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Solar Photovoltaic Electricity Generation: A Lifeline for the European Coal Regions in Transition †

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† The scientific output expressed is based on the current information available to the authors, and does not imply a policy position of the European Commission.

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Abstract: The use of coal for electricity generation is the main emitter of Greenhous Gas Emissions worldwide. According to the International Energy Agency, these emissions have to be reduced by more than 70% by 2040 to stay on track for the 1.5–2 °C scenario suggested by the Paris Agreement. To ensure a socially fair transition towards the phase-out of coal, the European Commission introduced the Coal Regions in Transition initiative in late 2017. The present paper analyses to what extent the use of photovoltaic electricity generation systems can help with this transition in the coal regions of the European Union (EU). A spatially explicit methodology was developed to assess the solar photovoltaic (PV) potential in selected regions where open-cast coal mines are planned to cease operation in the near future. Different types of solar PV systems were considered including ground-mounted systems developed either on mining land or its surroundings. Furthermore, the installation of rooftop solar PV systems on the existing building stock was also analysed. The obtained results show that the available area in those regions is abundant and that solar PV systems could fully substitute the current electricity generation of coal-fired power plants in the analysed regions.

Keywords: solar photovoltaics; PV potential; coal power plant; Paris Agreement

1. Introduction

In 2017, coal provided 26.8% of the worldwide total primary energy supply and was used to generate 9848 TWh of electricity representing 38.4% of the total production [1]. At the same time, the use of coal was responsible for 14.5 Gt of energy-related carbon dioxide (CO_2) emissions (44.3% of the total). To limit the global temperature increase below 2 °C, as envisaged by the Paris Agreement, CO_2 emissions from coal have to be reduced from 10.5 Gt in 2017 to about 1 Gt by 2040, according to the International Energy Agency (IEA).

In addition to the CO_2 emissions mentioned above, coal-fired power plants emit methane (CH_4) and are the largest source of sulphur dioxide (SO_2) from human activities. SO_2 is a major contributor to the production of acid rain and due to its transformation into particulates in the atmosphere, it is responsible for significant health problems like chronic bronchitis, aggravated asthma, and it can cause premature death. The particulate formation that also happens with nitrogen oxides is key to ground-level ozone (O_3) and causes smog and respiratory illnesses. Further pollutants from coal-fired power stations include arsenic (As), cadmium (Cd), carbon monoxide (CO), hydrocarbons, lead (Pb), mercury (Hg), volatile organic compounds (VOCs) and other toxic heavy metals [2].

Besides the air polluting effects of coal-fired power plants, the consequences for the local water supply have s to be considered as well. Coal mining, be it open-pit mining, mountain top mining or deep ground mining can have severe environmental impacts on groundwater levels and also contaminates nearby water resources like rivers, lakes or aquifers [3]. The contamination is caused by highly acidic water pumped from the mines, which contains heavy metals like As, copper (Cu) and Pb.

Another concern is coal ash, which remains after coal is burned. Coal ash contains significant amounts of toxic elements such as, Hg and Pb. The actual concentrations and composition of these toxic elements are determined by the type of coal used. Parts of the ash may be re-used, for example, to produce cement, but most of it is stored in landfills or ponds, which represent a safety risk if not maintained properly. In the latter case, heavy metals contained in the ash can diffuse into waterways nearby and lead to contamination of drinking water. Human exposure to coal ash is related to an increased risk for a number of serious health problems like cancer, heart damage, neurological disorders and reproductive problems [4].

Last but not least, coal-fired power stations need a vast amount of water for their operation. On one hand, water is needed to generate steam to drive the generator turbine, and on the other, water is needed to cool the plant. Three modes of cooling can be distinguished:

- **Once through:** These systems use water from nearby sources like aquifers, lakes, rivers or the ocean to cool the condensers and discharge the warm water back into the original source. The discharge of "heated" water has an impact on local aquatic species and can, for example, decrease fertility or reduce the oxygen content of the water. During heat waves, the extraction of water from such local sources can be limited in order to mitigate the temperature increase and protect the aquatic species.
- **Wet-recirculation or closed-loop:** In general, these systems use cooling towers where the water is exposed to ambient air. As some of the water evaporates before it is sent back to the power plant condenser, such systems take less water but have higher water consumption than plants using once-through cooling systems.
- **Dry-cooling:** In these systems, air is used to cool the steam from the turbine. Such systems can decrease the water consumption by up to 90%; however, this comes at higher costs and lower efficiencies in general, which require more coal and result in an increased environmental impact per unit of electricity produced.

All these factors are increasing the pressure on governments and private investors to end the use of coal for energy purposes. Since 2013, the number of financial institutions divesting from fossil energy companies is increasing. The funds committed to fossil fuel divestment increased to more than USD 6 trillion, according to an article in the Guardian, dated 10 September 2018 [5]. At the United Nations Framework Convention on Climate Change (UNFCCC) Conference of the Parties (COP) 23, the Powering Past Coal Alliance was formally launched, whereby nations and states committed to move from burning coal to cleaner power sources. Their founding declaration states: "To meet the Paris Agreement, analysis shows that coal phase-out is needed no later than by 2030 in the OECD and EU28, and no later than by 2050 in the rest of the world" [6]. Six new members joined the Alliance on the occasion of the COP24 in December 2018 and the Alliance currently includes 80 members, which represent 30 national governments, 22 sub-national governments and 28 businesses or organisations.

