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A European Assessment of the Solar Energy Cost: Key Factors and Optimal Technology

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Abstract: Solar energy has become one of the most important sources of energy all around the world. Only in the European Union, between 2010 and 2019, solar photovoltaic (PV) electricity generation capacity increased from 1.9 to over 133 GW. Throughout this work, an economic analysis of the production of photovoltaic solar energy utility scale facilities is performed, previously defining some theoretical concepts relating to electricity generation by means of photovoltaic modules, as well as commenting on studies that have inspired the project. In order to carry out this economic analysis, the locations of twenty capital cities within European Union countries are selected, in order to estimate their yearly solar PV energy produced under specific conditions. The Levelized Costs of Energy (LCOE) is calculated with the goal of comparing the profitability of each photovoltaic tracking technology: fixed, one-axis tracking systems (vertical or inclined) and two-axis tracking systems; including LCOE maps country-wise for each technology. A sensitivity analysis is also presented, in order to evaluate the significance and impact of the main variables involved in the analysis. The results show that one-axis tracking systems are the best option in all countries, reducing LCOE by more than 20% when compared to two-axis tracking system. The impact of wages is also significant. In higher latitudes, in most cases, wages also increase, hence the LCOE is higher and consequently less interesting for a potential investor.

Keywords: solar power; levelized costs of energy; economic assessment; european countries; PVGIS; photovoltaic energy; econometric model

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1. Introduction

Solar is an inexhaustible energy source, which can be gathered easily and converted into electric power only with the help of a photovoltaic module. In the current global context of transition from fossil fuels to cleaner energy sources, Europe is demonstrating a strong commitment, providing an opportunity to further improve the environmental performance of clean energy solutions. As a matter of fact, more new capacity was installed for solar than any other power generation technology in the EU in 2019 [1]. This commitment is also illustrated with the approval by the European Commission of a legislative package called "Clean Energy for all Europeans", finally completed in 2019. The focus of this program is threefold; (1) to improve energy efficiency, (2) to reduce greenhouse gas emissions and (3) to develop an electricity market system where the consumer plays a major role, allowing him to act as an active agent of the market [2–4].

In this new legal and technical framework, solar power plays a major role in the process of decarbonization of the energy system. According to Bloomberg NEF, solar energy might represent at least 36% of European total electricity mix by 2050, compared to a current 5% out of total energy generation [5]. Between 2010 and 2019, solar photovoltaic (PV) electricity generation capacity increased from 1.9 to over 133 GW. In order to reduce greenhouse gas (GHG) emission by 55% in 2030, between 325 and 375 GW_{DC} of PV capacity are required to be installed in Europe in the timeframe 2020 to 2030 [6]. For the sake of making this change happen, legal, technical, economic and regulatory local frameworks must be favorable, such that investment in new PV utility scale facilities become profitable. In recent years, technological advances have allowed a decrease in the costs of manufacturing and operating solar photovoltaic (PV) modules. The global capacity weighted-average total installed cost, for solar photovoltaic projects commissioned in 2019, was 995 USD/kW; 79% less when compared to 2010 data. The average module efficiency of crystalline modules has also increased; from 14.7% in 2010 to 19.2% in 2019. However, the distribution of efforts in transitioning to a low-carbon energy economy remains uneven among different countries, with some pursuing net-zero emissions while others continue to lack policy targets [7,8]. Overall, PV system prices have also been reduced, but at a slower pace than individual photovoltaic modules. Total costs for these facilities still vary significantly depending on the size, type of installation and the country where the system is installed, but they are changing fast [9,10].

The need to define a measure of the profitability of PV facilities, under certain conditions, is highly relevant in this context. This topic has been addressed by different authors in the literature. A method of creating a suitability map for solar power generation, in the European Union (EU) geographical area, is proposed by Perpiña-Castillo et al. [11]. One of the main conclusions of this study is the existence of large geographical areas in the EU with sizeable unexploited solar energy potential. However, it does not include the comparison of specific economic parameters between countries or regions, nor is the effect of changing the value of specific variables in the analysis addressed. An economic model to find the optimal PV installation type for seven EU countries is developed by Honrubia-Escribano et al. It is concluded that there are different solutions depending on the final use of the installation. Either way, the tracking system selected for the modules has a considerable impact on the final result of the assessment only in some specific countries [12]. There are specific studies which focus specifically in domestic rooftop PV facilities; it is stated in the literature that almost 25% of current electricity consumption in the EU could be produced by PV rooftops systems alone. However, the results depends on different factors, mainly a combination of investment cost, electricity tariffs, government policies and subsidies and solar insolation [13–15]. Feed-in-tariffs and their relationships to profitability of PV systems are also addressed in the literature, with case studies including Sweden, Germany, UK, Spain and Italy [16–22]. These authors agree on the importance of feed-in-tariff and subsidies and their strong correlation with the final profitability of photovoltaic grid-connected systems. In order to measure how profitable PV systems can be, one of the most important factors is the discount rate, a financial parameter, which allows the estimation of future cash flows. In the literature, it is stated that this parameter must reflect both the capital structure of companies and the market's volatility, also noting that PV projects are long-term investments, highlighting the fact that solar panel manufacturers guarantee at least 80% of initial production over the PV system's 25 year lifetime. A widespread approach used in practice and in the academic literature is the Weighted Average Cost of Capital (WACC) model. The WACC is obtained as the weighted average of the company's various sources of finance [23–25].

In recent years, technological evolution related to PV modules has been achieved in order to optimize the solar radiation received by the plates. One of the main advances relates to tracking systems, which allow the modules to follow the position of the sun, thereby increasing the input of solar radiation and electrical energy output [26]. A fixed PV installation is composed of panels which do not change their position over time, placed at a fixed angle which is, in most cases, the optimum tilt [27]. Fixed tilt arrays are simple in construction, easier to design and maintain, whereas tracking systems (single or two axis) can follow the apparent path of the sun's motion. As stated by some authors of the literature, the electricity generated with two-axis tracking increased by more than 30% when compared to fixed systems after one year of operation [28–31].

The contribution of this paper is to provide an assessment of different utility scale PV system configurations in 20 European locations (representing countries or group of countries), by calculating lifecycle produced energy and lifecycle costs for each of these locations and each of the four sun-tracking system considered (fixed, vertical one-axis, inclined one-axis and two axis tracking system). This allows us to compute the total cost of energy production through the LCOE calculation measure, obtaining the profitability of the optimal system in every country. Every PV configuration has the same size, measured by the concept of installed peak power, with 1 kWp each. As one of the main hypotheses of the study, the cost of materials is assumed to be constant among countries. However, labor costs present a significant degree of heterogeneity. Hence, they are addressed as one of the main variables to be estimated in this research. Afterwards, an econometric analysis for main variables involved in the analysis is performed, with the goal of quantifying their effect on the final result, in order to understand how strong the correlation between specific variables and the final result is.

It must be highlighted the importance of the literature in the current research. In Table 1, the main contributions of individual references cited in this section, with respect to the present study, are outlined and grouped by topic. It is also indicated the geographical region in which each research applies and the year of publishing. As can be appreciated, despite the existence of multiple studies and researches, which focus on different aspects of the economic profitability of solar PV technology, a country-wise comparison of LCOE costs have not been deeply explored in the literature.

The rest of the document is structured as follows: in Section 2, the case study (including different system configurations considered) is introduced, as well as every hypothesis, specific variables and parameters needed for the assessment. Furthermore, the main tool used in this research is described (PVGIS). In Section 3, the results of the assessment are presented, including the optimal PV maps, values of economic parameters for every location and the results of the sensitivity analysis. In Section 4, the econometric model to evaluate the influence of econometric and climatic variables in the final results is presented. Finally, in Section 5, the main conclusions of the study are outlined, including future lines of research.

Table 1. List of references and their main contribution to the present study case (source: own elaboration).

