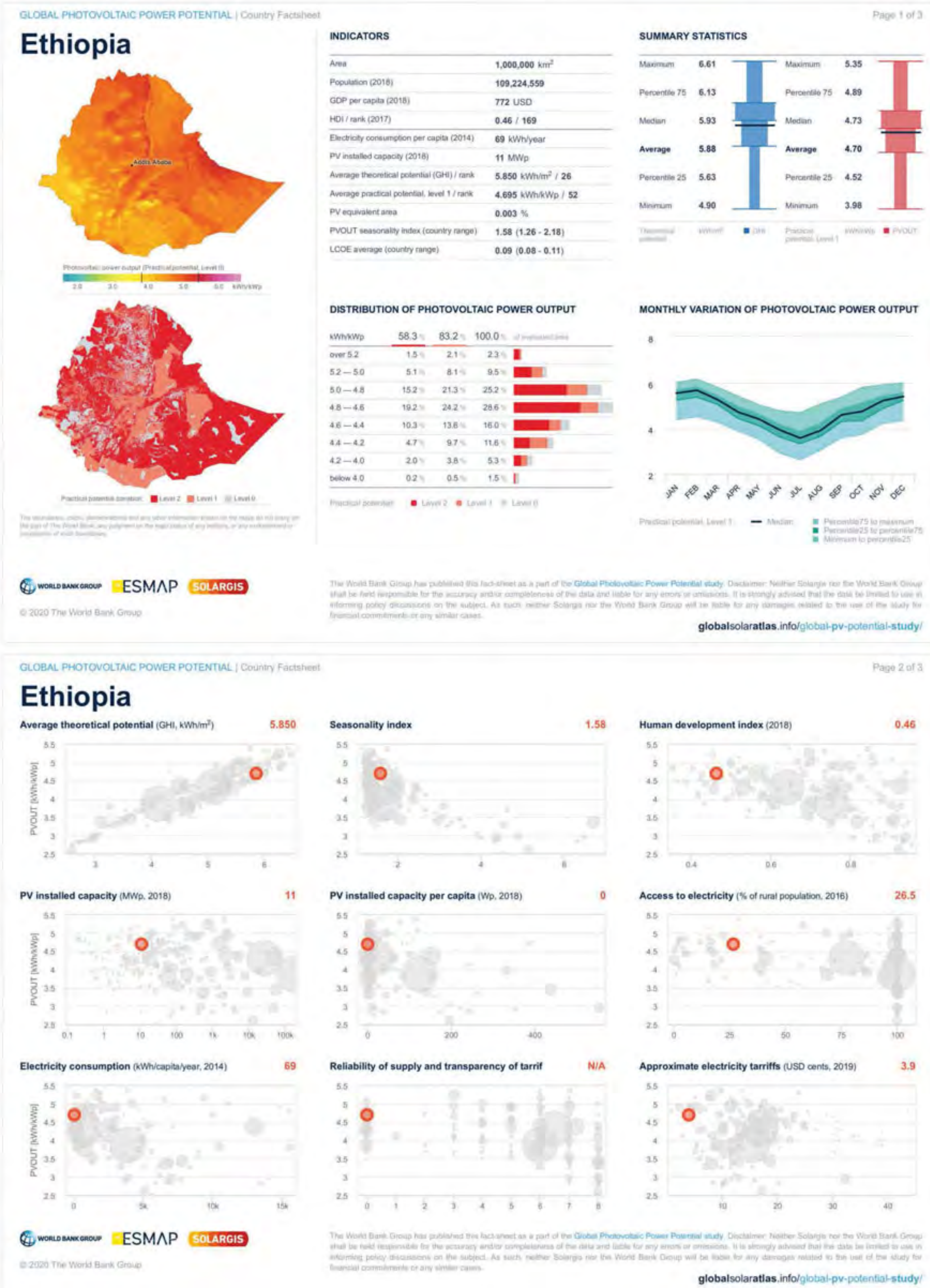
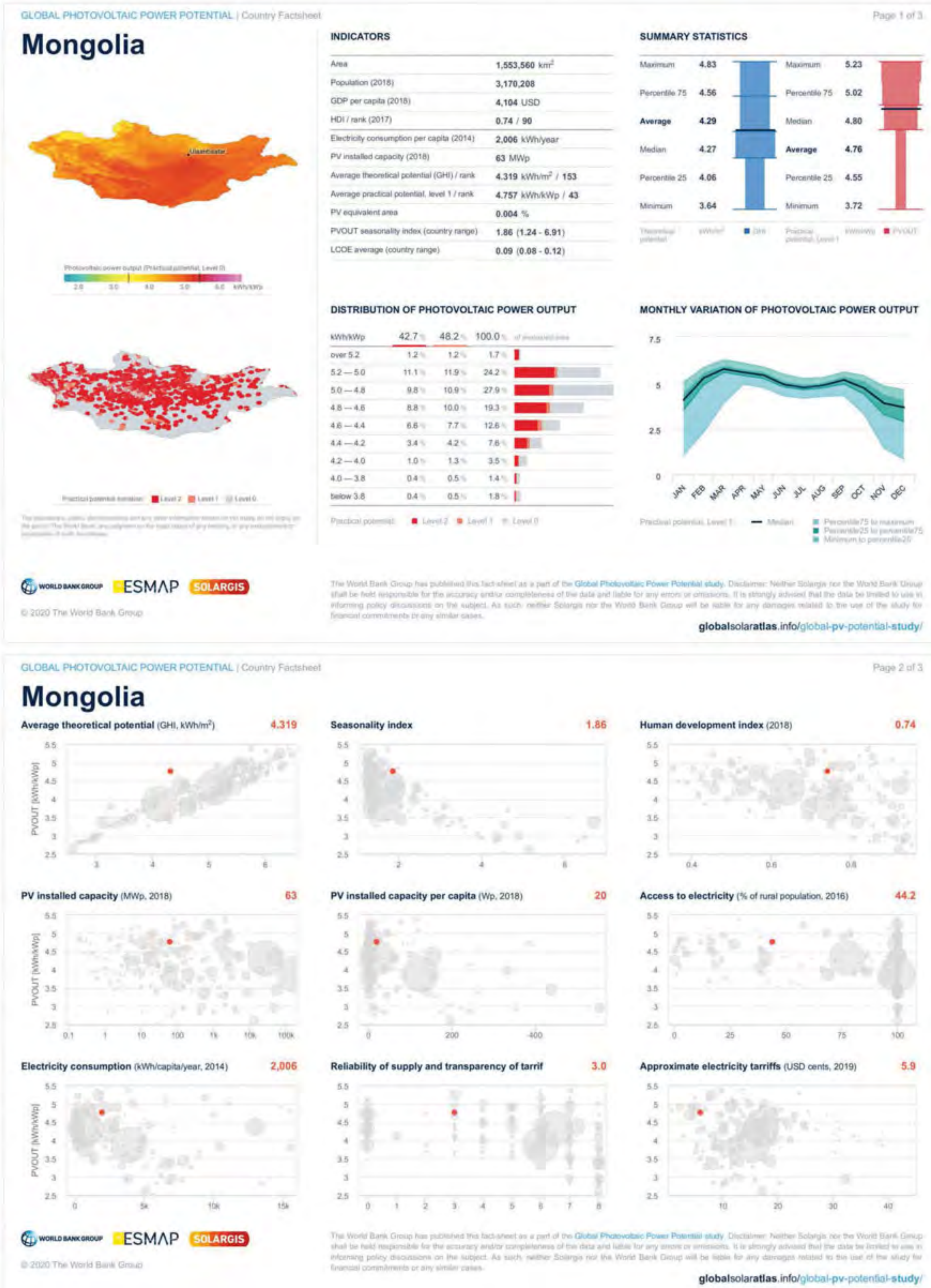