Just before the COP24 meeting in Katowice in December 2018, the European Commission published its strategic long-term "Vision for 2050–A Clean Planet for All," which outlines its ambition to realise a climate neutral economy [7]. To realise its goals, the share of renewable energy sources (RES) in EU has to exceed 60% by 2050 and the use of coal has to be drastically reduced.

Coal is still mined in 42 regions across 12 EU countries and represents the most available local fuel in the EU with significant economic activity [8]. Coal-fired power stations still operate in 21 EU Member States (MS) and represent about a quarter of the EU's electricity production. The 248 coal power plants that are operational in the EU (as of February 2019), have a total power capacity of 152.5 GW. Approximately two-thirds of these plants use hard coal (170 plants with a total capacity of 97.1 GW) and the remaining plants use lignite as fuel (78 plants with a total capacity of 55.4 GW) [9].

The EU's annual electricity production from coal and other solid fuels was 692 TWh in 2016 [10], albeit on a decreasing trend. Presently, 14 European Union MS have already joined the Powering Past Coal Alliance, showing their commitment to advance the transition of these regions from coal powered energy generation to clean energy [6]. An economically viable and socially fair transition process towards phasing-out coal energy use is thus needed to honour the "well below 2 °C" target of the Paris Agreement.

The interest in synergies between renewable power and mining activities (or mines' closure) has grown in recent years and a number of solar, wind and battery storage installations have been tested in mining sites. By 2018, almost 2 GW of renewable power was commissioned and announced at mine sites, with the sector's investment in RES being anticipated to double by 2022 [11]. Solar photovoltaic (PV) electricity generation represents 37% of such investments [12] as it is a mature technology with continuously decreasing production costs. Using abandoned open-cast coal mines and their surroundings for the installation of utility-scale solar PV systems is an approach with several advantages. In the case of proximity to a coal power plant, such an approach takes advantage of the grid infrastructure that is already in place. Additional advantages are the existing infrastructure (e.g., access roads, fencing), trained personnel. Using reclaimed mine land for solar energy projects is particularly attractive for the mine's post-closure phase. Mining concession areas are generally larger than the mined area. Moreover, mining operations expand progressively during the operation lifecycle of the mine and portions of the site can thus be used for renewable power production.

The closure and reclamation of a mine operation involves obligations to restore, manage and monitor the closed site. At that point, the mine becomes a liability for the owning company [12] and the deployment of solar PV systems provides an opportunity for an alternative revenue source. Such installations can be combined with remediation works because reclaimed tailing dams provide wide flat areas that do not require clearing and are ideal for ground-mounted PV systems [13]. The utilisation of such degraded land for solar PV system installation can be part of an integrated coal mine reclamation and benefit from relevant funding. This could also address an important bottleneck in the exploitation of solar potential, i.e., land availability. Equally important is that obtaining licenses to operate in the mine's rehabilitated brownfield land may be easier and faster because generally there is no public opposition and no competition with agricultural activities. Abandoned mining sites do not favour traditional commercial or industrial reuse opportunities [14]. Thus, solar PV systems in mining sites are a viable option to help these regions in their transition from coal as a major source of economic activities by substituting the coal-fired electricity production with renewable-based one.

Examples of such a transformation include the 18 MW solar park next to the lignite power plant in Visonta, Hungary [15], the 5 MW Kellingley solar farm in the UK, and the 44 MW solar facility, Nanticoke Solar in Canada (near completion), which has been installed where the largest coal power plant of North America was previously standing [16]. In China, the 50 MW Yangquan solar project was installed on a collapsed coal mine.

A recent scientific modelling study has simulated how a full energy transition in Europe across the power, heat, transport, and desalination sectors could be realised by 2050 [17]. The study describes the necessary technological mix of renewable energy sources, storage options and power to gas options. It also analyses the economic consequences and the necessary political framework, which is mandatory for such a transition. One of the key findings of the study is that photovoltaic electricity generation will play a major role in this process. A common question asked in this context is whether or not there is sufficient land available in the different geographic regions to realise such a scenario and what are the potential land use implications. Therefore, the aim of this paper is to analyse the available technical potential on a Nomenclature of Territorial Units for Statistics (NUTS) level NUTS-2 level in the mentioned Coal Regions in Transition (CRiTs). The NUTS-2 regions are the basic regions for the application of regional policies.

2. Materials and Methods

The present study focuses on EU regions with ongoing coal mining activities that intend to identify, develop and implement projects to implement a viable economic and technological transformation. In late 2017, selected EU regions were designated as Coal Regions in Transition (CRiT) according to the relevant terms of reference [18]. CRiT regions span 12 EU Member States and are defined at a territorial classification of NUTS-2 level (basic regions for the application of regional policies). Economic activities in these regions are closely linked to operational mines and coal-fired power plants. Figure 1 illustrates the CRiT regions with light yellow colour and provides the corresponding NUTS-2 classification codes. It also shows the operational coal-fired plants that are located inside the CRiT or in their vicinity, that is, within a 30 km distance. In total, 111 coal-fired stations operate within the CRiT (83.2 GW) and another 20.5 GW are located within a 30 km distance (Figure 1).

