Efficiency of investments in solar power in the EU countries

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Abstract

The aim of the study is to assess efficiency of investments in solar power in the EU countries in 2015. The Data Envelopment Analysis (DEA) method is implemented to evaluate relative efficiency of their solar power performance for electricity generation. The installed solar capacity is used as the input variable. Four variables: solar electricity generation (the baseline model), the environmental output, the economic output and the energy dependence output are used to measure efficiency of investments in solar power.

The study reveals that three countries: Germany, Spain and Ireland are efficient when the relation between the investments in solar power and the volume of energy generated by solar farms is considered. However, when additional aspects of solar power efficiency are included different countries benefit. Inclusion of the environmental output reveals that efficiency increases the most in Poland, Malta, Bulgaria, Cyprus and the Czech Republic, where coal is the main energy source. Taking into account the economic aspect, i.e. the costs of generating energy from non-renewable energy sources, an increase in the efficiency scores is noted in countries in which oil (Malta and Cyprus), or natural gas (Lithuania, Belgium, Luxembourg) are used as the main energy source.

Keywords: *Data Envelopment Analysis (DEA), solar power generation*

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1 Introduction

Over the last 20 years the EU countries considerably increased their dependence on renewable energy sources, especially in the area of electricity generation. The share of renewable energy sources in total electricity generation grew more than twofold - from 13.9% in 1995 to 29.9% in 2015. As a result, the share of solar power generation in renewable energy generation increased from 5.7% in 2010 to 29.1% in 2015 (w 1995 this share was only 0.01.%). Also the cumulative installed solar power capacity increased by about 2000 times between 1995 and 2015 (from 49 MW in 1995 to 94864 MW in 2015).

Such rapid development of renewable energy sources in the EU countries results from the common energy policy aimed at improving energy security and reducing greenhouse gas

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emissions. In accordance with the Directive 2009/28/EC, the EU member states should increase the share of energy obtained from renewable sources in their overall energy consumption. The European climate and energy package specifies targets to be achieved by 2020.

Since the EU countries differ a lot when solar radiation is taken into account, the issue of the extent to which investments in solar power translate into the volume of electricity generation in particular EU countries seems worth investigating. Since solar electricity generation, which can replace non-renewable energy sources, influences their economic, social and environmental aspects, it requires in-depth analysis.

The aim of the study is to assess efficiency of investments in solar power in the EU countries (excluding Estonia and Latvia, which did not generate any solar power in the analysed period). The analysis uses cross-sectional data set from 2015. The DEA method is implemented to evaluate relative efficiency of particular countries' solar power performance in electricity generation. The installed solar capacity is used as the input variable, and it approximates solar power investment or capital. The output variables refer to the volume of solar electricity generation, which allows for measuring solar power performance in electricity generation, and selected factors from the areas of energy security (energy dependence), environmental protection, and economy, which allows for identifying the benefits of investments in solar power in the EU countries.

Efficiency of renewable energy is a frequently studied issue, and most papers investigating to use Data Envelopment Analysis (DEA) as the empirical framework. Mardani et al. (2017) offer a comprehensive review of DEA applications in energy efficiency. A comparison of different sources of renewable energy is proposed in Cristóbal (2011), Kim et al. (2015), Karpińska (2016) and the assessment of efficiency of renewable energy sources referring to wind can be found in, among others, Wu et al. (2016), Sağlam (2017), Frodyma et al. (2018), to biogas – in Lijó et al. (2017), and to hydroelectric power – in Barros et al. (2017). Only several papers deal with solar power efficiency (Sueyoshi and Goto, 2014; Sueyoshi and Goto, 2017; Imteaz and Ahsan, 2018).

The paper contributes to the existing literature in two aspects. Firstly, its novelty lies in the selection of objects for the analysis, that is the EU countries, which have not been compared in this context so far. There are two reasons why the EU countries are an interesting object of study. First, all EU countries are obliged to meet the targets set in the climate and energy package. Some of them offer certain incentives (e.g. feed-in tariffs, green certificates), which are supposed to increase investments in solar power but might result in inefficiency of solar power installed. Second, the EU countries are highly diversified with reference to their solar resources. Southern Europe countries have a great advantage in the solar potential over the northern ones. Secondly, the DEA models include variables describing environmental, economic and energy security aspects, which have not been analysed in previous studies. The inclusion of these factors offer a much broader view on solar efficiency in EU the countries.

