Evaluation of primary energy factor values of photovoltaics: The case of Lithuania

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It is necessary to evaluate primary energy consumption from renewable energy resources in energy efficient buildings in accordance with the requirements of the European Parliament and Council Directive 2010/31/EC "Energy performance of buildings". The problem is that in different EU countries, there are no unified methods that evaluate primary energy factor values of photovoltaics. Another problem is that there are various calculation methods, which are lack of clear description, and the results of these methods are inaccurate. In this paper a comparison of different methods for the evaluation of primary energy factor values of photovoltaics are given and as a case study the case of Lithuania was chosen. The comparison showed that empirical value of primary energy factor for photovoltaics is much smaller than that currently used in the EU standard.

Keywords: primary energy, photovoltaics, evaluation methods, Lithuania

INTRODUCTION

Energy balance takes into account of various energy streams entering the national energy network, their transformation and losses in supply is up to the final consumer. To avoid repetitive evaluation of these streams, it is important to distinguish between primary and secondary energy.

Thus, the need for primary energy necessary to generate one unit of secondary energy is based on primary energy factors (PEF), which are also referred to as conversion factors describing the total amount of energy in the energy generation chain up to the final usage (Fig.1) [1].

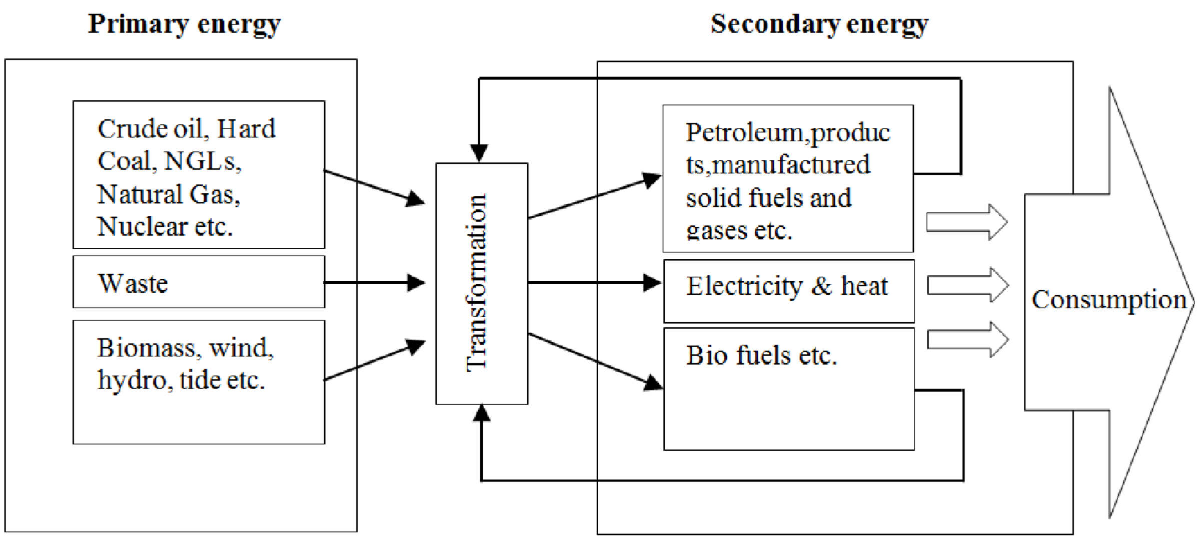

Fig.1. Interdependence of primary and secondary energy [1]

Every country has a different energy generation and supply chain, so the PEF values also differ accordingly.

However, only a few countries make these values publicly available (Table 1).

According to the information presented in Table 1, national building standards of the EU countries are either missing some data or give unspecified renewable energy values, which make it unclear whether these values are, in fact, applied for photovoltaic energy or are only politically justified having no direct relation to engineering or science.

Various methods may be applied to calculate primary energy factor (PEF) for the production of electrical energy (Table 2) [23].