FIGURE 3.21: AN EXAMPLE OF COUNTRY FACTSHEET (MONGOLIA)



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4.2 APPLIED DATA SETS

PV power potential © 2019 Solargis

Global horizontal irradiation © 2019 Solargis

Direct normal irradiation © 2019 Solargis

Air temperature © 2019 ECMWF, NASA, and Solargis

Administrative boundaries © 2019 Cartography Unit, GSDPM, World Bank Group

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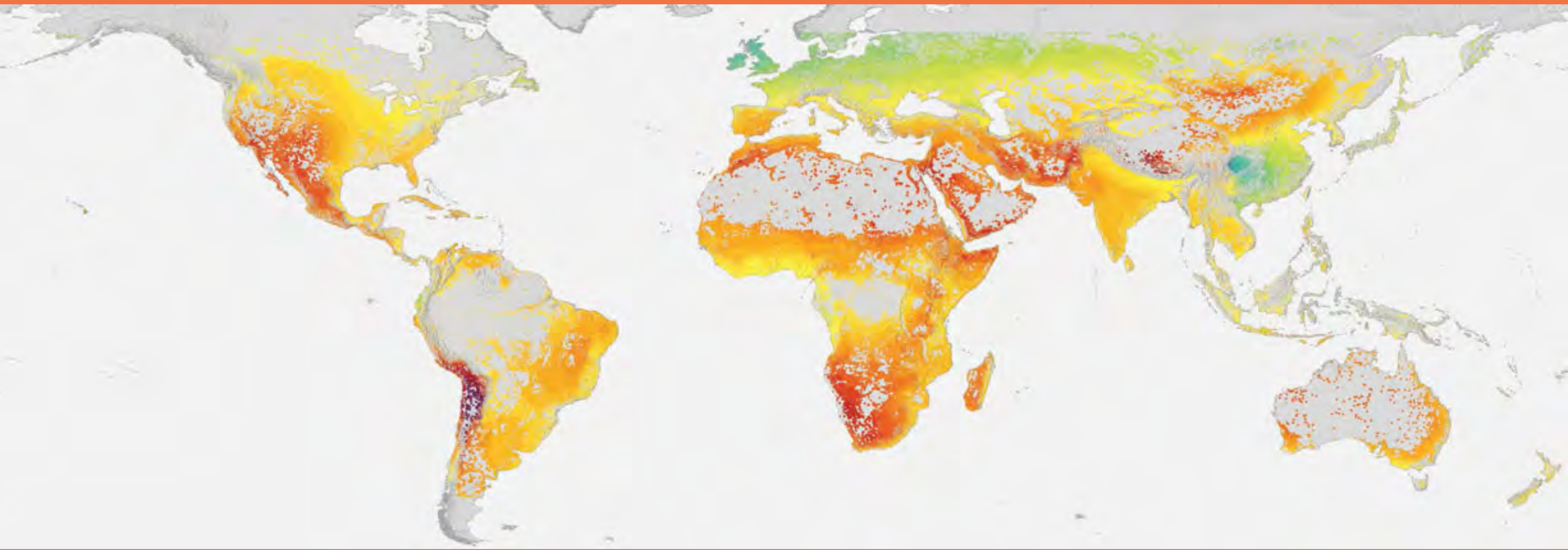

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