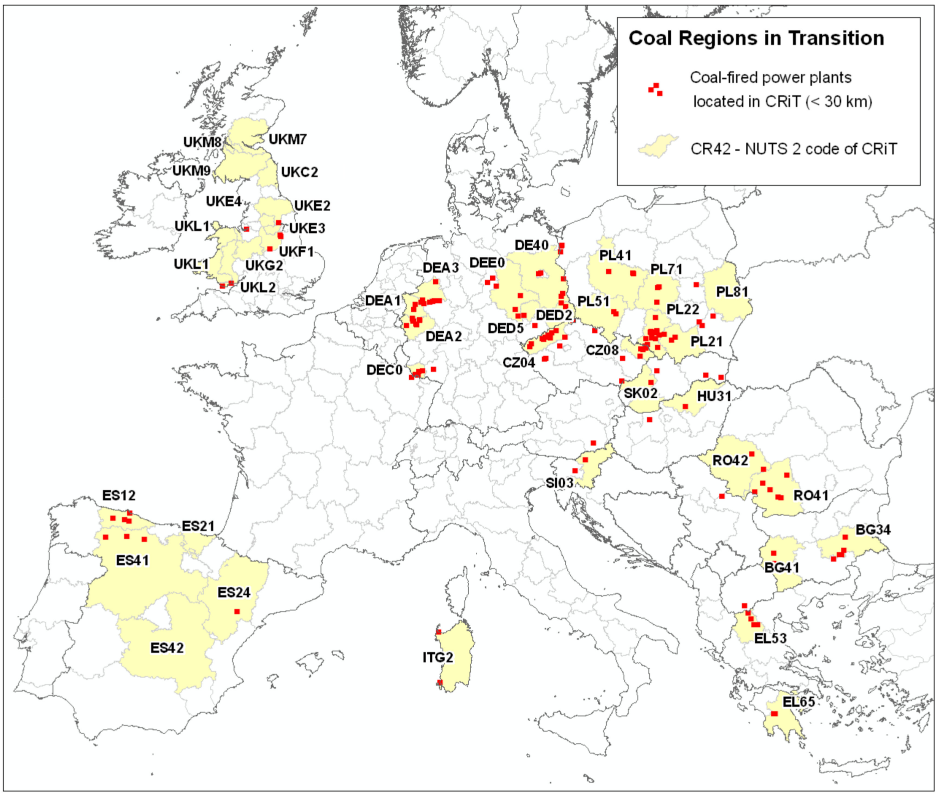

Figure 1. EU Coal Regions in Transition (CRiT) and coal power generation plants. Data source: [15].

A detailed list of the CRiT is provided in Table 1, together with their NUTS-2 classification [19]. The expected yearly sum of electricity generated by a 1 kWp solar PV system in the region is also provided.. These values correspond to the regional average for a representative PV system configuration (see Section 2.4) and can act as a proxy to distinguish regions with particularly advantageous solar resources.

Table 1. EU Coal Regions in Transition, NUTS codes and average annual solar electricity output.

NUTS 2016	Region	Nominal Annual Yield kWh/kWp	NUTS 2016	Region	Nominal Annual Yield kWh/kWp
BG34	Yugoiztochen	1317	PL21	Malopolskie	1010
BG41	Yugozapaden	1274	PL22	Slaskie	1015
CZ04	Severozápad	1008	PL41	Wielkopolskie	1018
CZ08	Moraskoslezko	1015	PL51	Dolnoslaskie	1022
DE40	Brandenburg	1002	PL71	Lodzkie	1020

Table 1. *Cont.*

NUTS 2016	Region	Nominal Annual Yield kWh/kWp	NUTS 2016	Region	Nominal Annual Yield kWh/kWp
DEA1	Düsseldorf	985	PL81	Lubelskie	1028
DEA2	Köln	987	RO41	Sud-Vest Oltenia	1264
DEA3	Münster	970	RO42	Vest	1180
DEC0	Saarland	1040	SI03	Vzhodna Slovnija	1154
DED2	Dresden	1007	SK02	Stredne Slovensko	1147
DED5	Leipzig	1033	UKC2	Northumberland & Tyne & Wear	864
DEE0	Sachsen-Anhalt	1008	UKE2	North Yorkshire	883
EL53	Dytiki Makedonia	1365	UKE3	South Yorkshire	913
EL65	Peloponnisos	1525	UKE4	West Yorkshire	882
ES12	Principado de Asturias	1141	UKF1	Derbyshire and Nottinghamshire	919
ES21	País Vasco	1164	UKG2	Shropshire and Staffordshire	919
ES24	Aragón	1558	UKL1	West Wales & Valleys	909
ES41	Castilla y León	1511	UKL2	East Wales	906
ES42	Castilla-La Mancha	1626	UKM7	Eastern Scotland	806
HU31	Észak-Magyarország	1168	UKM8	S.W. Scotland	793
ITG2	Sardegna	1510	UKM9	North Eastern Scotland	828

The analysis provides an assessment of the technical potential to generate electricity from photovoltaic systems in each of the 42 coal extraction CRiT regions (NUTS-2 level, 2016 definitions) [19]. It assessed the areas that are technically available for ground-mounted and rooftop systems and the corresponding annual electricity production of an idealised PV system. Both the potential installed capacity and the annual energy yield are reported.

2.1. Ground-Mounted Systems on Open-Pit Mines

In the present study, a spatial data layer of 405 open-pit coal mines was developed based on the spatial distribution of mining areas suggested by the CORINE Land Cover data set [20]. This input data was extended by the EC Joint Research Centre's Coal Mine Database (JRC-CMDB), developed in 2017 [8] and combined with manually digitised vector data based on satellite imageries. The final geodata set contains the following attributes of the mining areas, which are additional to the original sources: geographic coordinates of the mining centroids, orthogonal area (m^2) of the open-pit mine, perimeter (m) of the mining sites, location-specific nominal PV yield (kWh/kWp), location-specific yield of the PV system (kWh/m^2), suitable area for PV installation based on morphometric parameters, modelled technical yield (GWh/year), and estimated technical power capacity (GW).

