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Energy efficiency of wind power plants, Case of Lithuania

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The use of energy from wind power plants in a building must be subdivided into renewable and non-renewable energy. Wind power efficiency increases with less auxiliary, i.e. non-renewable energy to produce the same share of electricity. The conditions and circumstances of wind power use are assessed in the calculation of the values of the primary renewable and non-renewable energy factor. The European Standard EN 15603 covers the main principles for calculating primary factors for renewable and non-renewable energy. However, the specific factor values for electricity produced in different wind power plants are determined in accordance with national conditions and requirements. In this article, in accordance with the main regulations of EN 15603, the main factor of non-renewable energy of different power-generating wind power plants was calculated using electricity generation and Lithuanian wind power data and Lithuanian climate conditions in 2007. -2014. Research has shown, that the values of non-renewable primary energy factor for wind turbines operated in Lithuania and calculated according to EN 15603 methodology is 97 % lower than the numeric indicator from the same standard used for calculations.

Keywords: Primary energy, renewable energy, wind power, auxiliary energy, energy efficiency

INTRODUCTION

Declared values of primary energy are used in energy policy making, setting energy saving goals or reporting energy efficiency in the national and international energy statistics, scenarios, environmental impact assessments, European legislation (Directive 2006/32/EB, Directive 2012/27/EU, Directive 2009/28/EC, Directive 2010/31/EU); SEC 2011) and standards (EN 15603:2014; EN 15316-4-5:2007). The demand of primary energy, required to produce one unit of secondary energy, is calculated by means of primary energy factors (PEF). They are called the conversion factors that characterize the entire totally primary energy demand in the energy supply chain to the final consumer. According to the standard EN 15603:2014 totally primary energy is divided into renewable primary energy and non-renewable primary energy.

According to the directive 2010/31/EU it is recommended to use renewable energy sources and to reduce the share of non-renewable energy in the buildings by erecting energy-efficient buildings. Different sources of renewable energy are used in buildings, e.g. sun, wind, hydro, biomass, geothermal, biogenic fraction of waste. They have different PEFs. Energy consumption is one of the areas where PEF values may be meaningful for the end user when energy source selection decisions are made with the aim to meet the requirements for a nearly zero-energy building (passive house). Literature sources mainly analyse the issues of wind turbine efficiency: wind turbine components (propellers, gear-boxes, generators, transformers) [1–3], accumulation and integration into power grids [4]. Wind parameters receive much attention in the evaluation of renewable energy sources in buildings, however, little information is given about the characteristics of wind energy source. The parameters of wind energy use are not sufficiently analysed too [5]. PEF in production of electricity from wind is calculated by using different methodologies (Tab.1).

The data given in Tab.1 shows that different methodologies render different PEF values for the evaluation of wind energy, therefore it is difficult to compare the values of primary energy or primary energy factors. The primary energy factor for the same source of renewable energy may differ significantly depending on the type of primary energy and applied calculation method [11].

The data are given in Tab.1 also shows that PEF values depend on the energy production and supply chain. Energy production and supply chains differ by countries and subsequently, PEF values are also different. Unfortunately, only a few countries publicly announce this data (Tab.2).

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Table 1. Parameters of different methodologies for the evaluation of primary energy produced from the wind

$MJ_{primary\ energy}$/ $MJ_{electricity}$	Description of primary energy evaluation	PEF	PEF value	Literature source
1. Zero equivalent method	Does not evaluate electrical and thermal energy production from renewable energy sources	Total primary energy	0.000	[6]
2. 2a Direct equivalent	Evaluates electrical and thermal energy production from non-fossil renewable energy and nuclear energy sources	Total primary energy	1.000	[7]
2b Amount of physical energy	Evaluates the primary form of energy obtained in generation process	Total primary energy	1.000	[8]
2c Alternate	Evaluates the primary form of energy that is included into the statistical energy balance prior to conversion to the secondary or tertiary form of energy	Total primary energy	2.500	[9]
3. Only non-renewable primary energy	-	Non-renewable primary energy	0.032	[10]
4. 4a Effectiveness of technical conversion	Evaluates the entire energy production chain by separating the renewable and non-renewable energy	Non-renewable primary energy Renewable primary energy	0.032 2.500	[9,10]
4b Amount of physical energy	Evaluates the primary form of energy produced in the generation process	Non-renewable primary energy Renewable primary energy	0.032 1.000	[8,10]

The data are given in Tab.1 also shows that PEF values depend on the energy production and supply chain. Energy production and supply chains differ by countries and subsequently, PEF values are also different. Unfortunately, only a few countries publicly announce this data (Tab.2). National standards and norms governing construction work in many EU member states do not include these documents or do not further specify the renewable energy values; therefore it is not clear whether these values are valid for defining wind energy or are merely politically grounded values not meant for technical or scientific applications.