2 Methodology and data

The CCR model, proposed by Charnes, Cooper, Rhodes in 1978 (Charnes et al., 1978), assumes constant returns to scale, and the modification of the model presented in 1984 by Banker, Charnes and Cooper (Banker et al., 1984) (the BCC model) allows for variable returns to scale. The BCC model allows for assessing countries not only from the perspective of pure technical efficiency (the best use of input/investments) but also from the perspective of economies of scale (operating within the area of optimal benefits), thanks to which it is possible to discover whether inefficiency of a given country in the area of solar power results from wasting investments or from operating within non-optimal economies of scale. The DEA method is based on a comparison of a group of decision making units (DMUs), in which each unit has a certain degree of freedom of decision. In other words, this method allows for identifying efficient units which later set the efficiency level desired for and possible to obtain by other units. In our study one European country is treated as one decision making unit. Following the assumptions of the DEA method, the inputs and the outputs are greater than or equal zero, and for each decision making unit there exists at least one input and one output greater than zero. The task is to find the minimum value of parameter θ, which makes it possible to decrease inputs in such a way that the efficiency level is not changed. A decision making unit is efficient if $\theta = 1$; a unit is inefficient if $\theta < 1$.

The data on which the empirical analysis is based describe different aspects of solar power efficiency in the EU countries. The sample of 26 European Union member states includes: Austria, Belgium, Bulgaria, Croatia, Cyprus, the Czech Republic, Denmark, Finland, France, Hungary, Greece, Germany, Ireland, Italy, Lithuania, Luxembourg, Malta, the Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, and the United Kingdom. All data describe the EU countries in 2015 and are obtained from the European Commission webpage[4].

The DEA models include one input variable and a subset of four output variables.

[4] Energy datasheets: EU-28 countries (https://ec.europa.eu/energy/en/data-analysis/country) accessed on 10.01.2018.

The installed solar capacity (MW) per capita in 2015 (**CAP**) serves as the input variable in the DEA models. The variable is a proxy for total investment in solar power in particular countries, which cannot be measured directly. The data describing investments in renewable energy (including solar power) are available since 2010 for the EU counties and do not include previous investments (*EurObserv'ER*).

The most significant variable used as the output in the DEA models in our study is gross electricity generation from solar (TWh per capita) in 2015 (**GEN**), which is the most common output variable used in previous studies assessing efficiency of solar power.

The environmental output of solar power (**ENV**) is the second output variable in the DEA models, and it measures carbon dioxide emissions avoided thanks to solar power. In order to calculate the CO_2 avoided, the following formula is used:

$$ENV = \frac{GHE}{TPES} \cdot GEN,$$

where: GHE is total CO_2 emission from power station, TPES is total primary energy supply, and GEN is gross electricity generation from solar power per capita in 2015. For countries with the highest CO_2 emissions from power stations in total primary energy supply, the change into solar power generation is the most significant, as vast amounts of CO_2 are avoided.

The economic output of solar power (**ECON**) is the third output variable in our study. To calculate **ECON**, the prices of energy sources and the contribution of each energy source in TPSE in a particular country are needed. The following formula is used:

$$ECON = CFF \cdot GEN,$$

where: $CFF = \sum_{i=1}^{3} TPES_i \cdot price_i$; where *i* indicates: coal, oil, natural gas, $TPES_i$ - total primary energy supply generated from *i* energy sources in 2015, *GEN* - gross electricity generation from solar per capita in 2015. The more expensive energy sources are used in a given country, the more efficient solar power in terms of economy is in it.

The energy dependence output of solar power (**DEP**) is the fourth output variable. This variable is calculated as:

$$DEP = \frac{IMPORT}{TPES} \cdot GEN,$$

where: *IMPORT* is total import of energy in 2015, *TPES* – total primary energy supply in 2015, *GEN* – gross electricity generation from solar per capita in 2015.

The more energy dependent a country is, the more beneficial - in terms of energy security - solar power generation is. On the other hand, if countries do not import any energy (i.e. they are energy self-sufficient), there is no benefit of solar power in this aspect.

The variables described above are used in the DEA model to analyse efficiency. The comparison of the analysed countries reveals that Germany has the highest installed solar capacity (490 MW per capita (**CAP**)), and the countries above the third quartile are: Italy, Belgium, Greece, Luxemburg, the Czech Republic and Malta. The countries below the first quartile are, apart from Ireland, which is the country with the lowest capacity, Finland, Poland, Sweden, Croatia, Hungary and Lithuania. When gross electricity generation from solar power (**GEN)** is considered, Germany is the leader (477 TWh per capita). Other countries with high values are: Italy, Greece, Spain, Belgium, Malta and the Czech Republic. The highest values of the environmental output (**ENV**) per capita are noted in Greece, Germany and Bulgaria. The greatest reduction of costs of energy sources replaced by energy generated by solar per capita (**ECON**) is noted in Italy, Malta and Belgium. Countries with the greatest volatility in the area of energy dependency per capita (**DEP**) are Malta, Greece and Belgium. Energy dependency indicates to what extent a country relies on import to meet its energy requirements. Summing up, the distribution of particular variables is skewed, which means that most EU countries have all variables below the average for the whole European Union. The lowest values of the variables are found in Ireland, Poland, Finland and Sweden.