Mapping the suitability of open-pit mines for PV systems was completed by digital terrain analysis using the latest EUDEM25 (ver.1.1.) with a spatial resolution of 25 m [21]. Mining surfaces fulfilling the following pre-set conditions were considered potentially suitable for PV system installation if they had moderate steepness (criterion i) and a favourable azimuth (criterion ii):

i. slope inclination: ≤30 degrees
ii. slopes' azimuth faces to the east (45°–135°), south (135°–225°) or west (225°–315°), where 0° marks north.

The PV yield was determined by the available surface in each class multiplied by the relevant nominal annual yield of PV system shown in the third column of Table 1. Correction factors were applied for east- and west-facing slopes as such installations are expected to produce approximately 20% less electricity compared to south-facing systems installed at the same location. Figure 2 shows the site selection steps in the example of a 22 km^2 mining area in Lower Silesia (Turów coal mine, Poland, Dolnoslaskie, PL51).

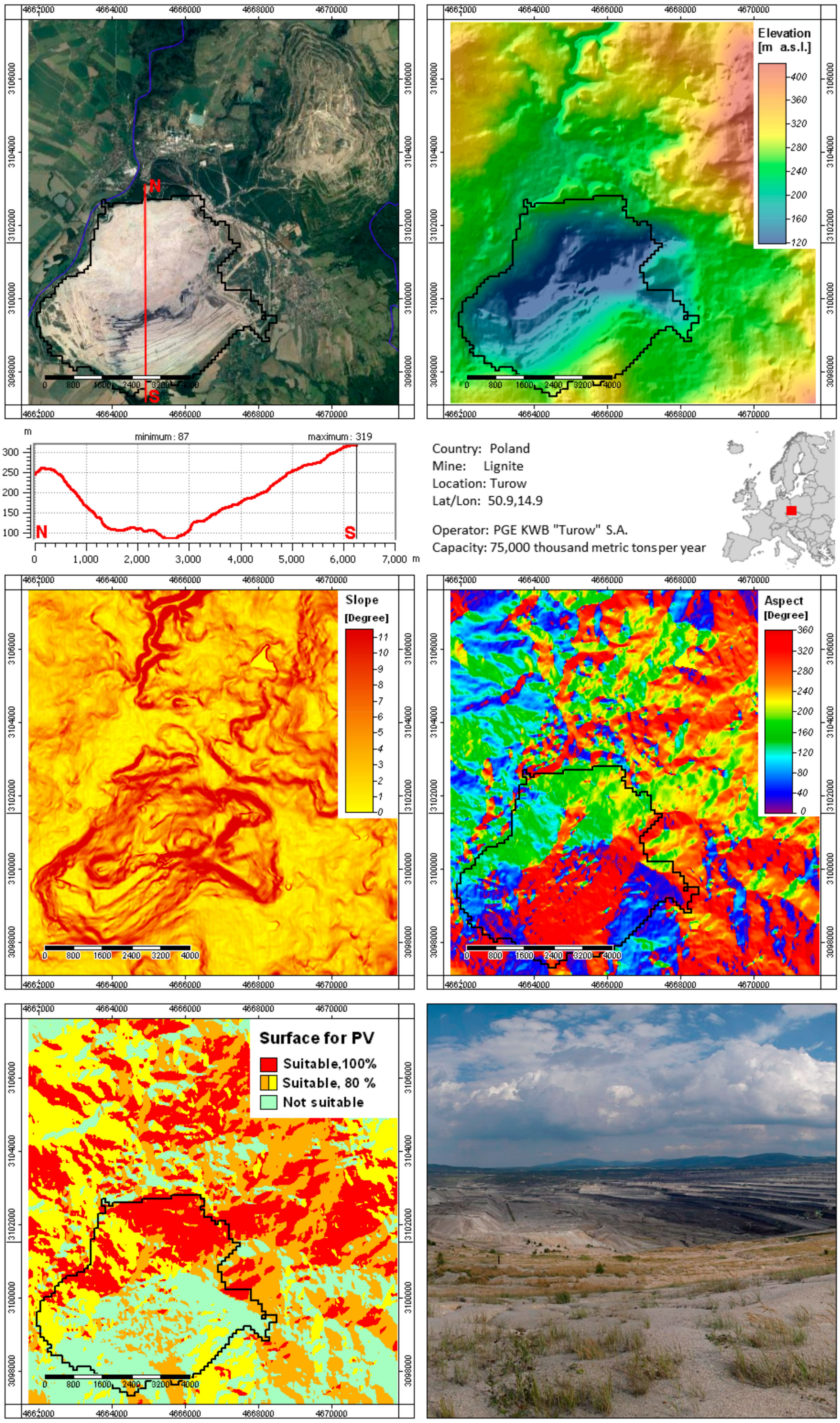

Figure 2. Digital terrain analysis (surface modelling, north-south profile cross-section, digital elevation model, slope steepness and aspect characteristics) and suitability mapping for PV system installation in one of the analysed mines. (aerial photo from Google, 2018, panorama photo seen from the west in 2012, Wikipedia).