Table 2. Wind electricity energy values used in construction work standards of EU countries

Country	Primary energy factor	Total primary energy factor	Non-renewable primary energy factor	Renewable primary energy factor	Literature source
Austria	-	-	-	-	[12]
Belgium	-	-	-	-	[13]
Cyprus	-	-	-	-	[14]
Czech-Republic	-	-	-	-	[15]
Denmark	-	-	-	-	[16]
Estonia	-	-	-	-	[17]
Finland	-	-	-	-	[18]
France	1.000	-	-	-	[19]
Germany(1)	-	-	-	-	[20]
Germany(2)	-	1.030	0.030	1.000	[21]
Greece	-	-	-	-	[22]
Hungary	0.000	-	-	-	[23]
Ireland	-	-	-	-	[24]
Italy	-	1.000	0.000	1.000	[25]
Netherlands	-	-	-	-	[26]
Poland	-	1.000	0.000	1.000	[27]
Slovakia	-	-	-	-	[28]
Slovenia	-	-	-	-	[29]
Spain -	-	-	-	-	[30]
Sweden	-	0.050	-	-	[31]
United Kingdom	1.000	-	-	-	[32]

Note: - not mentioned.

According to the data presented in Tab.2, presumably, the energy consumed by the wind turbines is not included in the total energy produced from the renewable source, i.e. wind energy. Power to the internal system of wind turbines is supplied from batteries/condensers or from the electrical grid. Various equipment of wind turbines use electric power and its energy consumption may reach up to 0.1% of the total produced energy, in other cases up to 10-20% of the rated power of the wind turbines [33].

MATERIALS AND METHODS

Primary energy calculation methodology

Energy efficiency of a building is calculated as the balance of the used and produced energy. The main aim of constructing energy efficient buildings is to increase the share of renewable energy and decrease the demand for primary energy. PEF of electrical energy produced on-site or nearby or renewable energy supplied from the electrical grid has a direct influence on the calculation of the total primary energy factor. There are two possibilities: to increase the share of electricity produced from renewable energy sources in electrical grids (Baake found that in 2020 PEF in European electricity grids will drop to 2.500 compared to the current PEF, in 2030 it will drop to 1.650 and in 2050 it will drop to 1.200 [34]) and to use electricity produced on-site or nearby from renewable sources, including wind turbines [35].

In almost all sources of renewable energy part of the energy is non-renewable, therefore the requirement for nearly zero-energy buildings in the Directive 2010/31/EU is to use more than half of the energy produced from renewable sources. It may be related only to the amounts of renewable and non-renewable primary energy, consumed by the building, but not with the energy produced from renewable or non-renewable sources. Therefore, it is not correct to use the methodologies presented in Tab.1 for the calculation of PEF in photovoltaic/wind power systems. In this regard, PEF of wind turbines shall be calculated using the methodology described in EN 15603:2014.

The total primary energy demand of the building is calculated (Eq.1):

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

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

The total primary energy may be calculated by equation 2:

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

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

Methodology for the evaluation of electrical energy production rom wind energy source

Kot method [36] was chosen for the evaluation of electrical energy produced by a wind turbine, taking into consideration the effect of factors on the efficiency. According to this method, electrical energy produced by a wind turbine is calculated from Eq.3:

$$P_e = \frac{1}{2} \pi R^2 \rho V^3 C_P \eta_g \eta_c \quad (3)$$

where:
ρ is air density, kg/m^3;
R is turbine rotor radius, m;
V is wind speed, m/s;
C_p is turbine power factor;
η_g is generator efficiency;
η_c is inverter efficiency.

Cp factor is calculated from Eq.4:

$$C_P = \frac{P_M}{P_W} \quad (4)$$

where:
P_M is mechanical power, W;
P_W is wind power, W.