Topic	Reference	Year	Region	Contribution
Optimal utility scale PV	Perpiña-Castillo et al. [11]	2016	European Union	Creation of a suitability map for solar power generation in the EU, using LCOE for comparison. There are still large geographical areas with unexploited solar energy potential.
	Honrubia-Escribano et al. [12]	2018	European Union	Direct replication of PV power plants that were successful in a particular country should be avoided, due to the difficulties in the economic performance assessment.
Rooftop PV	Bódisa et al. [13]	2019	European Union	Almost 25% of current EU electricity consumption could be produced by PV rooftop systems (currently 5% in the EU)
Economic model—PV profitability	Rodrigues et al. [14]	2016	Global	Suitability of PV systems in specific countries depends on a combination of investment cost, electricity tariff, government incentives, and solar radiation.
	Dusonchet, Telaretti [15]	2015	European Union	Optimal results for PV systems in the EU are obtained in those countries in which an electricity compensation scheme is active.
Local Feed-in-tariffs (FiT), regulations and economic parameters for PV profitability	Monarca et al. [16]	2018	Italy	Solar irradiation levels higher than those initially assumed by policymakers in Italy, have caused excessive rents and windfall profits for PV project developers.
	Murphy, McDonnell [17]	2017	Ireland	In order to encourage the future uptake of PV, Solar PV systems in Ireland needs to be included in the Renewable energy Feed-in-Tariff scheme. This would allow the achievement of similar economic payback times, as have been done in other European countries.
	Stridh et al. [18]	2014	Sweden	Electricity costs will increase in the next 30 years. PV installation costs will reduce during the life cycle of the installation. This fact makes PV a suitable option in Sweden.
	Baur, Uriona [19]	2018	Germany	Reneweable energies are needed to enable Germany to fulfill its energy targets. PV is a technology that can relieve the German network if combined with a storage system.
	Lomas et al. [20]	2018	Spain	Policy changes, regarding renewable energy generation, increase regulatory risks, as they create an environment of uncertainty for investment. The consequence of such risk increase is that investors will require a higher return on their capital (equity) which will result in a higher Weighted Average Cost of Capital.
	López-Prol [21]	2018	Germany, Spain	Designing innovation and diffusion policies in the context of high uncertainty and rapid technological change is proven to be hard.
	Castaneda et al. [22]	2020	UK	Battery storage has the potential to transform the current power system, reduce the revenue of utilities, and become an opportunity for new business models.

Table 1. *Cont.*

Topic	Reference	Year	Region	Contribution
Discount rate estimation	Zhang et al. [23]	2012	China	PV projects are long-term investments and solar panel manufacturers guarantee at least 80% of initial production over the PV system's 25 year lifetime.
	Ibbotson, Chen [24]	2003	Global	The discount rate is defined by the market, but must also take into account the cost of capital of companies.
	Guaita-Pradas, Blasco-Ruiz [25]	2020	Spain	Discount rates should reflect both the capital structure of companies and the market's volatility.
Sun-tracking PV systems	Eke, Senturk [29]	2012	Turkey	30.79% more electricity was obtained in a double-axis sun-tracking system when compared to a latitude tilt fixed PV system after one year of operation.
	Axaopoulos, Fylladitakis [30]	2013	Greece, Germany, UK	Energy production of using two-axis tracking systems increased by an average of 31.3% when compared to a fixed-axis system.
	Toribio [31]	2016	Spain	An inclination angle of 15° for one-axis tracking systems provides a better performance in summer, whereas 35° optimizes total annual generation.

2. Materials and Methods

2.1. Estimation of Grid-Connected PV System Energy Production

In order to estimate the electricity produced in each considered European country, a specific open tool called Photovoltaic Geographical Information System (PVGIS) is used [32]. Photovoltaic Geographical Information System (PVGIS) is supported by the European Commission Joint Research Centre (JRC), with the main purpose of researching solar resource assessment, photovoltaic (PV) performance studies and the dissemination of knowledge and data about solar radiation and PV performance. This web application allows users to obtain data about solar radiation regarding PV systems energy production in almost any place all over the world [33]. It offers the chance to simulate different PV configuration systems in order to estimate the net electricity produced by the facility.

All estimations performed in this research are for grid-connected PV systems, since the GHG reduction targets assumed by most countries require them to increase the contribution of RES to the energy mix. Therefore, off-grid systems are not part of this study. The main inputs for PVGIS in this study are: latitude and longitude of every location, type of sun-tracking technology and peak power. More details about the energy production estimation process, by using PVGIS, can be found in Appendix A. In Table 2, a summary of variables used in this text is presented.

Table 2. Glossary of main variables and acronyms presented in this text (source: own elaboration).

Variable	Description
C_t	Yearly total costs of the PV facility for year *t*.
E_t	Yearly energy production of the PV facility for year *t*.
E_i	Yearly in-plane irradiation.
F_t	Yearly fuel costs. The value of this variable is zero in PV facilities.
H	Hardware costs for PV facilities.
I_0	Initial investment for PV facilities.
I	Installation costs for PV facilities.
$LCOE$	Levelized costs of energy.
M_t	Operation and maintenance costs for PV facilities in year *t*.
T_{fixed}	Average installation and soft costs component for the European common market in PV facilities with fixed-axis tracking system.
$T_{vertical-axis}$	Average installation and soft costs component for the European common market in PV facilities with fixed-axis tracking system.
$T_{inclined-axis}$	Average installation and soft costs component for the European common market in PV facilities with inclined-axis tracking system.
$T_{two-axis}$	Average installation and soft costs component for the European common market in PV facilities with two-axis tracking system.
SC	Soft costs of PV facilities.
r	Discount rate.
w	Wage of workers yearly value.
$WACC$	Weighted Average Cost of Capital.
φ	Normalization of the wage of workers around the value of 1.

2.2. Costs of Energy Production

In order to evaluate and compare the cost of energy production between selected case studies and each configuration of PV systems, the concept of Levelized Cost of Energy (LCOE) needs to be introduced. The LCOE is defined by Huld et al. as the price at which electricity must be generated from a specific source to break even over the lifetime of the project. It is an economic assessment of the cost of the energy-generating system including all costs over its lifetime: initial investment, operations and maintenance, cost of fuel and cost of capital [34].

Two methods for estimating the LCOE are described by Chamorro-Gomez, Abadie: the first one considers a yearly timeframe, so it yields a yearly estimate of the LCOE. The second one, instead, keeps the whole lifetime of the facility when computing its LCOE; it thus results in a life-cycle estimate [35].

This said, there are some similarities between both, for instance, their reliance on the net-present-value methodology and the scant use of market prices. Unfortunately, they have some common issues, such as the proper way to account for risk. In the present study, the second method mentioned in the previous paragraph, regarding a multi-period plant-level LCOE approach is selected, since it provides a higher degree of accuracy by assessing the whole life-cycle of the PV facility. In Equation (1), the LCOE is displayed as the sum of the initial investment (I_0) and the costs of the PV facility during its lifecycle, divided by the energy production of the facility during its lifetime.

$$LCOE = \frac{I_0 + PV(lifecycle\ costs)}{PV\ (lifetime\ energy\ production)} \tag{1}$$

Total costs are the sum of "Capex costs" (Capital expenditures) and "Opex costs" (Operational expenditures). Capital expenditure costs include pre-development costs, construction costs and infrastructure cost. Operation expenditure costs are composed of fixed opex, variable opex, insurance, connection costs (both, initial costs for connecting to the grid and a renting cost in those countries in which it is applicable), carbon transport and storage costs, decommissioning fund costs, heat revenues, fuel prices and carbon costs [35]. To sum up, capital expenditures include costs associated to the initial investment (including costs of material and labor costs which are specially significant in the current case study) while operational expenditures include costs such as utilization, maintenance or taxes.

The stream of real future costs and electrical outputs identified in year t are discounted back with a discount rate, to a present value. The present value of costs (C_t) is then divided by the present value of lifetime energy output (E_t), giving Equation (2) as a result. The stream of real future costs and electrical outputs identified are discounted back with discount rate (r) for an investment period of n years [36].

$$LCOE = \frac{\sum_{t=0}^{n} \frac{C_t}{(1+r)^t}}{\sum_{t=0}^{n} \frac{E_t}{(1+r)^t}} \tag{2}$$

Yearly total costs (C_t) are composed of an initial investment (I_0), yearly operation and maintenance costs (M_t) and yearly fuel costs (F_t). The initial investment is a one-off payment, hence it is not discounted and is taken out of the summation. Fuel costs are zero in PV projects.

$$C_t = I_0 + M_t + F_t \tag{3}$$

Equations (2) and (3) can be combined and expressed as in Equation (4).

$$LCOE = \frac{I_0 + \sum_{t=1}^{n} \frac{M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \tag{4}$$

In Equation (4), the total costs are presented in the numerator of the expression, it is composed of the sum of the investment expenditures in year 0 (I_0), plus a summation of the operation and maintenance expenditures (M_t) and fuel expenditures (F_t) over the lifecycle of the facility, from year 1 to n using the index t. The denominator is composed of the summation of energy production of the facility during the lifecycle of the installation (E_t). The discount rate is represented with r. Since in PV facilities fuel expenditures for producing energy are zero, Equation (4) can equivalently be written as shown in Equation (5).

$$LCOE = \frac{I_0 + \sum_{t=1}^{n} \frac{M_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \quad (5)$$

For the sake of simplicity, the effect of PV modules degradation is not being accounted for in this research, since the effects on the final outcome of this work are not significant.