2.2. Ground-Mounted Systems on CRiT Surrounding Areas

The potential installation of ground-mounted systems was estimated by assessing suitable areas in the selected regions. The analysis started with the CORINE Land Cover data set [19], which provides data on the type of land cover for the EU and candidate countries at a resolution of 100 m and is divided into four overall classes:

(1) Artificial surfaces (urban areas, buildings, road and rail networks, ports, airports, mineral extraction sites, sports facilities, etc.),
(2) Agricultural areas (arable lands, rice fields, vineyards, pastures, agro-forestry areas, etc.),
(3) Forest and semi-natural areas (scrub and/or herbaceous vegetation, bare rocks, dunes, etc.),
(4) Glaciers, wetlands and water bodies.

Class 1 was excluded since the building rooftop area is calculated separately (see below). Other artificial surfaces or inland water bodies could also be exploited e.g., parking areas, roads, urban waste sites, lakes, reservoirs, but refined location-specific analyses are needed to systematically address these opportunities. Classes 3 and 4 were also excluded as the installation of solar PV systems should not involve deforestation or have a negative impact on natural areas. Moreover, installing PV systems on glaciers, wetlands and water bodies is either not possible or requires special designs (e.g., floating PV systems [22]), a topic that exceeds the scope of the present study.

Accordingly, the analysis only included agricultural areas of CLC Class 2 to host ground-mounted PV systems. Two sub-classes were considered from CLC Class 2: non-irrigated arable lands (CLC 211) and pastures (CLC 231). These were then subject to two further restrictions:

(a) Protected areas according to the Natura 2000 database [23] were excluded (on average this accounts for 6% of arable land and 16% of pastures).
(b) Land forms where slopes are steeper than 20 degrees or north-facing and steeper than 5 degrees were excluded. On average, the constraints related to terrain morphometry exclude 12% of arable lands and 30% of pastures.

To analyse the relevant terrain characteristics (e.g. slope steepness, slope orientation/exposure/aspect, surface roughness), the SRTM (Shuttle Radar Topography Mission) digital elevation model (DEM) with a spatial resolution of approximately 30 m has been processed. The source SRTM dataset is available from the Consortium for Spatial Information [24]. Following the application of the described constraints, only a small fraction of the estimated land area (3%) was considered as suitable for ground-mounted PV systems. The selection of this value was based on the EU average for value set-aside land. The latter refers to arable land that farmers choose not to cultivate and devote to soil and environment conservation uses. The average EU value is thus used here as a proxy for agricultural areas potentially available for non-agricultural purposes. Notably, PV technologies are generally suitable for dual-use approaches that combine electricity and agricultural production [25].

2.3. Rooftop-Mounted Systems

Buildings offer considerable potential for the deployment of PV and allow better geographic correlation of supply and demand. A harmonized database on the EU building stock with the required level of detail is lacking. To overcome this, a multi-layer approach was recently developed by the authors [26] and it was applied in the analysed CRiT to determine the total detectable building footprint area. To do this, the analysis used the land cover dataset and the European Urban Atlas to validate information on EU built-up areas (to a resolution of 10 m × 10 m and 2.5 m × 2.5 m) derived from the European Settlement Map [27,28]. The results were then refined using correction factors derived from comparisons with cadastre data, as well as analysis of building-by-building LIDAR digital elevation models for a limited number of benchmark locations.

The PV energy productivity was calculated for the rooftop locations following the methodology described above for ground-mounted systems. While the assumption of array spacing may be conservative for rooftop installations, it compensates for not addressing other factors such as non-optimal orientation and shading effects.

2.4. Estimation of Potential Solar PV Output

To estimate the PV energy productivity, the instantaneous PV power at a specific location was calculated taking into account the in-plane irradiance, spectral content of the sunlight, and the module temperature, which depends on air temperature, wind speed and irradiance. The latter were obtained by the up-to-date information available in the Photovoltaic Geographical Information System (PVGIS) repository [28] maintained at the authors' laboratory.

For the ground-mounted systems, the PV system mounting configuration was assumed to be free-standing racks facing south at an inclination angle of 20 degrees (40 degrees for locations north of 60° N). The area required was calculated assuming 5.5 m^2 per kWp of PV modules, i.e., 18.2% efficiency. The distance between the module racks was calculated to avoid shadowing of one rack over other modules, especially in winter. Calculation of the PV energy yield was performed using the JRC's PVGIS methodology [29], using hourly solar radiation data for the period 2005–2016. The calculation assumes crystalline silicon modules, with balance-of-system losses of 10%. The anticipated annual energy yield per unit of power (kWp) varies from 793 kWh/kWp in northern regions (see Table 1: South Western Scotland, UK) to 1626 kWh/kWp in southern regions (Castilla-La Mancha, Spain). As these values are spatial aggregations for each region based on past observations, a year-to-year variability of the order of 5% is expected.

3. Results

Table 2 reports the results of the analysis for each region, listing the land area considered available, the power capacity potential (in GW) and the relevant annual electricity yield if the power potential is fully exploited. Results are provided per installation type; the columns on the left side show the estimated solar PV technical potential for ground-mounted utility-scale systems in the CRiT. The analysis shows a technical potential of 580.1 GW for such systems if only a fraction (3%) of the suitable land in CRiT is utilised. A full utilisation of the estimated technical potential would require 7570 km^2 of land and the expected annual electricity production would be 704.8 TWh.

Table 2. Calculated available surface, potential power capacity and annual electricity yield in CRiT per installation type.