In theory, Cp value may not exceed the limit expressed by Betz law, Eq.5. In typical turbines this value varies ~0,4 [37]:

$$C_{P\max} = \frac{16}{27} \approx 0{,}593 \quad (5)$$

Climate data and investigated location of case study

Wind turbines across the entire territory of Lithuania were tested in order to determine the influence of electrical energy cost on the value of wind PEF. Lithuania is situated in the Middle Latitudes. According to Alisov’s climate classification, Lithuania is in the zone of a temperate climate and the sub-region of the Atlantic-European continental zone. Only the climate of the Baltic Sea coast is close to the western European climate and can be assigned to a separate South Baltic climate sub-region. South-western and western winds prevail in the major part of Lithuanian territory, with western and south-eastern winds on the coastal zone. The average wind speed at 10-meter height ranges from 4 m/s to 6.5 m/s. The highest wind speed is in the coastal zone, where it reaches 5 – 6.5 m/s and decreases moving away from the coast eastwards [38].

The highest wind speeds in the center of Lithuania are observed in November – January and in October – December in the coastal zone; the lowest wind speeds are in June – July.

Table 3. Basic characteristics of the studied wind turbine

No of tested Wind turbines	Total installed power capacity	Turbine capacity	No of turbine	Turbine type	No of blades	Blade length	Tower height	Turbine location
	MW	MW				m	m	
1A	39.100	2.000	20	horizontal	3	41	85	Šilutė district
2A	34.000	2.000	17	horizontal	3	41	97	Kretinga district
3A	21.400	2.000	10	horizontal	3	41	85	Šilutė district
4A	20.000	2.000	10	horizontal	3	41	85	Tauragė district
5A	16.000	2.750-3.000	6	horizontal	3	41	85	Kretinga district
6A	12.000	2.000	6	horizontal	3	41	78	Šilutė district
1B	0.800	0.800	1	horizontal	3	21	45	Kretinga district
2B	0.800	0.800	1	horizontal	3	21	45	Mažeikiai district
3B	0.600	0.600	1	horizontal	3	20	42	Mažeikiai district
4B	0.250	0.250	1	horizontal	3	15	50	Jurbarkas district
5B	0.250	0.250	1	horizontal	3	15	50	Mažeikiai district
6B	0.250	0.250	1	horizontal	3	15	45	Kaišiadoriai district
7B	0.250	0.250	1	horizontal	3	15	55	Kalvarija district
8B	0.225	0.225	1	horizontal	3	14	50	Tauragė district

In June and July, Lithuanian wind turbines produce about two times less energy compared to December and January. In the summertime, the highest wind speed is between midnight and 6 AM. In the morning it increases until noon and reaches a peak at about 2 PM. The peak speeds last until 6 PM and afterward start dropping to the minimum values that are reached about midnight. In the wintertime, the changes of wind speed are less due to lower fluctuation of air mass temperatures influenced by smaller amounts of solar radiation energy. Wind energy resources in Lithuania were evaluated by measuring data from meteorological stations as well as measurements obtained from various research centers in the regions. The western part of the country is the most suitable for wind turbines because of prevailing wind speeds and more developed transmission networks [39].

Depending on the prevailing wind speeds the efficiency of new wind turbines in Lithuania is 24-25 %, whereas the efficiency of old wind turbines is only 10-18 % [39]. The total capacity of wind turbines operating in Lithuania is 281 MW (the mainland potential is ~1500 MW, and the offshore potential is ~1000 MW). 111 single or group wind turbines are connected to the Lithuanian power grid: 10 small turbines (from 2 to 55 kW) and 101 big turbines (from 160 to 39100 kW) [40].

Research object

Data (Tab. 3) for research (for the period 2007-2014) were collected from 100 wind turbines and 11 wind farms operating in Lithuania. The data were collected by interviewing wind turbine owners/operators and by analyzing the reports of electricity transmission system operators [40].

The analysis of collected data revealed that the majority of wind turbine operators do not collect and systemize any data, do not have accounting instruments or are connected to other electrical energy users. The report of the Lithuanian electricity transmission system operator contains only the amounts of electricity transmitted from all wind turbines to the power grid for certain periods. Therefore, 6 wind farms and 8 wind turbines were selected for the study. The analysis of their results is presented in the following chapter.

RESULTS

The value of the primary non-renewable energy factor depends on the relationship between the amount of non-renewable primary energy and the balance of renewable energy produced by the wind turbine and consumed non-renewable electrical energy (Eq.2). The value of non-renewable energy source factor increases with the increase of consumed non-renewable electrical energy or the decrease of renewable electrical energy produced by the wind turbine. The methodology provided in EN 15603:2014 gives only one PEF value for wind turbines irrespective of their capacity. The influence of wind turbine capacity on the PEF value is unknown. Therefore, it would be useful to classify wind turbines which were studied into groups of different capacity, to determine their PEFs, and afterward to compare the obtained values with the values provided in EN 15603:2014.