2.3. Case Study

2.3.1. Studied Locations

The main goal of this case study is to compare the profitability of PV facilities for different countries in the European Union. In order to fulfill this objective, twenty locations across the EU have been selected. These locations correspond to the surrounding area of capital cities of each European Union country, except for those countries which are less than 65,000 km^2 in size. In which case, they have been grouped with bordering countries which meet similar conditions, whether these bordering countries are over or under the aforementioned size limit is not required, the key point is that the aggregated total area is greater than it. For instance, the LCOE estimates for Belgium, Luxembourg and Netherlands all correspond to the Brussels location. Latvia, Lithuania and Estonia, Croatia and Slovenia, Denmark and Sweden, Slovakia and Hungary or Italy and Malta are also grouped. Table 3 includes the aforementioned information for every chosen location. Minimun and maximum average temperature values are available in weatherspark.org [37]. The climatic zones (according to the Köppen climate classification) have also been added to the table; this information is available in climate-data.org [38].

Table 3. List of selected locations with coordinates min/max average temperature values and climate zones (source: own elaboration with Photovoltaic Geographical Information System (PVGIS), WeatherSpark.com and climate-data.org [37,38]).

Country/Group of Countries	Location	Latitude	Longitude	Köppen Climate Classification	Min. Avg. Temperature	Max. Avg. Temperature
Austria	Vienna	48.2	16.392	Cfb	−3 °C	26 °C
Belgium, Luxembourg and Netherlands	Brussels	50.846	4.358	Cfb	1 °C	23 °C
Bulgaria	Sofia	42.698	23.321	Cfb	−5 °C	29 °C
Croatia and Slovenia	Zagreb	45.813	15.977	Cfb	−3 °C	28 °C
Cyprus	Nicosia	35.197	33.343	BSh	6 °C	33 °C
Czech Republic	Prague	50.078	14.414	Cfb	−4 °C	24 °C
Finland	Helsinki	60.168	24.946	Dfb	−9 °C	22 °C
France	Paris	48.859	2.346	Cfb	1 °C	26 °C
Germany	Berlin	52.514	13.39	Cfb	−2 °C	25 °C
Greece	Athens	37.98	23.727	Csa	5 °C	32 °C
Hungary and Slovakia	Budapest	47.499	19.049	Cfb	−4 °C	28 °C
Ireland	Dublin	53.349	−6.259	Cfb	3 °C	19 °C
Italy and Malta	Rome	41.896	12.492	Csa	4 °C	29 °C
Latvia, Lithuania and Estonia	Riga	56.949	24.107	Dfb	−6 °C	22 °C
Poland	Warsaw	52.232	21.007	Dfb	−5 °C	24 °C
Portugal	Lisbon	38.708	−9.137	Csa	8 °C	29 °C
Romania	Bucharest	44.432	26.109	Cfa	−5 °C	30 °C
Spain	Madrid	40.402	−3.703	Csa	1 °C	33 °C
Sweden and Denmark	Stockholm	59.331	18.057	Cfb	−6 °C	22 °C
United Kingdom	London	51.506	−0.104	Cfb	2 °C	23 °C

BSh: Hot semi-arid climate. Cfa: Humid subtropical climates. Cfb: Oceanic climate. Csa: Mediterranean hot summer climates. Dfb: Warm-summer humid continental climate.

The effect of average temperatures on the final LCOE results is studied in the econometric model presented in Section 4. Despite PV systems performing better with lower temperatures, greater temperatures often indicate higher values of yearly solar irradiation for a specific location. Regarding climate zones, their possible relationship with the final results is briefly addressed in the conclusions in Section 5.

2.3.2. Investment and Operation Expenditures

In order to obtain the LCOE for every location, as shown in Equation (5), it is necessary to estimate the initial investment (I_0) and the operation and maintenance costs (M_t). It must be highlighted that the investment costs are not equal for each country and, according to the study performed by the International Renewable Energy Agency (IRENA), the investment costs (I_0) can be divided into three main categories: Installation (I), Soft Costs (SC) and Hardware costs (H) [7]. Installation costs are the expenditures related to the setup of the PV system, including mechanical and electrical installation. Soft costs include not only the expenditures of all relevant permits, but also all overhead costs such as marketing, sales and administrative costs associated with the system [39]. Hardware costs comprise every piece of material needed to build the system: module, inverter, racking and electrical wiring. In order to estimate future cash flows, the lifetime of the PV facility is considered as 25 years.

IRENA, 2020 proposes a detailed breakdown estimation for different countries around the world regarding system costs (Installation, Soft costs and Hardware) [7]. Given the fact that the present study is focused on European countries, costs for Germany in the aforementioned reference are selected as a benchmark. Since every country in this work belongs to the European Union, system costs for every location are assumed to be equal to the benchmark, accepting the hypothesis that, in the European Union, there exists a Common Market. From the benchmark data selected for PV systems costs estimations, it is concluded that hardware costs represent two thirds (66%) of the total costs on average, with the remaining one third (33%) shared between installation and soft costs. As described in Section 1, four different tracking systems for PV modules are considered in this work: fixed, one-axis tracking (divided between inclined-axis and vertical-axis) and two-axis tracking. With more complex and advanced tracking systems, a better energy performance can be achieved, but at a higher initial cost and more expensive yearly maintenance. Given the fact that the most frequent configuration for PV installations is based on one-axis tracking systems [40], it is assumed that previously defined benchmark costs correspond to this tracking technology, since this information is not specified by IRENA, 2020 [7]. Fixed-axis and two-axis tracking systems costs are extrapolated by using tracking data outlined by IRENA, 2012, assuming that costs grow linearly between tracking technologies [41]. These assumptions are also supported by the data presented in a study performed by the National Renewable Energy Laboratory (NREL), a national laboratory of the U.S. Department of Energy. In this technical report, a disclosure of costs for utility-scale PV facilities is performed, with hardware costs representing 65% of the overall value of costs [42].

Regarding operation and maintenance (O&M) costs, in this research they have been defined according to the information presented by Drury et al., in which for fixed angle PV systems, they represent around 1% of total PV costs per year, with 1.28% and 1.5% out of total installation expenses for one-axis and two-axis tracking systems, respectively [43].

According to the hypothesis described in previous paragraphs, hardware and maintenance costs are shown in Table 4.

Table 4. Hardware and yearly maintenance costs for every photovalic (PV) tracking system considered (source: own elaboration with hypothesis based on data from [7,41,43]).

PV Technology	Hardware Costs (H) [EUR]	O&M Costs (M_t) [EUR/yr]
Fixed plate	460	$0.01 \cdot I_0$
Vertical-axis	533	$0.0128 \cdot I_0$
Inclined-axis	533	$0.0128 \cdot I_0$
Two-axis	666	$0.015 \cdot I_0$

Note: Original estimations made in US dollars. Converted to Euro with exchange rate: 0.89 EUR/USD.

Total investment costs can be expressed as shown in Equation (6). I_0 represents the Initial Investment and is the sum of hardware costs (H), soft costs (SC) and installation costs (I). Soft (SC) and installation costs (I) can be combined and defined as dependent on the wage (w) of workers, by creating a new combined parameter: $T\ \varphi$ (T is a scalar parameter which results from computing a vector of four components with the same value: $\frac{1}{2}H$, for each PV configuration. This results from the hypothesis detailed in Section 2.3.2. which states that 66% of total costs correspond to hardware costs on average for countries in the European Union. The remaining 33% of costs are computed as a function of labor costs. $T = \frac{1/3}{2/3} \cdot H$). T is the average installation and soft costs component for the European common market. φ is a dimensionless set of values which consists of the normalization of the wage of workers around the value of 1, corresponding this value to the average of the yearly wage for every country accounted for, as described in Equation (7). In this equation, i represents the country index. φ_i is the normalized wage of country i and $\overline{w}$ is the average wage for all countries considered. Since the sum of Soft costs and Installation costs can be expressed as dependent of the costs of Hardware, in this economic model, the only source of variation of total installation expenses between countries, which belongs to the European common market, is the labor costs term. This term increases or decreases the constant average value of Soft and installation for the European region, depending on the country. Wage information for considered European countries is available at datosmacro.expansion.com [44]

$$I_0 = H + SC + I = H + T \cdot \varphi = H + \left(\frac{1}{2} \cdot H \cdot \varphi\right) \tag{6}$$

$$\varphi_i = \frac{w_i}{\overline{w}} \tag{7}$$

where i = 1, 2, 3 . . . , 20.