NUTS 2016	CRiT Available Land			Suitable Mining Area			Suitable Rooftop Area		
	Area km^2	Power GW	PV Yield Twh/Year	Area km^2	Power GW	PV Yield TWh/Year	Area km^2	Power GW	PV Yield TWh/Year
BG34	198.0	18.2	24.0	88.3	7.2	9.5	23.7	2.2	2.8
BG41	64.4	6.0	7.6	34.2	2.8	3.6	27.3	2.5	3.2
CZ04	85.1	6.0	6.0	75.1	4.7	4.7	17.9	1.2	1.3
CZ08	54.9	4.0	4.0	0.0	0.0	0.0	18.6	1.3	1.4
DE40	328.0	20.6	20.6	94.6	5.7	5.7	72.6	4.6	4.6
DEA1	74.9	5.0	4.9	23.9	1.5	1.5	72.9	4.8	4.7
DEA2	97.3	6.7	6.6	51.2	3.1	3.1	63.6	4.3	4.3
DEA3	146.5	9.5	9.2	2.7	0.2	0.2	46.3	3.0	2.9
DEC0	22.2	1.6	1.7	0.5	0.0	0.0	19.8	1.4	1.5
DED2	102.8	6.9	7.0	32.5	2.0	2.0	35.1	2.4	2.4
DED5	66.5	4.4	4.6	9.7	0.6	0.6	21.0	1.4	1.4
DEE0	375.1	24.3	24.5	24.4	1.5	1.5	62.6	4.1	4.1
EL53	47.6	4.7	6.4	91.8	8.1	11.1	3.8	0.4	0.5
EL65	9.8	1.0	1.5	15.3	1.4	2.1	6.4	0.7	1.0

Table 2. *Cont.*

NUTS 2016	CRiT Available Land			Suitable Mining Area			Suitable Rooftop Area		
	Area km^2	Power GW	PV Yield Twh/Year	Area km^2	Power GW	PV Yield TWh/Year	Area km^2	Power GW	PV Yield TWh/Year
ES12	27.5	2.5	2.8	8.4	0.7	0.8	9.6	0.9	1.0
ES21	27.7	2.5	3.0	0.8	0.1	0.1	16.4	1.4	1.6
ES24	264.1	25.3	39.4	13.2	1.1	1.7	13.7	1.3	2.0
ES41	843.6	79.9	120.7	31.9	2.4	3.6	37.4	3.5	5.3
ES42	653.4	64.7	105.2	8.3	0.7	1.2	28.8	2.9	4.6
HU31	131.3	10.1	11.8	19.3	1.4	1.6	23.8	1.8	2.1
ITG2	133.5	13.1	19.9	1.0	0.1	0.1	32.0	3.1	4.7
PL21	152.9	10.9	11.1	3.9	0.3	0.3	36.0	2.6	2.6
PL22	130.8	9.1	9.3	10.2	0.6	0.7	47.1	3.3	3.4
PL41	489.7	31.2	31.8	51.1	2.9	3.0	42.9	2.7	2.8
PL51	275.1	18.7	19.1	12.0	0.7	0.7	37.6	2.6	2.6
PL71	303.8	19.9	20.3	51.7	3.1	3.1	27.7	1.8	1.9
PL81	407.7	27.3	28.1	0.5	0.0	0.0	30.8	2.1	2.1
RO41	345.4	30.5	38.5	50.7	3.9	4.9	38.9	3.4	4.3
RO42	343.7	29.1	34.4	2.8	0.2	0.2	34.9	2.9	3.5
SI03	34.2	2.8	3.3	0.7	0.1	0.1	16.2	1.3	1.5
SK02	209.8	16.2	18.5	1.1	0.1	0.1	42.8	3.3	3.7
UKC2	80.1	4.4	3.8	6.7	0.3	0.3	17.7	1.0	0.9
UKE2	150.8	8.8	7.7	4.2	0.2	0.2	11.0	0.7	0.6
UKE3	24.1	1.4	1.3	9.7	0.5	0.5	16.8	1.0	0.9
UKE4	25.4	1.5	1.3	7.6	0.4	0.4	24.7	1.5	1.3
UKF1	93.6	5.7	5.3	7.2	0.4	0.4	26.0	1.6	1.5
UKG2	141.2	8.8	8.1	1.6	0.1	0.1	23.8	1.5	1.4
UKL1	181.2	11.7	10.7	13.9	0.8	0.8	31.7	2.1	1.9
UKL2	104.8	6.7	6.1	3.1	0.2	0.2	17.5	1.2	1.1
UKM7	137.0	7.8	6.3	6.9	0.4	0.3	15.3	0.9	0.7
UKM8	15.5	0.9	0.7	1.9	0.1	0.1	15.9	0.9	0.7
UKM9	169.4	9.5	7.8	35.8	1.6	1.3	11.5	0.6	0.5
Total	7570.2	580.1	704.8	910.6	62.2	72.2	1220.3	88.0	97.3

The central part of Table 2 shows the estimated mine area that is technically fit to host ground-mounted solar PV systems of utility scale. In addition to the regions' surrounding area, an additional 910.6 km^2 of degraded land on mine sites could potential host utility scale PVs. A full utilisation of the technical potential would add 62.2 GW of PV that is expected to produce 72.2 TWh per year of operation.