The calculated f_{Pnren} factors of the analyzed (>1) MW wind turbines/farms are presented in Fig.1.

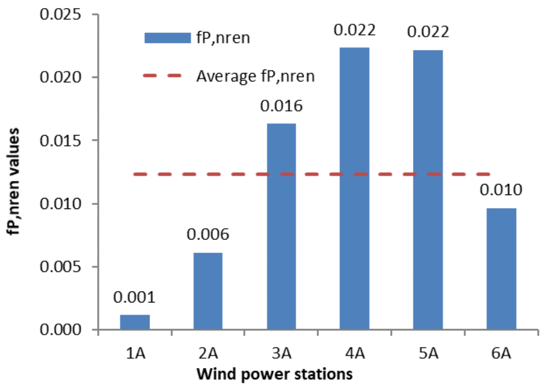

Fig.1. Relationship between f_{Pnren} and wind power in (> 1) MW wind turbines

The calculated f_{Pnren} factors of the analyzed (<1) MW wind turbines/farms are presented in Fig.2.

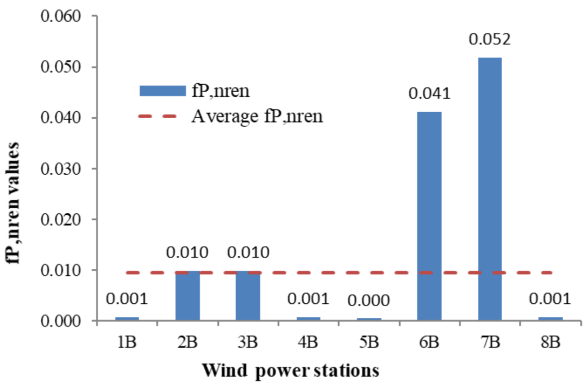

Fig.2. Relationship between f_{Pnren} and wind power in (<1) MW wind turbines f_{Pnren}.

From the data presented in Fig.2, it may be concluded that the average numeric indicator of a f_{Pnren} factor in wind turbines/farms of (>1) MW capacity is 0.012 kW·h (the dotted line). The lowest f_{Pnren} factor value 0.001 is in wind turbine 1A, the highest factor value 0.022 kW·h is in wind turbines 4A and 5A.

The average numeric indicator of the f_{Pnren} factor in wind turbines/farms of (>1) MW capacity illustrated in Fig.2 is 0.009 (the dotted line). Wind turbines 1B, 4B, 5B and 8B have the lowest f_{Pnren} factor value 0.001, and wind turbine 7B has the highest factor value 0.052.

The obtained results lead to the conclusion that f_{Pnren} factor value is influenced by the capacity of wind turbines. A trend is observed that in wind turbines of (>1) MW capacity this indicator decreases with a higher installed power capacity of wind turbines.

Another test was done by taking into consideration the influence of the average wind speed and the balance of produced and consumed electrical power on f_{Pnren} value. The test results are presented in Figs. (3 – 10).

Fig.3 illustrates the average distribution of produced and consumed electric power in (>1) MW wind turbines/farms by months.

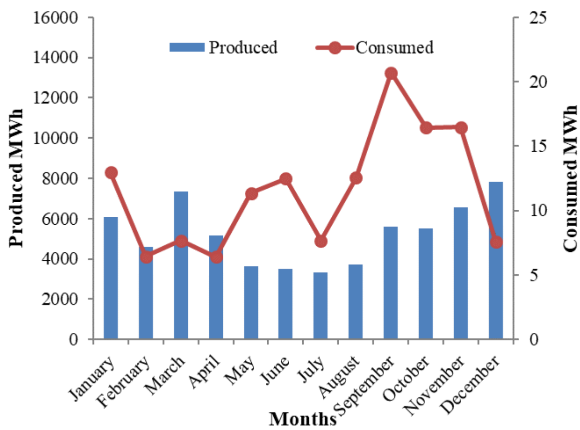

Fig.3. Average performance of (> 1) MW capacity wind turbines/farms

Fig.4 illustrates the average distribution of produced and consumed electric power in (<1) MW wind turbines/farms by months.