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Table 1. Photovoltaic electrical energy values in EU building standards

Country	Primary Energy Factor	Total Primary Energy Factor	Non-Renewable Primary Energy Factor	Renewable Primary Energy Factor	References and remarks
Ireland	2.45	-	-	-	[2]
Austria	-	-	-	-	[3]
Belgium	-	-	-	-	[4]
Czech Republic	-	1.0	0	-	[5]
Denmark	2.5	-	-	-	[6]
Denmark	1.8	-	-	-	[6 since year 2020]
United Kingdom	-	-	-	-	[7]
Estonia	-	-	-	-	[8]
Greece	-	-	-	-	[9]
Spain	-	-	-	-	[10]
Italy	-	2.174	2.174	-	[11]
Cyprus	1	-	-	-	[12]
Poland	-	1	0	1	[13]
Netherlands	-	-	-	-	[14]
France	1	-	-	-	[15]
Slovakia	-	-	-	-	[16]
Slovenia	0	-	-	-	[17]
Finland	-	-	-	-	[18]
Sweden	-	0.17	-	-	[19]
Germany	-	1	0	-	[20]
amorphous (DE)	-	1.29	0.27	1.03	[21]
mono crystal (DE)	-	1.53	0.47	1.05	[21]
poly crystal (DE)	-	1.25	0.23	1.02	[21]
Hungary	0	-	-	-	[22]

Table 2. Parameters of different methods for the estimation of primary solar energy (photovoltaics)

$MJ_{primary\ energy}/MJ_{electricity}$		Primary energy evaluation description	PEF	PEF value	References
1.	Zero equivalent	Electricity and thermal energy production from renewable energy sources are not estimated	(Total) primary energy	0	[24]
2.	2a -Direct equivalent	Electricity and thermal energy production from non-combustible renewable energy sources and nuclear energy are estimated	(Total) primary energy	1.0	[25-27]
	2b-Physical energy content	Primary energy form appeared during generation process is estimated	(Total) primary energy	1.0	[28]
	2c-Substitution	It is seen as a form of energy, which first is included in the statistical energy balance before transforming into the secondary or tertiary form of energy	(Total) primary energy	2.5	[29-33]
3.	Only non-renewable primary energy	-	Non-renewable primary energy	0.15	[34]
4.	4a-Technical conversion efficiencies	Is evaluated all energy production chain, seperating renewable and non-renewable energy.	Non-renewable primary energy	0.15	[29,30,34]
			Renewable primary energy	7.5	
	4b-Physical energy content	Is treated as the first form of energy appeared during the generation process.	Non-renewable primary energy	0.15	[28,34]
			Renewable primary energy	1.0	

The data given in Table 2 demonstrates that PEF values for photovoltaic energy estimation differ throughout the methods. Depending on the type of primary energy and the evaluation method applied, primary energy factor of the same renewable energy source may significantly vary [35-37].

The analysed literary sources were lack of data on PEF evaluation: the established PEF values differ considerably regarding the same type of energy due to a great number of methods to estimate PEF. So far no systematic research on the topic has been done and for this reason the aim of the paper is to determine the most suitable method to establish PEF for photovoltaic power stations. The calculation method is based on the statistical data obtained from the Lithuanian photovoltaic power stations. The values determined for photovoltaic power stations are going to be applied for building energy certification to ensure the implementation of the goals and regulations determined by Directive 2010/31/EU.

METHODOLOGY

Energy performance of buildings is the balance between the amount of energy generated and consumed in a building. The type and amount of energy consumed depend on various factors, for instance architectural solutions and engineering systems of a building, climate of the country and its level of economic development. Compared to the underdeveloped countries, in the economically developed ones, buildings consume more energy due to the use of various domestic appliances [38]. The key purpose in constructing energy efficient buildings is to increase the amount of renewable energy supply and reduce the use of primary non-renewable energy sources. Here two principal opportunities emerge: the first one is to increase the amount of renewable energy in electrical energy networks [39], and the second one – to use electrical energy generated from renewable energy sources, i.e. photovoltaic power stations in or nearby the building [40].

Following the requirements of Directive 2010/31/EU, more than a half of energy consumed in nearly zero-energy buildings is required to derive from renewable sources. However, all renewable energy sources include a certain amount of non-renewable energy that is not evaluated, which is why the methods provided in Table 2 are not accurate enough for calculating PEF of photovoltaic power stations. Taking the mentioned (methods) into consideration, the method provided in the standard EN 15603:2014 is applied to determine PEF of photovoltaic power stations. Therefore, the total demand for primary energy in a building is calculated as follows (Eq.1) [41]:

$$E_p = \sum (E_{del,i} f_{P,del,i}) - \sum (E_{\exp,i} f_{P,\exp,i}) \quad (1)$$

where: E_p – primary energy demand; $E_{del,i}$ – final energy demand by the energy carrier; $f_{P,del,i}$ – primary energy factor depending on the energy carrier; $E_{exp,i}$ – final energy exported by the energy carrier; $f_{P,exp,i}$ – primary energy factor of the exported energy carrier.