The right side of Table 2 shows the available solar PV technical potential in existing buildings of the analysed CRiT. The existing building stock in urban and rural areas of the analysed regions offers a notable option for distributed rooftop PV systems. The total available net rooftop area that could host PV systems is estimated at 1220.3 km^2. This area could potentially host an additional 88 GW of small-scale rooftop PV with an annual electricity output of more than 97 TWh.

Thus, full utilisation of the identified technical potential in the CRiT (730.3 GW) could contribute a total 874.3 TWh from PV, potentially replacing the electricity output of the current coal power plants operating in the EU, provided that sufficient flexible production and storage capacities are added. The installation of such a scale of PV systems would be revolutionary for the EU and global market as it would be equal to installations six times higher than those existing at the end of 2018 (117 GW) in the EU [30].

The estimated electricity generation of coal-fired power plants located in CRiT, and the modelled technical potential of solar systems are visualised in Figure 3. It is shown that even a partial utilisation of the estimated technical potential could replace (or even exceed) the current coal-based electricity produced in most of the CRiT.

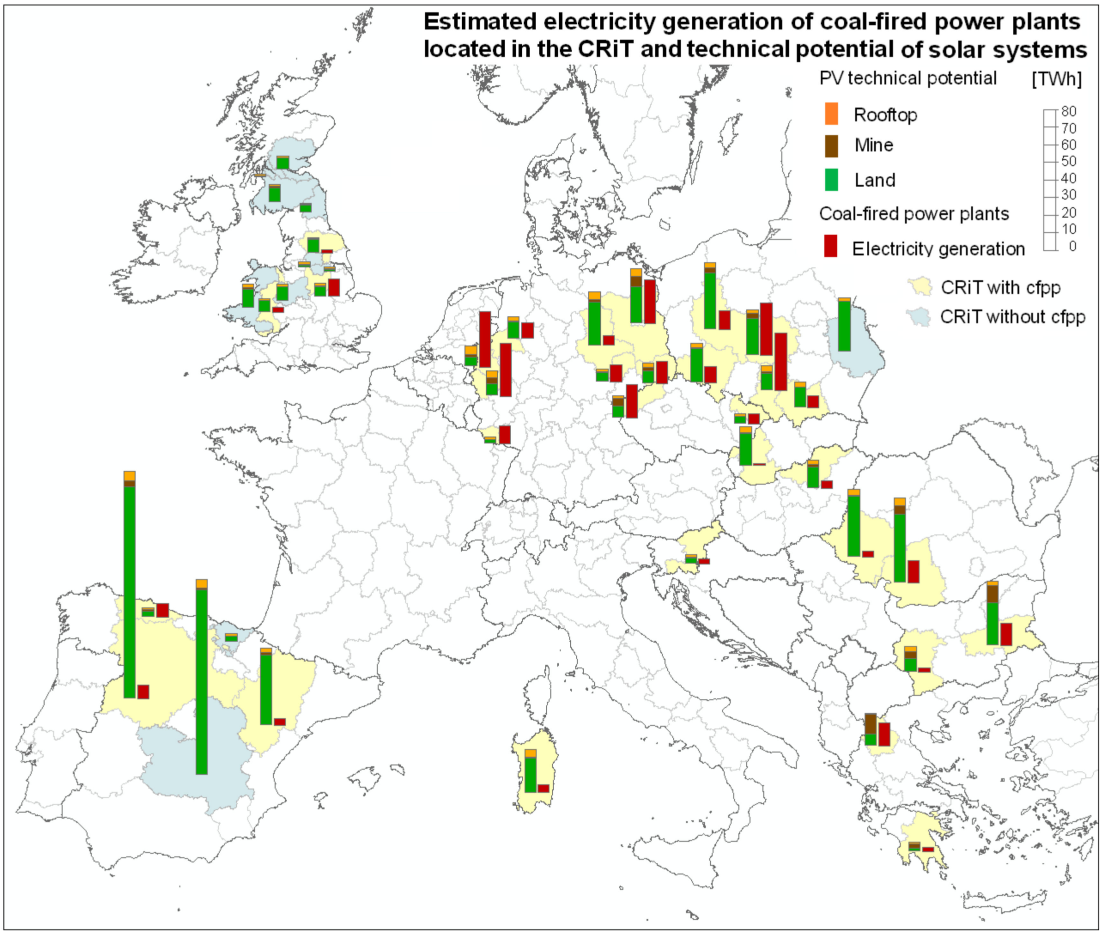

Figure 3. Comparison of estimated electricity generation of coal-fired power plants (CFPP) located in the CRiT and the modelled technical potential of solar systems.

Accordingly, the gradual installation of large-scale solar farms could go hand-by-hand with the planned decommission of existing coal power plants. The estimated output from the full exploitation of the technical potential is 874.3 TWh and this could potentially compensate for the retired thermal units if supported with proportionate storage-flexible units. A recent pan-European analysis implemented by the authors also analysed the economic viability of rooftop PV systems in the EU, including the CRiT [26]. Using retail electricity tariffs as a proxy, the analysis showed that almost half of the available technical potential (47%) would produce electricity at a lower cost than the current retail prices. This figure refers to rooftop systems and is an indication of the economic potential of PV in the selected regions.

4. Discussion

The two types of PV systems described above have different economic rationales: ground-mounted systems can vary between a few kWs to hundreds of MWs. The larger systems, that is, >50 MW are also called utility PV plants. Such plants have the advantage of economies of scale, which reduces capital investment costs (CAPEX) as well as operation and maintenance (O&M) costs. The electricity generated by such plants can either be sold by a direct power purchase agreement (PPA) or traded in electricity wholesale markets.