3 Results

In order to analyse efficiency of investments in solar power in the EU countries, we consider various models with the capacity as the input variable and selected combinations of variables described in section 2 as the output variables. All models are presented in Table 1.

Table 1. Input-output variables of eight models.

	GEN	***GEN_ENV***	***GEN_ECON***	***GEN_DEP***	***ALL***
CAP	X	X	X	X	X
GEN	X	X	X	X	X
ENV		X			X
ECON			X		X
DEP				X	X

Note: in bold: variable name, in italics: the name of the model.

The relative efficiency scores (θ) of investments in solar power in 26 EU countries in 2015 for input-oriented BCC models are presented in Table 2. The position of a given country in the rank is given in the parentheses for each model. The efficiency levels of investments in solar power in the first model (*GEN*) are not very high. The overall efficiency (BCC efficiency) scores range from 0.26 to 1.00, and the average BCC efficiency score is 0.50. The relative efficiency scores in models with two output variables are higher than in models with one output variable. The average BCC efficiency scores are about 0.54-0.56 in all these models (*GEN_ECON, GEN_ENV, GEN_DEP*), and the relative efficiency scores range from about 0.27 to 1.00. The highest average BCC efficiency score equals 0.61 in the model with all outputs (*ALL*), and the relative efficiency scores range from 0.27 to 1.00. The results reveal that the efficiency scores of the last model (ALL), which is the most comprehensive one regarding the number of input and output variables, are greater than the efficiency scores of the remaining seven models.

Table 2 reveals that Germany, Spain and Ireland are the countries with the maximum efficiency score of solar power generation (*GEN*) (equal 1.00), while the least efficient country is the Netherlands (with the relative efficiency score 0.26). When the models account for additional aspects, such as the environmental output, the economic output and the energy dependence output, it is possible to obtain a broader picture of benefits connected with investing in solar power in the EU countries. Taking into consideration both solar power generation and the environmental output (*GEN_ENV*) (Table 2), increased efficiency is noted in Greece, in which, as in Germany, Spain and Ireland, the efficiency scores of solar power generation equal 1.00. Countries with coal as the main source used in electricity generation (such as Poland (in 2015 79% of its total electricity generation comes from plants using coal), the Czech Republic (49%), Bulgaria (46%), Greece (43%), and Germany (44%), together with Cyprus and Malta, in which 91% of electricity is generated in plants using heating oil) gain the most: the efficiency score in Bulgaria increases by 87%, in Poland by 63%, in Cyprus by 59%, the Czech Republic by 52% and in Malta by 44%. When both solar power generation and the economic output (*GEN_ECON*) (Table 2) are taken into account, the most efficient countries with respect to investing in solar power include, apart from Germany, Spain and Ireland, also Cyprus, Italy and Malta. Taking into account the economic aspect, i.e. the costs of generating energy from non-renewable energy sources, an increase in the efficiency scores (a greater value of parameter θ by 127% in Malta, in Cyprus by 72%, in Belgium by 48%, in Lithuania by 33%, in Luxembourg by 28%) and a higher position in the rank is noted in countries in which the main energy source is oil (i.e. Malta, in which in 2015 as much as 92% of total electricity generation comes from plants using heating oil and Cyprus (91%)), or natural gas (i.e. Lithuania (40% of its energy comes from plants using natural gas), Belgium (35%), Luxembourg (30%)). Apart from the improvement of their position in the rank, the value of parameter θ also increases.

Table 2. The efficiency scores of the input- and output oriented BCC models.