Wage values, φ parameter and $T \cdot \varphi$ can be consulted in Table 5. $T \cdot \varphi$ is computed for each PV technology considered in the study.

Table 5. Wages, ϕ and $T \cdot \varphi$ parameters for each country/group of countries (source: own elaboration with wages data from expansion [44]).

Country/Group of Countries	w [EUR/yr]	φ	$T_{fixed} \cdot \varphi$ [EUR]	$T_{vertical\text{-}axis} \cdot \varphi$ [EUR]	$T_{inclined\text{-}axis} \cdot \varphi$ [EUR]	$T_{two\text{-}axis} \cdot \varphi$ [EUR]
Bulgaria	7105	0.25	57.54	66.63	66.63	83.28
Romania	9312	0.33	75.95	87.95	87.95	109.93
Latvia, Lithuania and Estonia	11,881	0.42	96.67	111.93	111.93	139.91
Poland	12,716	0.45	103.57	119.93	119.93	149.91
Croatia and Slovenia	12,776	0.45	103.57	119.93	119.93	149.91
Hungary and Slovakia	12,978	0.46	105.87	122.59	122.59	153.24
Czech Republic	14,945	0.53	121.98	141.25	141.25	176.56
Portugal	18,343	0.65	149.60	173.23	173.23	216.53
Greece	21,214	0.75	172.62	199.88	199.88	249.84
Cyprus	23,052	0.81	186.43	215.87	215.87	269.83
Spain	26,923	0.95	218.65	253.18	253.18	316.47
Italy and Malta	31,292	1.1	253.18	293.15	293.15	366.44
France	39,436	1.39	319.92	370.44	370.44	463.04
Finland	43,984	1.55	356.75	413.08	413.08	516.34
Sweden and Denmark	44,212	1.56	359.05	415.74	415.74	519.68
United Kingdom	44,453	1.57	361.35	418.41	418.41	523.01
Ireland	46,774	1.65	379.76	439.73	439.73	549.66
Austria	47,120	1.66	382.07	442.39	442.39	552.99
Belgium, Luxembourg and Netherlands	48,455	1.71	393.57	455.72	455.72	569.64
Germany	50,546	1.78	409.68	474.37	474.37	592.96
Average (w)	**28,375.85**	**1**	**-**	**-**	**-**	**-**

3. Results

In this section, the process of estimating the LCOE for each given country in the study is outlined. Prior to this last step, total costs and energy produced by the solar PV facility need to be obtained. As is described in previous sections, the estimations are performed for 20 countries/group of countries and 4 different tracking systems, allowing a comparison between 80 specific cases.

3.1. Energy Production

As is outlined in Section 2.1, so as to obtain yearly energy produced by a PV facility, PVGIS is used in this work. For every specific location, a set of parameters relating to the PV facility needs to be introduced. One of the main variables of the facility is size. Size can be measured by the concept of installed peak power. This concept is defined by the European Commission Joint Research Centre as: "the power that the manufacturer declares that the PV array can produce under standard test conditions, which are a constant 1000 W of solar irradiation per square meter in the plane of the array, at an array temperature of 25 °C" [32]. Since the main goal of this study is a cost comparison between countries, a standard value of 1 kWp (kilowatt-peak) is considered for every case. Regarding the efficiency of the system, a constant value of system loss of 14% has been selected for the present research, since this is the default value proposed by the PVGIS tool. It is also taken into consideration the hypothesis of same installation conditions and materials for every country; hence, this parameter remains constant for all cases. In Table 6 a summary of the specific values to simulate the PV installation is displayed. A more detailed definition of these variables is found in Appendix A.

Table 6. Main parameters of PV facilities studied (source: own elaboration).

Variable Name	Value
Solar radiation database	PVGIS-SARAH
PV technology	Crystalline silicon
Installed peak power	1 kWp
System loss	14%
Slope and azimuth	Optimize when possible (according to the tracking system)

With this information, PVGIS is able to estimate the yearly energy production of a PV installation for each location. In Table 7, the output parameters for Vienna (and every tracking system considered) is displayed. The most important variable for this study is the yearly PV energy production [kWh], which can be defined as the net electricity produced by the installation after all losses are accounted for.

Table 7. Output parameters for Vienna (Austria). Fixed-angle and tracking systems (source: own elaboration with PVGIS data).

Output Parameter	Fixed Axis	Vertical Axis	Inclined Axis	Two-Axis
Slope angle [°]	38 (opt)	55 (opt)	40 (opt)	-
Azimuth angle [°]	0 (opt)	-	-	-
Yearly PV energy production (E_t) [kWh]	1141.26	1467.03	1467.08	1503.23
Yearly in-plane irradiation (E_i) [kWh/m^2]	1430.99	1820.38	1821.05	1866.99
Year to year variability [kWh]	57.15	76.8	76.2	79.0

A complete list of yearly energy production values for every site and tracking technology is found in Table 8. Significant differences can be observed in this parameter among different regions. Countries like Finland, Latvia and Ireland, with colder climates and a lower solar insolation during the year, have less amount of energy production than Spain, Greece or Portugal (countries with higher solar radiation during the year). As can be observed, with more complex sun-tracking systems, the solar energy collected by the PV modules is also higher.

Table 8. Overview table of yearly energy produced and discount rate per country and tracking system (source: own elaboration with data from PVGIS tool and [45]).

Country/Group of Countries	E_t Fixed Axis [kWh/Year]	E_t Vertical Axis [kWh/Year]	E_t Inclined Axis [kWh/Year]	E_t Two-Axis [kWh/Year]	Discount Rate [%]
Cyprus	1673.98	2201.72	2211.41	2278.81	7.07
Spain	1638.01	2197.49	2203.96	2271.69	6.34
Greece	1620.34	2126.42	2133.4	2195.32	7.07
Portugal	1573.95	2095.18	2105.46	2168.06	6.1
Italy and Malta	1510.4	1993.58	1996.05	2054.64	6.69
Romania	1263.14	1609.72	1613.04	1650.41	6.63
Hungary and Slovakia	1220.09	1572.05	1571.77	1611.42	5.85
Bulgaria	1220.04	1544.37	1547.55	1588.75	6.63
Croatia and Slovenia	1191.15	1531.36	1533.08	1570.78	6.53
Austria	1141.26	1467.03	1467.08	1503.23	5.66
France	1115.79	1431.95	1429.89	1468.82	5.96
Czech Republic	1051.66	1343.23	1341.32	1373.47	6.2
Germany	1025.12	1323.49	1320.52	1353.51	5.16
Poland	1024.06	1321.91	1320.23	1351.1	5.92
Belgium, Luxembourg and Netherlands	1008.73	1292.85	1291.05	1324.88	5.56
United Kingdom	999.58	1278.75	1274.09	1310.93	5.67
Sweden and Denmark	954.96	1282.9	1275.47	1308.67	5.41
Ireland	947.39	1206.16	1199.88	1236.94	5.43
Latvia, Lithuania and Estonia	943.39	1237.5	1232.82	1262.06	5.89
Finland	917.65	1221.44	1215.31	1242.82	5.4

3.2. Discount Rate

The discount rate plays a major role when estimating LCOE, since it provides a measure of the profitability for the investment. In order to enrich the analysis, different discount rates for investment in a PV project are calculated for each country. Estimating this index is complex and may vary across different sectors and countries, since it is dependent on the cost of capital, investment risks, taxes, etc. In this text, the methodology proposed by Núñez et al. is used. This methodology is based on the WACC method with two main two hypotheses: (1) there exists a unity of capital goods, technology and capital markets in the European Union and (2) there are country-specific characteristics in terms of taxation and business risks [45]. A detailed description of the method by which the discount rate has been estimated on the basis of the WACC has been included in Appendix B. In Table 8, a summary of estimated discount rates per country is displayed.

3.3. Total Costs Estimation

According to the methods described in Section 2.3.2, total costs of a standard PV facility are estimated for every country and tracking technology. In Table 9, the estimations for Vienna (Austria) are displayed. The same process is applied across every location. In Appendix C, a full summary of total costs is displayed for every country/group of countries considered in this study.

Table 9. Cost Summary of PV facilities for Vienna (Austria) (source: own elaboration).

Country	PV Tracking Technology	Investment Costs			Maintenance Costs
		H [EUR]	$SC + I$ [EUR]	I_0 [EUR]	M_t [EUR/yr]
Austria	Fixed	460.32	382.07	842.39	8.42
	1-axis (V & I)	533	442.39	975.39	12.48
	2-axis	666.25	552.99	1219.24	18.29

3.4. LCOE Results

With the information regarding yearly energy produced by the PV facility, costs, wages and discount rates, the LCOE value for every location is estimated by using Equation (5).