The total primary energy may be calculated by Eq.2:

$$f_{P,tot} = f_{P,nren} + f_{P,ren} \quad (2)$$

where: $f_{P,tot}$ – total primary energy; $f_{P,nren}$ – non-renewable primary energy; $f_{P,ren}$ – renewable primary energy.

Evaluation method of electrical energy generated from photovoltaic energy sources

Energy generated in photovoltaic systems can be evaluated by different methods varying in their degree of simplicity and accuracy. Among all, three principal methods may be distinguished: empirical correlation, analytical accounting and detailed modelling [42]. Analytical accounting method was chosen to calculate the parameters of the photovoltaic power stations analysed herein. Following the method, electrical energy generated in a photovoltaic power station can be estimated by Eq.3:

$$E_{PV} = PR \cdot P_n \cdot \frac{H_T}{G_{STC}} \quad (3)$$

where: E_{PV} – amount of electrical energy generated in a photovoltaic power station during the analysed period of time, kWh; PR – efficiency coefficient of the station, P_n – nominal capacity of the station determined under standard testing conditions, kW; H_T – total amount of solar radiation onto the surface of a photovoltaic module, kWh/m^2; G_{STC} – solar radiation under standard testing conditions, kW/m^2.

PR coefficient is estimated following formula 4 [43]:

$$PR = k_\theta \cdot k_Q \cdot k_{BI} \cdot k_\gamma \cdot k_w \cdot k_s \cdot \eta_{inv} \cdot k_{\deg} \quad (4)$$

where: k_θ – optical reflection reduction coefficient; k_Q – spectral reduction coefficient; k_{BI} – minor exposure reduction coefficient; k_γ – module temperature reduction coefficient; k_w – installation loss reduction coefficient; k_s – dirt reduction coefficient; η_{inv} – inverter conversion efficiency; k_{deg} – module ageing reduction coefficient.

Potential of solar energy in Lithuania

According to Alisov's climate classification, the territory of Lithuania is in temperate climate zone and so can be ascribed to the south-western sub-area of the Atlantic continental zone [44] (Fig.2).

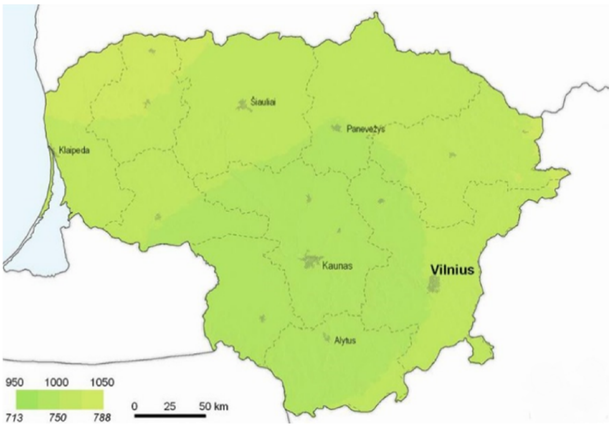

Fig.2. Potential of solar electrical energy in the Lithuanian territory [45]

Multiannual observation data suggests that the average annual solar radiation impinging onto the horizontal surface of Lithuania reaches approximately 1000 kWh/m^2. Sunlight lasts the longest in the western part and shortens while moving towards the eastern, i.e. 1840-1900 h/year and 1700 h/year accordingly [46].

Generative efficiency of photovoltaic power stations is directly dependent on solar radiation [44]. In order to use solar radiation to its maximum under the Lithuanian climate conditions photovoltaic modules are directed towards south with 25°-45° lean angle from the horizontal plane. Such orientation of one square metre of the area of a photovoltaic power station generates 130-160 kWh electrical energy annually under the Lithuanian climate conditions [47].

The analysed photovoltaic power stations

The total capacity of photovoltaic power stations operating in Lithuania sums up to 60.60 MW. Lithuanian electricity transmission system encompasses 1969 unique photovoltaic power stations or station groups: 1953 small power stations (from 1 to 199.68 kW), 12 medium (from 225 to 999.6 kW), and 4 large ones (from 1488.81 to 2559.84 kW) [48].