Country	*GEN*	*GEN_ENV*	*GEN_ECON*	*GEN_DEP*	*ALL*
AT	0.35 (17)	0.35 (18)	0.39 (17)	0.35 (19)	0.39 (20)
BE	0.34 (18)	0.34 (19)	0.50 (10)	0.42 (14)	0.50 (13)
BG	0.47 (9)	0.88 (7)	0.47 (12)	0.47 (12)	0.88 (8)
CY	0.58 (7)	0.92 (5)	**1.00 (1)**	0.60 (8)	**1.00 (1)**
CZ	0.38 (13)	0.58 (11)	0.38 (19)	0.38 (16)	0.58 (12)
DE	**1.00 (1)**	**1.00 (1)**	**1.00 (1)**	**1.00 (1)**	**1.00 (1)**
DK	0.27 (25)	0.28 (25)	0.27 (25)	0.28 (25)	0.29 (24)
ES	**1.00 (1)**	**1.00 (1)**	**1.00 (1)**	**1.00 (1)**	**1.00 (1)**
FI	0.33 (19)	0.33 (20)	0.33 (20)	0.33 (20)	0.33 (22)
FR	0.37 (15)	0.37 (16)	0.40 (14)	0.37 (17)	0.40 (17)
GR	0.98 (4)	**1.00 (1)**	0.98 (7)	**1.00 (1)**	**1.00 (1)**
HR	0.43 (11)	0.43 (13)	0.43 (13)	0.43 (13)	0.43 (16)
HU	0.27 (24)	0.27 (26)	0.27 (24)	0.27 (26)	0.27 (26)
IE	**1.00 (1)**	**1.00 (1)**	**1.00 (1)**	**1.00 (1)**	**1.00 (1)**
IT	0.88 (5)	0.88 (6)	1.00 (1)	0.88 (6)	1.00 (1)
LT	0.38 (14)	0.38 (15)	0.50 (11)	0.57 (9)	0.58 (11)
LU	0.31 (21)	0.31 (22)	0.40 (16)	0.31 (22)	0.40 (19)
MT	0.44 (10)	0.63 (9)	**1.00 (1)**	**1.00 (1)**	**1.00 (1)**
NL	0.26 (26)	0.30 (23)	0.26 (26)	0.48 (11)	0.48 (14)
PL	0.28 (23)	0.46 (12)	0.28 (23)	0.28 (24)	0.46 (15)
PT	0.62 (6)	0.68 (8)	0.62 (8)	0.66 (7)	0.69 (9)
RO	0.52 (8)	0.62 (10)	0.52 (9)	0.52 (10)	0.62 (10)
SE	0.35 (16)	0.35 (17)	0.38 (18)	0.35 (18)	0.38 (21)
SI	0.40 (12)	0.40 (14)	0.40 (15)	0.40 (15)	0.40 (18)
SK	0.33 (20)	0.33 (21)	0.33 (21)	0.33 (21)	0.33 (23)
UK	0.28 (22)	0.28 (24)	0.28 (22)	0.28 (23)	0.28 (25)

Note: In bold: the maximum efficiency score of the solar power (equal 1.00).

After adding the energy security aspect to solar power generation (*GEN_DEP*) (Table 2), Malta joins the list of the most efficient countries (its efficiency score increases by 127% in comparison with the basic model) and Greece (2%). Considerable improvement is also noted in Netherlands (the efficiency score grows by 87%), Lithuania (49%) and Belgium (by 23%).

Including all variables in the analysis of efficiency yields the greatest number of solar efficient countries. Countries already mentioned above (efficient with respect to two various input variables), remain efficient also in this stage: i.e. Germany, Spain, Ireland, Greece, Malta, Italy and Cyprus. Hungary turns out to be the least efficient country in this extended model. In other words, if efficiency of investments in solar power is considered not only from the perspective of electricity generation but also from the perspective of social, economic and environmental benefits resulting from replacing non-renewable energy sources with solar power, the countries which benefit the most are: Malta (the efficiency score increases by 127%), Bulgaria (87%), Netherlands (87%), Cyprus (72%), and Poland (63%).

Conclusions and discussion

The objective of the study is to assess efficiency of investments in solar power in the EU countries. The DEA method is used as an empirical framework. The installed solar capacity is used as the input variable. Four variables: solar electricity generation, the environmental output, the economic output and the energy dependence output are used to measure efficiency of investments in solar power, which also allows for identifying the benefits of investing in solar power in the EU countries.

In particular, our findings can be summarised in two main points.

First, the study reveals that Germany, Spain and Ireland are efficient both when only solar power generation is considered and when the relation between the investments in solar power and the volume of energy generated by solar farms is considered. The results are quite surprising, since only one of these countries is located in the south of Europe, however, they are in line with the results obtained by Sueyoshi and Goto (2014).

Second, the inclusion of environmental, economic or energy dependence outputs, demonstrates that different countries benefit from solar power investments. If efficiency of solar power takes into account socio-economic and environmental benefits resulting from replacing non-renewable energy sources with solar power, Malta, Cyprus, Greece, and Italy gain the most.

Poland, Malta, Bulgaria, Cyprus and the Czech Republic gain the most as far as investments in solar powers and the improvement of the air quality and the reduction of greenhouse gases emissions are concerned. Including the environmental output in the analysis reveals that efficiency increases the most in countries where the main energy source is coal. This result is connected with a high level of carbon dioxide emissions resulting from burning coal, which is considerably reduced when coal is replaced with solar power. Malta, Cyprus, Belgium, Lithuania and Luxembourg gain the most in the economic aspect, as power generated from solar is much cheaper than power generated from fossil fuels. That is why including the economic output indicates the greatest improvement in efficiency in countries which obtain electricity from natural gas or heating oil instead of coal. This effect is the consequence of high prices of these fuels.

Malta, the Netherlands, Lithuania and Belgium gain the most in the aspect of energy security taking into account the dependence output in the assessment of efficiency of investments in solar power.

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