The results are shown in Table 10. For each location, the optimal PV tracking configuration regarding costs is highlighted in green, while the worst option is marked in red. It can be observed that, for the given combination of investment and maintenance costs, wages, energy produced and specific discount rates, one-axis tracking systems (either inclined or vertical) are the best option for every location considered. This tracking system provides a good balance between efficiency in harvesting solar energy and costs. When comparing Figures 1 and 2, it is clearly visible how vertical-axis tracking is in all cases a cheaper tracking technology LCOE-wise than fixed-axis, despite higher energy production coming at a higher initial investment and O&M costs. On the other hand, two-axis tracking systems' higher efficiency does not outweigh the high costs of purchasing and maintaining these facilities, being always the worst option when choosing a tracking system for the PV facility, as displayed in Figure 3.

Table 10. Levelized Cost of Energy (LCOE) results per location and tracking technology (source: own elaboration).

Country/Group of Countries	Fixed [EUR/MWh]	Vertical Axis [EUR/MWh]	Inclined Axis [EUR/MWh]	Two-Axis [EUR/MWh]
Portugal	36.2337	32.50922	32.3505 (*b*)	40.21194 (*w*)
Spain	39.5217	35.16306	35.05983 (*b*)	43.51782 (*w*)
Cyprus	39.04112	35.36865	35.21367 (*b*)	43.66297 (*w*)
Greece	39.47233	35.83917	35.72191 (*b*)	44.35575 (*w*)
Romania	41.4339	38.78028	38.70046 (*b*)	48.36632 (*w*)
Bulgaria	41.42474	39.03341	38.9532 (*b*)	48.51834 (*w*)
Hungary and Slovakia	42.50919	39.42892 (*b*)	39.43595	49.25845 (*w*)
Italy and Malta	46.32328	41.85519	41.8034 (*b*)	51.92476 (*w*)
Croatia and Slovenia	45.8143	42.51618	42.46848 (*b*)	53.01171 (*w*)
Poland	50.73258	46.96097 (*b*)	47.02073	58.83019 (*w*)
Czech Republic	52.19678	48.7958 (*b*)	48.86529	61.07026 (*w*)
Latvia, Lithuania and Estonia	54.26215	49.43151 (*b*)	49.61916	62.0645 (*w*)
France	64.63869	60.17671 (*b*)	60.2634	75.11086 (*w*)
Austria	66.55716	61.91094	61.90883	77.40213 (*w*)
Sweden and Denmark	75.76658	67.48314 (*b*)	67.87625	84.79127 (*w*)
Germany	73.37522	68.05128 (*b*)	68.20434	85.33294 (*w*)
United Kingdom	74.18403	69.33581 (*b*)	69.5894	86.6417 (*w*)
Finland	78.55951	70.62216 (*b*)	70.97838	88.96253 (*w*)
Belgium, Luxembourg and Netherlands	75.69628	70.63932 (*b*)	70.7378	88.3238 (*w*)
Ireland	78.43453	73.71098 (*b*)	74.09677	92.12207 (*w*)

(*b*): Best PV configuration cost-wise for each country/group of countries. (*w*): Worst PV configuration cost-wise for each country/group of countries.

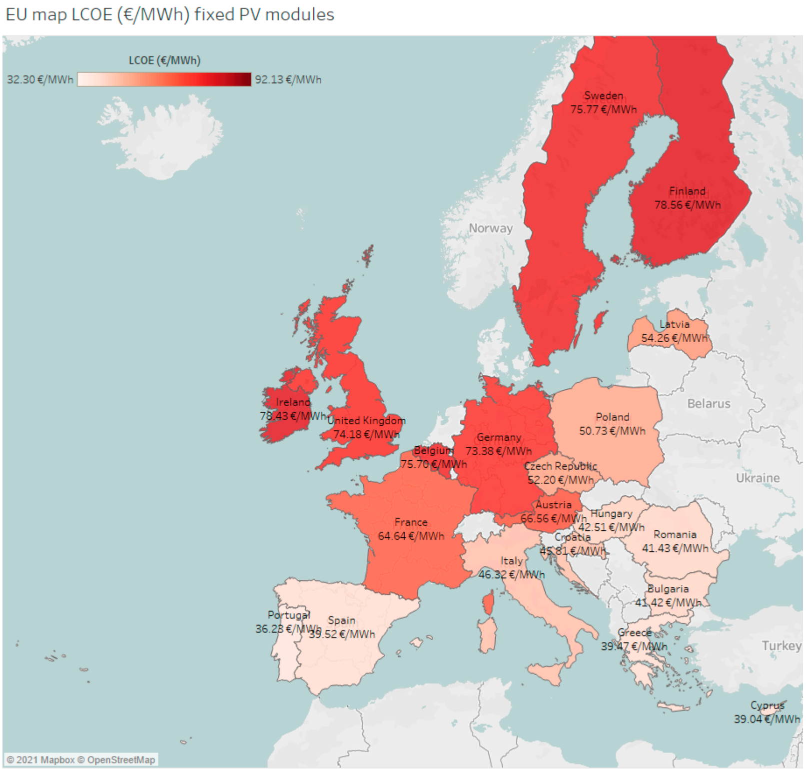

Figure 1. EU map LCOE (EUR/MWh)—fixed-axis PV modules (source: own elaboration with Open StreetMap layer [46]).

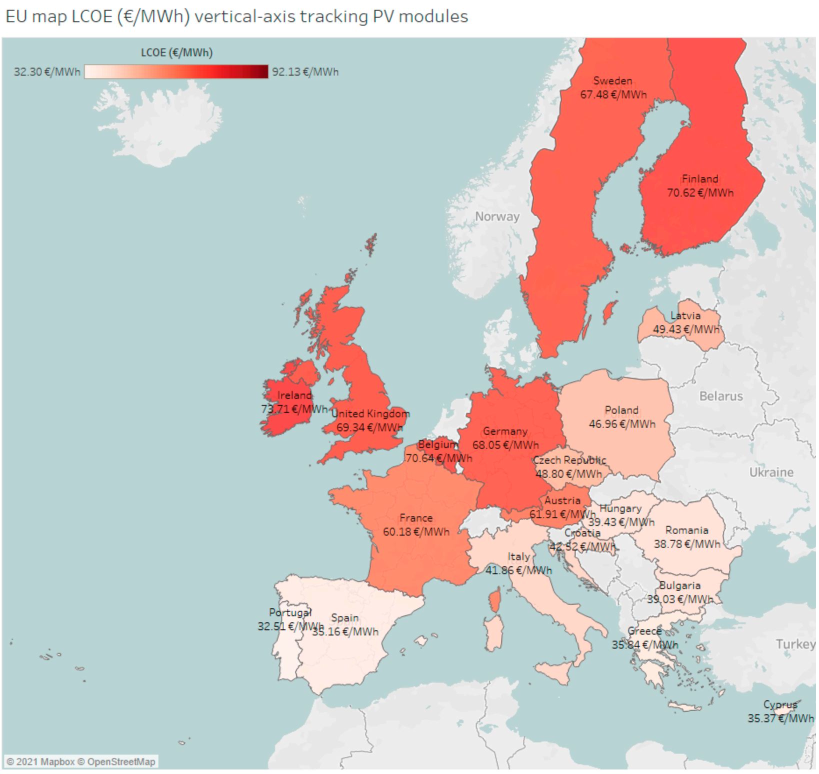

Figure 2. EU map LCOE (EUR/MWh)—vertical-axis tracking PV modules (source: own elaboration with Open StreetMap layer [46]).