Since the level of solar radiation is similar in the whole territory of Lithuania, the most suitable places to install photovoltaic power stations are selected on the basis of other parameters, such as the development of transmission network infrastructure as well as the synthesis of local climate conditions and relief [49].

The research has been carried out on the basis of statistical data obtained from 30 photovoltaic power stations (Table 3-5) and their analyses are presented in Section 3. PEF values were estimated by applying Eq.2, while technical parameters of photovoltaic power stations were analysed based on Eq.3.

Table 3. Main characteristics of the analysed photovoltaic power stations (0.02< >0.03 MW)

Studied photovoltaic power plants No	Installed capacity MW	Power plant location
1A	0.028	Kaunas region
2A	0.028	Akmenės region
3A	0.029	Kaunas region
4A	0.030	Molėtai region
5A	0.030	Šiauliai region
6A	0.030	Kaunas city
7A	0.030	Kaunas region
8A	0.030	Elektrėnai region
9A	0.030	Raseiniai region
10A	0.030	Telšiai region

Table 4. Main characteristics of the analysed photovoltaic power stations (0.01< >0.02 MW)

Studied photovoltaic power plants No	Installed capacity MW	Power plant location
1B	0.010	Vilkaviškis region
2B	0.012	Marijampolė region
3B	0.012	Vilnius region
4B	0.014	Kaunas city
5B	0.014	Mažeikiai region
6B	0.015	Kaunas region
7B	0.017	Palanga city
8B	0.018	Kaunas city
9B	0.018	Visaginas city
10B	0.020	Mažeikiai region

Table 5. Main characteristics of the analysed photovoltaic power stations (<0.01MW)

Studied photovoltaic power plants No	Installed capacity MW	Power plant location
1C	0.001	Rokiškis region
2C	0.002	Ukmergė region
3C	0.003	Kaunas city
4C	0.003	Kaunas city
5C	0.004	Varėna region
6C	0.005	Vilnius region
7C	0.006	Mažeikiai region
8C	0.008	Vilnius city
9C	0.010	Vilnius city
10C	0.010	Alytus region

RESULTS AND DISCUSSION OF LITHUANIAN PHOTOVOLTAIC POWER STATION ANALYSIS

The primary value of the non-renewable energy factor depends on the ratio of the amount of primary energy to renewable energy generated in a photovoltaic power station and non-renewable electrical energy consumed. If the amount of the consumed non-renewable electrical energy increases or the amount of the generated renewable electrical energy drops, the primary value of the non-renewable energy factor rises.

The methodology in EN 15603:2014 provides a single PEF value for photovoltaic power stations regardless of the different capacity they have, thus the influence of electrical capacity on the PEF value is not known. Therefore, it is reasonable to group the analysed photovoltaic power stations depending on their capacity and establish their PEF values, which then in turn could be compared to the values presented in EN 15603:2014 methodology.

Fig.3 provides *the calculated* factors f_{Pnren} of the analysed photovoltaic power stations of (0.02< >0.03) MW capacity.

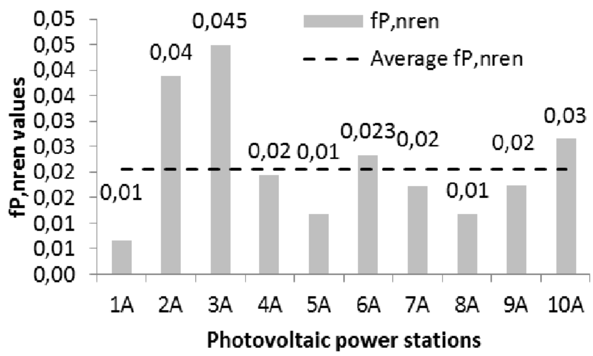

Fig.3. f_{Pnren} factors of photovoltaic power stations of (0.02< >0.03) MW capacity

Fig.4 gives f_{Pnren} factors of the analysed photovoltaic power stations of (0.01< >0.02) MW capacity.