These large-scale installations are attracting increasing interest from institutional investors and electricity companies alike. The competitiveness of such projects in general depends on the local market conditions including competition amongst energy providers, policy stability, the regulatory framework and access to capital [30,31]. PV PPAs and solar auctions in the 42 CRiT resulted in prices as low as USD 45/MWh (EUR 40/MWh) in Spain up to USD 96/MWh (EUR 86/MWh) in Poland.

Rooftop installations have higher capital costs, which vary considerably in the European Union between USD 1000/kWp (EUR 890/kWp) and 3000/kWp (EUR 2680/kWp). The variation is due to different market conditions, building codes and local regulations. In addition, the value added tax (VAT) can vary between 0% and 27%. However, electricity generated by rooftop PV systems can be consumed either fully or in part on-site. Therefore, the competitiveness of PV power is correlated to the local industrial or residential retail prices. Rooftop PVs also provide a better geographical match between supply and demand. This fact is becoming more relevant due to increasing electrification rates in heating and cooling as well as the transport sectors. Besides the self-consumption of PV generated electricity in commercial buildings and single family homes, self-consumption for tenants in multi-apartment buildings is gaining more and more attention, despite the existing regulatory challenges [32].

The rapid decarbonisation of our power supply is mandatory to stay on track towards a 1.5° scenario outlined in the special report of the Intergovernmental Panel on Climate Change (IPCC) [33]. Due to the rapid and massive increase of variable RES power capacity including multi GW PV systems a new focus of attention now are the issues of integrating these RES power capacities into the different power systems. Scientists have characterised the rapid upscale of renewables as the shift from take-off phase-1 to a break-through phase-2 [34]. Phase-1 mainly relates to creating the framework for emerging technologies to reach market maturity as well as creating the institutional and regulatory frameworks. Solar PV technology has achieved that and reached phase-2, where the focus shifts away from supporting the new technology towards enabling systems. In order to achieve a (very) high share of PV in the power mix, more attention needs to be given to the pace of the transition [35]. This is due to the additional required actions to balance the system as well as the impacts on the operation of conventional thermal stations [36]. It is safe to assume that integration will be less challenging where sufficient flexible and storage capacities are already in place, and the complementarity of technologies is utilised [37]. A recent study by the Energy Watch Group and LTU University, which was presented at COP24 in Katowice in December 2018, simulated how a 100% RES-based energy transition could be realised by 2050 in Europe across the power, heat, transport, and desalination sectors [17].

The phase-out of coal for generating electricity is crucial to achieve this goal and offers additional health benefits at the same time. In the European Union, the number of people employed in this sector is estimated at about 240,000 (180,000 in the coal and lignite mining and 60,000 in coal and lignite power plants) for which socially acceptable job alternatives are needed.

According to the USA Solar Census, about 0.17 full time work equivalents (FTE) per MW and year of installed PV systems were needed for operation and maintenance (O&M) in 2018 [38]. However, this number will decrease over the next decade due to increased automation and digitalisation of O&M activities. The installation of larger PV systems requires about 3.5 FTE per MW. If the retirement of coal and lignite mines as well as the coal fired power stations goes hand in hand with the installation of larger PV systems over the next 15 years, the installation of 580 GW of PV power capacity could provide about 135,000 construction jobs per year. If the O&M FTE were to halve over the next 15 years, this sector could provide about 50,000 jobs by then. Additional jobs could come from the installation and services for rooftop systems. However, quantification is more difficult as these jobs are more dependent on local regulations and building codes.

5. Conclusions

This paper analysed the technical potential to install solar photovoltaic electricity generation system in the 42 EU CRiT. The available area is sufficient to generate the same amount of electricity that all the coal and lignite-fired power stations currently generate in the European Union. The aim was to show the technical potential, not to sketch a roadmap for how to achieve this. Possible pathways to achieving power systems with very PV penetration have been addressed in several studies, notably the 100% renewable plan from the Energy Watch Group and LTU University. However, that study did not elaborate on the area requirements, which are addressed in this paper. It is recognised that the energy transitions may vary substantially across regions and different transition pathways are expected in different regions [35]. Again by analysing at regional level, differences among CRiT areas are highlighted in the present study.

Further analysis also needs to be done in order to analyse the technical requirements of an energy system for a phase out of coal through renewable electricity. Such an analysis then has to take into account the actual load curves, the time variable generation of electricity, required storage capacities and complementary additional renewable electricity generation sources.

Author Contributions: Each of the co-authors (K.B., I.K., N.T., A.J.-W.) contributed to the development of the methodology to estimate the technical potential of solar photovoltaic systems. K.B. performed data mining and exploratory analysis on the required information, designed and applied the geospatial decision-making model to identify the suitable surfaces and PV yield of selected sites. She developed the harmonized GIS database and was responsible for visualization. I.K. collected and processed the input data on power generation and analysed the situation of coal-fired power plants. All authors (K.B., I.K., N.T., A.J.-W.) contributed to writing the text, have read and approved the final manuscript.

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Abbreviations

The following abbreviations are used in this manuscript:

CAPEX	capital investment costs
CFFP	coal-fired power plant
COP	Conference of the Parties
CRiT	Coal Regions in Transition
EU	European Union
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
MS	European Union Member States
OECD	Organisation for Economic Co-operation and Development
O&M	operation and maintenance costs
PPA	power purchase agreement
PV	Photovoltaic
RES	Renewable Energy Sources

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