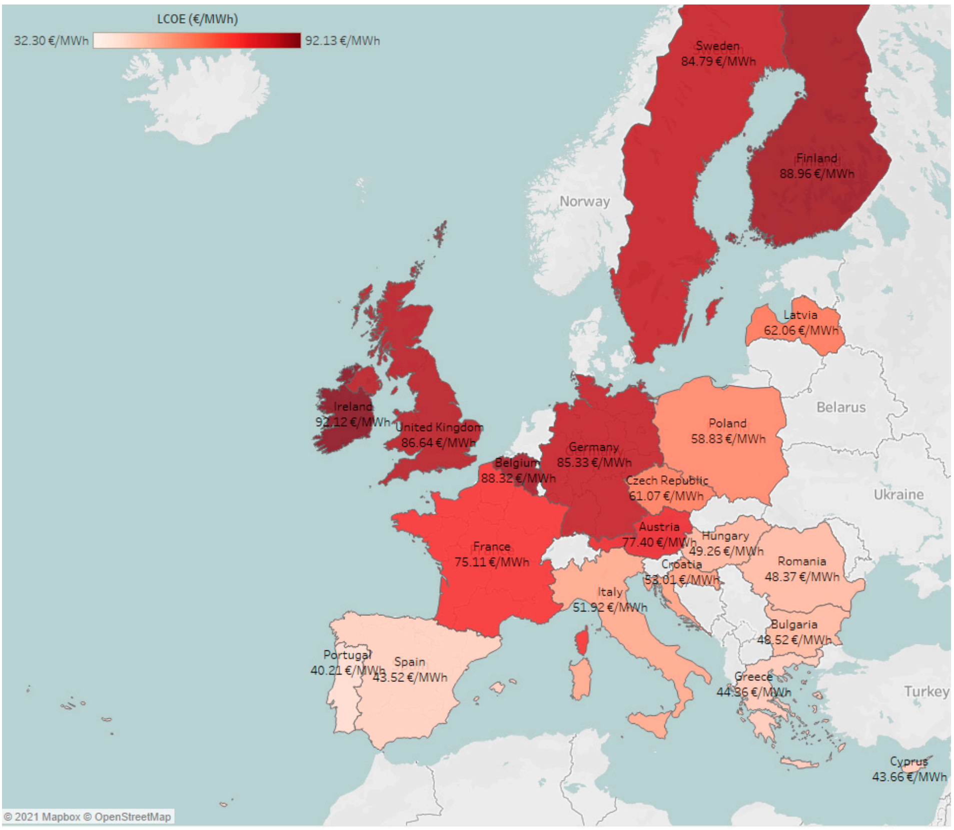

Figure 3. EU map LCOE (EUR/MWh)—two-axis tracking PV modules (source: own elaboration with Open StreetMap layer [46]).

Some other interesting facts can be highlighted by observing the LCOE maps (regarding the format of the figures, color-filled economic maps were chosen as the main representation of the results. The goal is to clearly convey differences in profitability for PV systems between countries, without displaying other variables, such as climate zone or solar irradiation, which could interfere with the economic assessment performed) shown in Figures 1–3. Northern latitudes are connected to higher costs in general, due to lower solar insolation during the year and hence, lower energy production. This happens for instance in Sweden, Germany, UK or Finland. The best countries, LCOE-wise, are Portugal, Spain, Cyprus and Greece with one-axis tracking systems, due to lower wages and higher yearly irradiation. As can be observed, the effect of wages is highly significant in the final results. Those countries with lower wages have, in most cases, smaller values of LCOE. For instance, countries like Latvia, with low yearly energy production, are cheaper than France. With respect to the climate zone of the most optimal countries LCOE-wise, Mediterranean (Csa) and hot semi-arid (BSh) climates are present in the locations with higher PV profitability. Even though Mediterranean climates often come with higher solar insolation, the effect of wages outweighs this effect in some specific cases like Romania and Bulgaria, hence a specific climate, such as the Mediterranean one, is not always an indication for a higher profitability in PV facilities. It must be remembered that these estimations have been performed for the capital city of each country or group of countries. Therefore, if, for example, Seville had been chosen as the representative location of Spain instead of Madrid, Spain's LCOE would have been even lower due to higher solar irradiation in this location and possible lower wage values. Another reminder is that those countries with lower extension have been grouped with neighboring countries. These regions are not colored in the optimal maps but are referenced in all result tables.

It is interesting to note that some of the best countries, LCOE-wise, considered in this study, still have an underdeveloped potential regarding solar PV; Portugal, Bulgaria and

Romania had in 2019 an accumulated total installed capacity in solar PV facilities of under 1500 MW_{peaks} each. In contrast, Germany, with a far from optimal LCOE value, had over 49,000 MW_{peaks} of accumulated total installed capacity in solar PV facilities by the end of the same year. Spain is a notable exception with over 9200 MW_{peaks} installed, being the second cheapest country, LCOE-wise, but it is still far from Germany [47].

4. Discussion

The results presented in the previous section show that the profitability of PV systems can differ greatly according to the specific conditions of a country or region, most notably due to socioeconomic and climatic parameters. In order to quantify the effect on the LCOE of the different determinants considered in this study, we propose to estimate a two-level mixed regression model for the dependent variable $LCOE_{ic}$ (in logarithm); the subscript "i" represents a particular PV configuration and "c" represents the country where it takes place—the estimation has been made with the statistical software STATA 15.0. The multilevel regression model can be seen as a generalization of the linear regression model, which allows the inclusion of random deviations other than those associated with the overall error term of the model—for multilevel analysis details, see for example Cameron, Trivedi [48], and Goldstein [49].

The fixed part of the model has the following explanatory variables: the global average of the endogenous variable, $Log(LCOE_{ic})$, for all the countries (τ_{00}); the dummy variables $\{FIXED_{ic},\ INCLINED_{ic},\ VERTICAL_{ic}\}$ which control for the tracking system of the PV panel (the two axis system is the reference configuration in the estimation); the dummy variables $\{H-DECREMENT_{ic},\ H-INCREMENT_{ic}\}$ which, respectively, control for $-/+$ 10% changes in the hardware cost (being the actual hardware cost the reference value in the estimated model); the O&M costs; the solar irradiation (MWh per m^2), which depends on the country and PV configuration; and those explanatory variables which collect idiosyncratic information from each country, such as the wage costs (in logarithm) and the maximum and minimum temperatures. The discount rate for each country is not statistically significant in the estimated model, probably due to its low variance. For its part, the random part of the model has the two following purely random effects: u_{0c}, which control for the specificity (level 2 random intercept) of every particular country; and ε_{ic}, which represents the overall or level 1 error term. The results of the estimation are represented in Table 11.

$$\text{Level 1 model}:$$
$$Log(LCOE_{ic}) = \alpha_{0c} + (\delta_{1c}, \delta_{2c}, \delta_{3c}) \begin{pmatrix} FIXED_{ic} \\ INCLINED_{ic} \\ VERTICAL_{ic} \end{pmatrix} + (\beta_{1c}, \beta_{2c}) \begin{pmatrix} H-DECREMENT_{ic} \\ H-INCREMENT_{ic} \end{pmatrix} + \gamma_1 log(WAGES)_c +$$
$$\gamma_2 OMCOSTS_{ic} + \gamma_3 MinTEMP_c + \gamma_4 MinTEMP_c + \gamma_5 IRRADIATION_{ic} + \varepsilon_{ic}\ \varepsilon_{ic}\ iid \sim\ N(0, \sigma_\varepsilon^2)$$

$$\text{Level 2 model}:$$
$$\alpha_{0c} = \tau_{00} + u_{0c}\ (random\ intercept);\ u_{0c}\ iid \sim\ N(0, \sigma_{u_0}^2), cov(\varepsilon_{ic}, u_{0c}) = 0$$

In order to achieve a better fit of the model, the endogenous variable (LCOE) has been estimated in logarithm (the R^2 coefficient is greater than 95%). Likewise, the individual effect of each country has been estimated as a random effect to allow the inclusion of those variables that remain constant within the country (namely; discount rate, minimum and maximum temperatures, and wage costs); the model has also been estimated by fixed effects (this is, with dummy variables by country), with no significant differences being observed in the coefficients of both models.

Table 11. Linear regression model for LCOE determinants (source: own elaboration).

Explanatory Variables		**Coefficients**
Dummy variables to control for tracking system (Reference: two axes)	Fixed axis	−0.206 ***
		(−29.67)
	Inclined axis	−0.235 ***
		(−68.30)
	Vertical axis	−0.236 ***
		(−68.43)
Dummy variables to control for Hardware price variation (%) (Reference: current price)	10% Hardware price (EUR) decrement	−0.107 ***
		(−91.29)
	10% Hardware price (EUR) increment	0.097 ***
		(82.73)
Cost per employee and year (in logarithm) (thousands of EUR)	Log(wage)	0.262 ***
		(10.53)
Operations and maintenance costs (EUR per kWp and year)	O&M cost	−0.0017 **
		(−2.64)
Temperature (Celsius degrees)	Minimum temperature of the country	−0.011 **
		(−3.26)
	Maximum temperature of the country	−0.028 ***
		(−6.59)
Solar irradiation (MWh per m^2)	Irradiation	−0.11 ***
		(−16.80)
	Constant	4.262 ***
		(24.96)

Note: *t* statistics in parentheses. Significance levels: ** $p < 0.01$, *** $p < 0.001$.