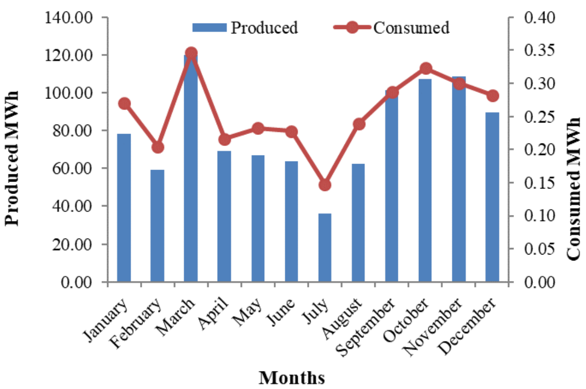

Fig.4. Average performance of (< 1) MW capacity wind turbines/farms

The results presented in Fig.3 reveal the inverse relationship between the produced and consumed electric power in (>1) MW capacity wind turbines/farms. According to [33], there are constant turbine-power demand in the production of wind energy. The annual average of turbine-power consumption is up to 0.22 % of the total electric energy production. The consumed amount of electric energy is not constant and changes dynamically within seasons; most often it is higher in the warm season and lower in the cold season, i.e. it may reach 0.10 % in winter and 0.36 % in summer.

Fig.4 reveals a direct relationship between the produced and consumed electric power in (<1) MW capacity wind turbines/farms. The average annual turbine-power consumption is up to 0.32 % of the total produced electric energy. The consumed amount of electric energy is not constant and changes dynamically by seasons, most often it is higher in the warm season and lower in the cold season, i.e. it may reach 0.28 % in winter and 0.41 % in summer.

The obtained results revealed the relationship between the produced and consumed electric energy in wind turbines. The relationship is inverse in high-capacity wind turbines and direct in lower capacity wind turbines.

Figs. (5, 6, 7) illustrates the relationship between analyzed (<1) MW capacity wind turbines/farms power productions, consumption and wind speed.

Comparing data presented in Fig. (5, 7) lead to the conclusions that the amounts of energy produced by (< 1) MW capacity wind turbines/farms increase with higher wind speeds.

Fig.6 compare to Fig.7 reveals that the relationship between the energy consumed by (<1) MW capacity wind turbines/farms and wind speed is difficult to define, because, in 2B, 3B, 6B and 7B wind turbines energy consumption and wind speed is closer to linear, i.e. wind turbines consume more energy at higher wind speeds. Meanwhile, in the rest wind turbines (1B, 4B, 5B and 8B) energy consumption by all analyzed period was stable and it seems wind speed has no influence for energy consumption.