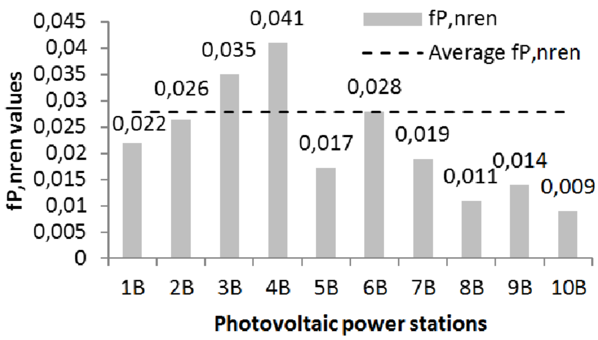

Fig.4. f_{Pnren} factors of photovoltaic power stations of (0.01< >0.02) MW capacity

Similarly, Fig.5 demonstrates f_{Pnren} factors of photovoltaic power stations of (< 0.01) MW capacity.

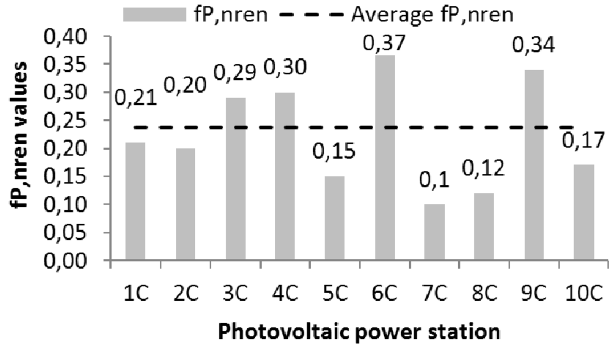

Fig.5. f_{Pnren} factors of photovoltaic power stations of (< 0.01) MW capacity

The average numerical value of f_{Pnren} factor for photovoltaic power stations of (0.02< >0.03) MW capacity equals to 0.021 (dotted line). The lowest f_{Pnren} factor – 0.01 was estimated for 1A, 5A, 8A power stations, while the highest – 0.45 for 3A station. In the case of photovoltaic power stations of (0.01< >0.02) MW capacity, the average numerical value of f_{Pnren} factor amounts to 0.028 (dotted line). Here, the lowest f_{Pnren} factor is 0.009 for 10B station and the highest – 0.041 for 4B station. Finally, the average numerical value of f_{Pnren} factor for stations of (< 0.01) MW capacity reaches 0.238 (dotted line). In this case, 7C power station received the lowest f_{Pnren} factor – 0.1, whereas the highest – 0.37 was for 6C station. Thus, the obtained results suggest that the capacity of photovoltaic power stations has influence on f_{Pnren} factor.

Analyzing produced and consumed electrical energy impact of photovoltaic fPnren index value, the following research was made, which results are presented in Fig.6 to Fig.8.

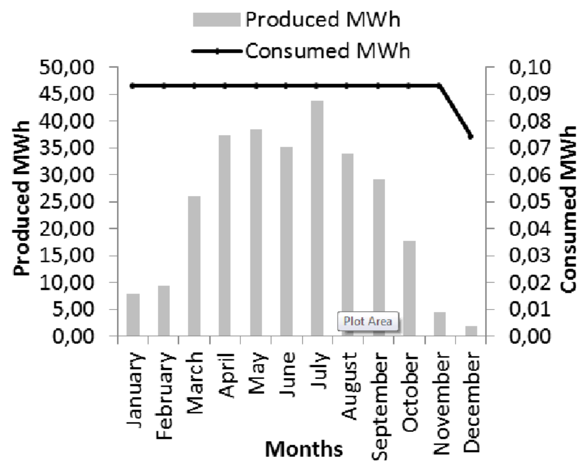

Fig.6. Average activity factors of photovoltaic power stations of (0.02< >0.03) MW capacity

Fig.6 provides average electricity production and consumption quantities by months of the analysed photovoltaic power stations of (0.02< >0.03) MW capacity.

Fig.7 provides average electricity production and consumption quantities by months of the analysed photovoltaic power stations of (0.01< >0.02) MW capacity.