The constant of the model, 4.262, reflects the overall mean (for all countries) of the LCOE in logarithm (which implies an LCOE level of EUR 70.9). Econometrically, this constant can also be seen as the prediction that the model would deliver if the tracking system has two axes, the hardware price is the current one, we do not take into account the country effect, and the rest of the explanatory variables of the model take null values.Regarding the determinants of the LCOE (in logarithm), starting with the tracking system, it is observed that the cheapest systems are those with one axis, followed by the one with a fixed system. Thus, using panels with vertical or inclined axis, instead of a two-axis configuration, reduces the LCOE by approximately 21% {= exp(−0.235) − 1}, while the reduction is 18.6% {= exp(−0.206) − 1} if the fixed axis is used. The dummy variables that control for percentage changes in the hardware cost reveal that when that cost varies by 10%, the LCOE varies slightly more than 10% in the same direction, so that the elasticity of the relationship is approximately unitary. Note that the cost of the hardware (in level or in logarithms) results in not being significant, possibly, because its effect is captured by the dummy of percentage variation of that cost.

Regarding other costs of the activity, the salary cost (expressed in logarithms) and the operation and maintenance costs are significant in the model. Thus, the LCOE elasticity to wage cost is 0.26 (inelastic relationship); this is, a 1% increase in wage costs increases LCOE by 0.26%. On the other hand, the O&M costs show a significant semi-elasticity relatively close to zero—note that these costs have a small variance.

Finally, the climatic conditions of the country are also important when explaining the LCOE. Thus, all other factors being equal, higher minimum and maximum temperatures reduce LCOE. When the minimum temperature rises one degree (all other factors being equal), the LCOE falls by 1.1%, while the said fall is 2.8% when the variable that increases by one unit is the maximum temperature. These results may seem counterintuitive if we consider that PV panels work best with low temperatures; however, these temperatures may also be capturing the best weather conditions in certain countries. Regarding solar irradiation, it can be observed that a unit increase of said irradiation (measured in MWh per m^2) reduces LCOE by 11%—observe that this explanatory variable is more significant in the model (it shows a lower *p*-value) than those referred to the maximum and minimum temperatures.

5. Conclusions

Technical advances in PV technology have allowed for not only the optimization in gathering and producing energy, but also a reduction of its associated costs. Considering the current broad range of options regarding PV system configurations, it is highly important to measure and compare profitability between these options. This is the main purpose of this work: to perform an economic comparative analysis of photovoltaic energy production for a specific set of countries. Europe, in the current technical and legal framework regarding PV technology, meets all the requirements to be considered a strong candidate for this study.

In this research, different methodologies for assessing profitability are presented, as well as economic parameters and a comparison of four PV configurations in different countries of Europe. In the results section, after obtaining cost values and economic parameters needed for the analysis, the estimation of LCOE is performed for each location, including optimal cost maps and the selection of the best tracking system for every case. In the discussion chapter, the most influential variables in the costs of energy production are identified and their weight is measured.

Regarding energy generation by the PV facility, production is generally lower in countries with higher geographical latitudes. In terms of cost of energy production, for the assumed investment and maintenance costs, the most optimal configurations are the one-axis tracking systems, either inclined or vertical, since their results are practically identical. The worst option is in all cases a two-axis tracking system, due to its high costs. It is also interesting to note the impact of wages. In higher latitudes, in most cases, wages are more expensive; hence, the LCOE is also higher. There are exceptions such as Latvia, with cheaper wages that outweigh to a certain extent its low energy production, making it a relatively profitable option for PV facilities. The impact of system configuration, climate conditions and wages in the LCOE results are supported by an econometric model. The model shows significant results for these main variables and also quantifies a reduction of a 21% by using one-axis tracking systems compared to a two-axis configuration. The remaining variables analyzed have been found to be significant, and their impact on the LCOE has been estimated.

The econometric model offers an interesting interpretation from a practical point of view. Assuming that climatic conditions are pre-established within each country, and that wage and maintenance costs will remain stable in the coming years in each country, we can see the model as a predictive tool about the effect that technological change (with increasingly cheaper facilities) may have on the LCOE indicator in the next years.

As for future lines of research, the inclusion of batteries as another option for PV systems is an important parameter to be studied and compared to the configurations described in this study. A deeper study of maintenance costs of the facility is also an option to be taken into account. In this context, fixed PV modules may still be a choice to be contemplated in certain cases due to their lower O&M expenses. The effects of subsidies and feed-in-tariffs are also interesting to be explored in future researches, since they could provide an even better overview of the differences of PV energy production costs between countries. The introduction of new models of photovoltaic modules, which increase the service life of PV systems to 40–50 years, as well as their consequences on payback of solar power plants, is also a topic to be considered, especially when compared to standard laminated modules [50]. Solar hybrid is also a promising field of study, which could provide higher efficiencies and a positive effect in the payback of the project [51]. A sensitive analysis could be applied with regard to the efficiency in the aforementioned scenarios, in order to assess the effect of technological advances in this variable.

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Appendix A. PVGIS Configuration and Main Parameters Considered

In this section, the different parameters and configuration options in PVGIS, for estimating the energy production of a PV system are described. Since different tracking systems are evaluated, the inputs for every given case vary slightly. It must be stressed that PVGIS has additional features, such as hourly solar radiation and data relating to PV energy, the Typical Meteorological Year or wind speed to name just a few. However, they are not relevant to this study and are not described further in this appendix.

Appendix A.1. Geographical Locations

First of all, a set of geographical locations is selected to be analyzed. Locations to be considered are identified by latitude and longitude. The effect of shadows is neglected in this study.

Appendix A.2. Solar Radiation Databases

PVGIS calculates solar radiation by using satellite images mainly from two databases: PVGIS-CMSAF and PVGIS-SARAH with some exceptions. The application automatically selects the appropriate database to obtain the most accurate results.

Appendix A.3. Inputs for PV System Calculations

- Solar radiation database: The most accurate database is automatically selected in every given case.
- PV technology: The performance of PV modules depends on the temperature and on solar irradiance, which are dependent on the type of PV modules. Crystalline silicon cells are selected for this research
- Installed PV peak power [kWp]: Power specified by the manufacturer which the PV array produces under Standard Test Conditions (STC).
- System loss: Every inefficiency which affects the final energy production of PV system. There exist several causes of system losses, related to cables, power inverter, dirt and so on. In PVGIS a default value of 14% is given for the overall loss of the system. This specific value will be adopted in this study.

Appendix A.4. Inputs for Fixed PV Modules

- Mounting position: For fixed systems, the way the modules are placed has a significant impact on the efficiency. In this study, free-standing configuration is selected, with racks placed on the floor.
- Slope of PV modules: It defines the fixed angle of the PV modules from the horizontal plane.
- Azimuth of PV modules: Orientation angle with respect to the south.

PVGIS calculates, for every given position selected, the optimal value for the slope and azimuth (assuming fixed values for the entire year). In this case, the azimuth is fixed to 0° (south-oriented PV modules) and the optimal inclination angle is calculated for every case.

Appendix A.5. Inputs for Tracking PV Modules

As previously stated, PVGIS allows the user to differentiate between fixed and sun-tracking PV modules as an input for calculations. PVGIS defines three different types of sun-tracking module configurations.

- Vertical axis tracking: One-axis sun-tracking system around a vertical axis with respect to the floor.
- Inclined axis tracking: One-axis sun-tracking system around an inclined axis.
- Two-axis tracking: In this configuration, the modules have two degrees of freedom which act as rotation axes.

PVGIS does not include the horizontal-axis tracking configuration as an option and as such, it is not considered in this study.

Appendix A.6. Outputs for Fixed PV Modules

PVGIS provides yearly values of energy production and in-plane solar irradiation among other parameters such as spectral effects or total loss. It also displays graphs of monthly values [33].

Appendix A.7. Outputs for Sun-Tracking PV Modules

The outputs are essentially the same as in fixed-axis configuration. The main difference is that results are now displayed for the selected sun-tracking configurations.

Appendix B. Discount Rate Estimation

According to [45], in order to estimate the discount rate for each European country i (DR_i), the first step consists in calculating the $WACC$ value for each country–for those companies which participate in their respective wholesale electricity markets. For this purpose, the well-known formula of the $WACC$ is used

$$WACC_i = \frac{E}{E+D}\, r_{Ei} + \frac{D}{E+D}\, r_D\, (1 - T_i) \tag{A1}$$

where $E/(E+D)$ and $D/(E+D)$ are respectively the equity and debt fractions of total capital employed, r_D is the cost of debt, and T_i and r_{Ei} are the profit tax and the cost of equity of each country i respectively. To obtain the cost of equity (r_{Ei}), the Capital Asset Pricing Model (CAPM) method is applied, as it is the most widely used in the financial context:

$$r_{Ei} = RRF_i + \beta_{elec}\, PM \tag{A2}$$

Substituting (A2) in (A1), we obtain (A3).

$$WACC_i = \frac{E}{E+D}\, (RRF_i + \beta_{elec}\, PMR) + \frac{D}{E+D}\, r_D\, (1 - T_i) \tag{A3}$$

where RRF_i represents the risk-free rate of return in country i, β_{elec} is the beta coefficient of European companies in the electricity market, and PMR is the Premium Market Risk.

Two sets of parameters can be differentiated in Equation (A3): those that present a common value for all the countries of the sample $\{E/(E+D), D/(E+D), \beta_{elec}, PMR, r_D\}$, and those whose values will depend on the country in which the activity is performed $\{RRF_i, T_i\}$. In order to assign values to the first group of parameters (common information), we take representative values from a group of European listed companies which are mainly active in the wholesale electricity market. These values are taken from the Spanish regulator [52,53], which, in turn, uses data from Bloomberg [54] and Dimson et al. [55]. Specifically, the estimated values are displayed in Equation (A4).

$$\{\frac{E}{E+D} = 0.45,\ \frac{D}{E+D} = 0.55,\ \beta_{elec} = 0.77,\ PMR = 4.75\%,\ r_D = 4.49\%\}. \tag{A4}$$

For the second set of variables, the country-varying variables $\{RRF_i, T_i\}$, the risk-free rates for each country (RRF_i) have been calculated by subtracting the 10-year sovereign bond yields of each country from that of Germany [56,57], while the tax profit (T_i) has been obtained from the "Deloitte International Tax Source Report" [58]. Finally, for the determination of the Discount Rate (DR_i), we apply the procedure used by the Spanish CNMC when calculating the rate of remuneration for regulated activities. The only parameter which has not been specified so far is the spread for additional risks, which, for the sake of simplicity, and since the peculiarities of each country are not known in depth, is maintained for all countries at the 0.5% proposed by the CNMC for the Spanish electricity distribution. Equation (A5) represents the formula used to obtain the Discount rates:

$$DR_i = \frac{WACC_i - T_i + Spread}{1 - T_i} \tag{A5}$$

Table A1 shows all the variables that change depending on the country considered –countries are ranked from highest to lowest DR_i.

Table A1. Financial variables by country. (Reprinted with permission from ref. [45]. 2021, Nunez, F.)

Country	T_i	RRF_i	r_{Ei}	$WACC_i$	DR_i
Greece	28.0%	2.10%	5.76%	4.37%	7.07%
Croatia	18.0%	2.75%	6.41%	4.91%	6.99%
Italiy	24.0%	1.79%	5.45%	4.33%	6.69%
Romania	16.0%	2.25%	5.91%	4.73%	6.63%
Spain	30.0%	0.81%	4.47%	3.74%	6.34%
Serbia	15.0%	1.75%	5.41%	4.53%	6.33%
Czech	19.0%	1.25%	4.91%	4.21%	6.20%
Portugal	21.0%	0.96%	4.62%	4.03%	6.10%
Slovenia	19.0%	1.01%	4.67%	4.10%	6.06%
Norway	22.0%	0.74%	4.40%	3.91%	6.01%
Latvia	20.0%	0.80%	4.46%	3.98%	5.98%
France	33.3%	0.03%	3.69%	3.31%	5.96%
Poland	19.0%	0.75%	4.41%	3.98%	5.92%
Hungary	9.0%	1.15%	4.81%	4.41%	5.85%
Lithuania	15.0%	0.75%	4.41%	4.08%	5.80%
UK	19.0%	0.30%	3.96%	3.78%	5.67%
Austria	25.0%	−0.01%	3.65%	3.49%	5.66%
Netherlands	25.0%	−0.17%	3.49%	3.42%	5.56%
Sweden	21.4%	−0.13%	3.53%	3.53%	5.49%
Ireland	12.5%	0.16%	3.82%	3.88%	5.43%
Finland	20.0%	−0.23%	3.43%	3.52%	5.40%
Denmark	22.0%	−0.44%	3.22%	3.37%	5.33%
Germany&Lux.	15.0%	−0.47%	3.19%	3.53%	5.16%
Switzerland	8.5%	−0.49%	3.17%	3.68%	5.03%

Appendix C. PV System Costs Per Country

A full disclosure of cost estimations for PV facilities in all countries considered in this research—according to the restrictions, hypothesis and system configurations described in the main text—is shown in Table A2.

Table A2. Cost estimation summary of PV facilities in capital cities of european countries (source: own elaboration).

Country	PV Tracking Technology	Investment Costs			Maintenance Costs
		H [EUR]	$SC + I$ [EUR]	I_0 [EUR]	O&M [EUR/Year]
Austria	Fixed	460.32	382.07	842.39	8.42
	1-axis (V and I)	533.00	442.39	975.39	12.48
	2-axis	666.25	552.99	1219.24	18.29
Belgium, Luxembourg and Netherlands	Fixed	460.32	393.57	853.89	8.54
	1-axis (V and I)	533.00	455.72	988.72	12.66
	2-axis	666.25	569.64	1235.89	18.54
Bulgaria	Fixed	460.32	57.54	517.86	5.18
	1-axis (V and I)	533.00	66.63	599.63	7.68
	2-axis	666.25	83.28	749.53	11.24
Croatia and Slovenia	Fixed	460.32	103.57	563.89	5.64
	1-axis (V and I)	533.00	119.93	652.93	8.36
	2-axis	666.25	149.91	816.16	12.24
Cyprus	Fixed	460.32	186.43	646.75	6.47
	1-axis (V and I)	533.00	215.87	748.87	9.59
	2-axis	666.25	269.83	936.08	14.04
Czech Republic	Fixed	460.32	121.98	582.30	5.82
	1-axis (V and I)	533.00	141.25	674.25	8.63
	2-axis	666.25	176.56	842.81	12.64
Finland	Fixed	460.32	356.75	817.07	8.17
	1-axis (V and I)	533.00	413.08	946.08	12.11
	2-axis	666.25	516.34	1182.59	17.74
France	Fixed	460.32	319.92	780.24	7.80
	1-axis (V and I)	533.00	370.44	903.44	11.56
	2-axis	666.25	463.04	1129.29	16.94
Germany	Fixed	460.32	409.68	870.00	8.70
	1-axis (V and I)	533.00	474.37	1007.37	12.89
	2-axis	666.25	592.96	1259.21	18.89
Greece	Fixed	460.32	172.62	632.94	6.33
	1-axis (V and I)	533.00	199.88	732.88	9.38
	2-axis	666.25	249.84	916.09	13.74
Hungary and Slovakia	Fixed	460.32	105.87	566.19	5.66
	1-axis (V and I)	533.00	122.59	655.59	8.39
	2-axis	666.25	153.24	819.49	12.29

Table A2. *Cont.*

Country	PV Tracking Technology	Investment Costs			Maintenance Costs
		H [EUR]	$SC + I$ [EUR]	I_0 [EUR]	O&M [EUR/Year]
Ireland	Fixed	460.32	379.76	840.08	8.40
	1-axis (V and I)	533.00	439.73	972.73	12.45
	2-axis	666.25	549.66	1215.91	18.24
Italy and Malta	Fixed	460.32	253.18	713.50	7.13
	1-axis (V and I)	533.00	293.15	826.15	10.57
	2-axis	666.25	366.44	1032.69	15.49
Latvia, Lithuania and Estonia	Fixed	460.32	96.67	556.99	5.57
	1-axis (V and I)	533.00	111.93	644.93	8.26
	2-axis	666.25	139.91	806.16	12.09
Poland	Fixed	460.32	103.57	563.89	5.64
	1-axis (V and I)	533.00	119.93	652.93	8.36
	2-axis	666.25	149.91	816.16	12.24
Portugal	Fixed	460.32	149.60	609.92	6.10
	1-axis (V and I)	533.00	173.23	706.23	9.04
	2-axis	666.25	216.53	882.78	13.24
Romania	Fixed	460.32	75.95	536.27	5.36
	1-axis (V and I)	533.00	87.95	620.95	7.95
	2-axis	666.25	109.93	776.18	11.64
Spain	Fixed	460.32	218.65	678.97	6.79
	1-axis (V and I)	533.00	253.18	786.18	10.06
	2-axis	666.25	316.47	982.72	14.74
Sweden and Denmark	Fixed	460.32	359.05	819.37	8.19
	1-axis (V and I)	533.00	415.74	948.74	12.14
	2-axis	666.25	519.68	1185.93	17.79
United Kingdom	Fixed	460.32	361.35	821.67	8.22
	1-axis (V and I)	533.00	418.41	951.41	12.18
	2-axis	666.25	523.01	1189.26	17.84

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