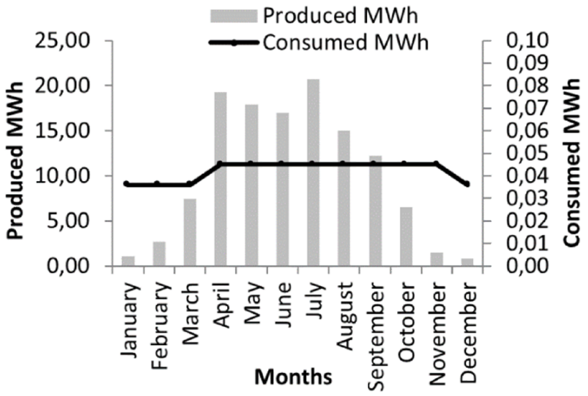

Fig.7. Average activity factors of photovoltaic power stations of (0.01< >0.02) MW capacity

Fig.8 provides average electricity production and consumption quantities by months of the analysed photovoltaic power stations of (<0.01) MW capacity.

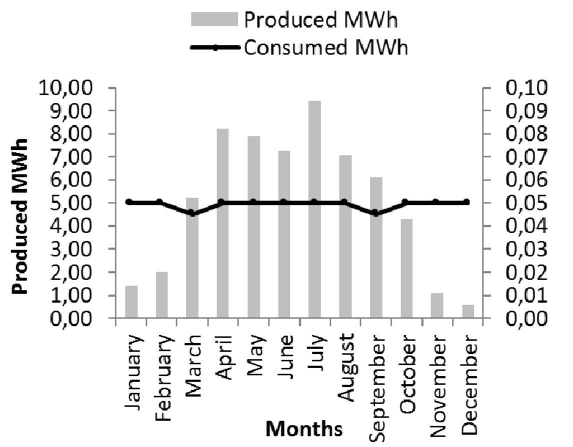

Fig.8. Average activity factors of photovoltaic power stations of (<0.01) MW capacity

The average annual of photovoltaic power stations of (0.02< >0.03) MW capacity from the total produced electricity amount equals to 0.9 %.

In the case of photovoltaic power stations of (0.01< >0.02) MW capacity, the average annual consumption from the total produced electricity amount equals to 1.24 %.

Finally, the average annual consumption value in percent for stations of (< 0.01) MW capacity reaches 2.1 %. Thus, the obtained results suggest that there is no relation between the produced and consumed electrical energy in photovoltaic power plants. Electricity consumption is almost constant each month. Fluctuations are small and can be explained by hardware factors. A comparison of photovoltaic power station capacities and f_{Pnren}, f_{Pren} and f_{Ptot} factors are presented in Table 6.

Table 6. Comparison of power station capacity and f_{Pnren}, f_{Pren} and f_{Ptot} factors

Index	Photovoltaic power stations that operate in Lithuania value in kW•h				According EN 15603:2014
	(0.02< >0.03) MW capacity	(0.01<>0.02) MW capacity	(<0.01) MW capacity	Average	
f_{Pnren}	0.021	0.028	0.238	0.038	0.7
f_{Pren}	1	1	1	1	1
f_{Ptot}	1.021	1.028	1.238	1.038	1.7

The data in Table 6 indicates that the average non-renewable primary energy factor of the Lithuanian photovoltaic power stations is 0.038, which is 20 times less (i.e. only 5,4% of the standard value from the standard) than the factor given in the standard EN 15603:2008 and currently used for the calculations. Such a difference may be explained by the lack of clarity in the conditions and criteria applied to established the mentioned standard factor. A country that relies on the standard EN 15603 has two options: to apply the factor given therein or to determine the factor by invoking the presented calculation methodology and taking into account the specificity of their own country. In the latter case, the quite rapid development of photovoltaic power station technologies that impacts the values of the factor should also be considered.

CONCLUSION

Having applied the EN 15603:2014 methodology to estimate f_{Pnren}, f_{Pren} f_{Ptot} factors, the average numerical values of 0.038, 1 and 1.038 were determined accordingly (photovoltaic power stations of 0.02< > 0.03 MW capacity – 0.021, 1 , 1.021; those of 0.01< > 0.02 MW capacity – 0.028, 1, 1.028; and <0.01 MW capacity – 0.238, 1, 1.238). These results are going to be applied for building energy certification to ensure the implementation of the goals and regulations determined by Directive 2010/31/EU.

Since the capacity of photovoltaic power stations varies, it is reasonable to classify them accordingly for the evaluation and calculation of PEF factor because the probability of errors and inaccuracies increases if only a single general numerical value is used in the calculations.

To monitor the future implementation of the goals set in the EU directives and regulations related to energy saving and the use of renewable energy sources, it is highly advisable that all the EU members use the same or similar methodology to estimate the primary energy factor of renewable and non-renewable energy sources.

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