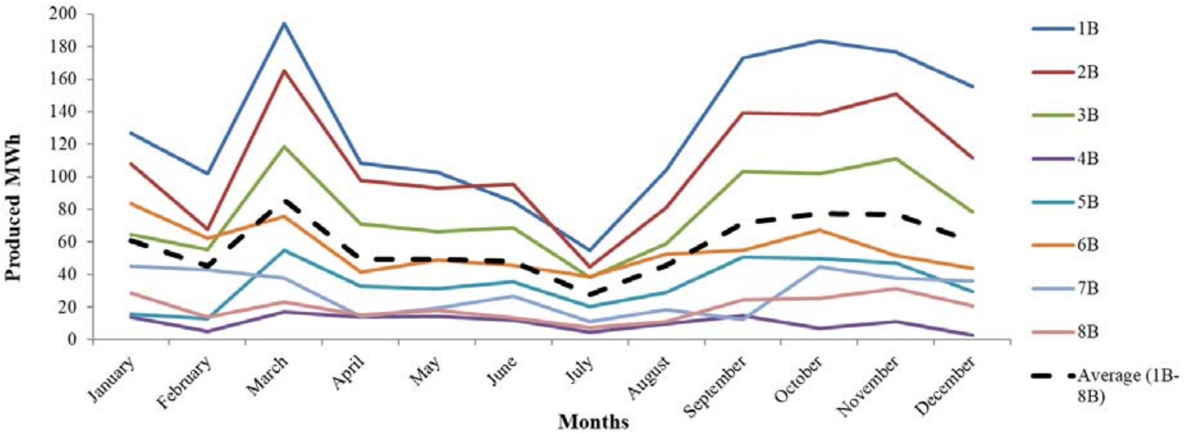

Fig.5 Electricity production performance of (<1) MW capacity wind turbines/farms

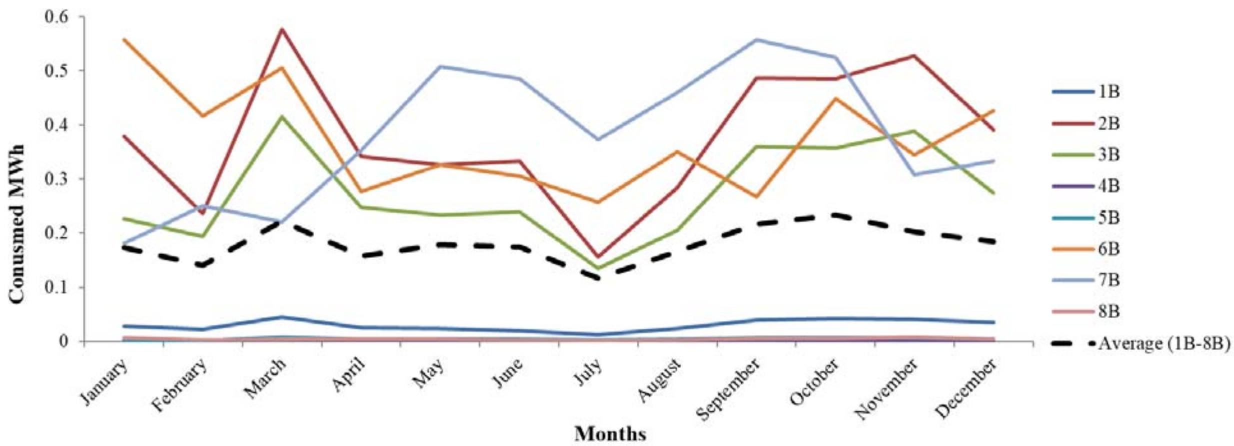

Fig.6. Electricity consumption performance of (<1) MW capacity wind turbines/farms

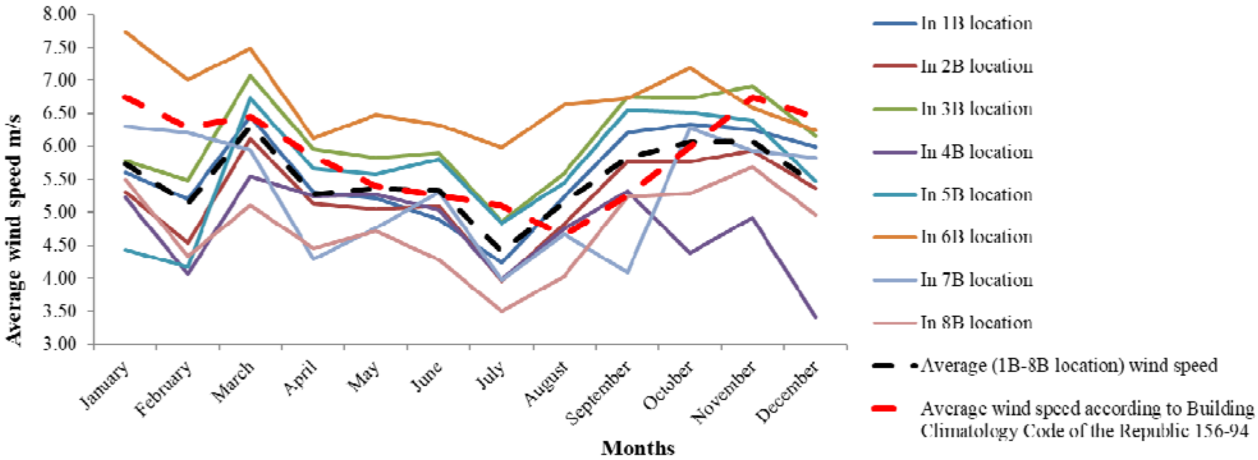

Fig.7. Wind speed in (<1) MW capacity wind turbines/farms

The resulting fluctuations for energy production and consumption may be explained by the efficiency of the wind turbine [1-3, 33] as well actual climate conditions of analysed wind turbines/farms location.

Evaluating according to Building Climatology Building Code of the Republic 156-94 (the dotted red line) in Fig.6 is not enough due to actual wind speed in real time.

Figs. (8, 9, 10) illustrates the relationship between analysed (>1) MW capacity wind turbines/farms power productions, consumption and wind speed.

Comparing the data presented in Figs. (8, 10) which shows that with higher wind speedsthe amounts of energy produced by (> 1) MW capacity wind turbines/farms are tend to increase.

Fig.9 compared to Fig.10 reveals that the relationship between the energy consumed by (>1) MW capacity wind turbines/farms and wind speed is closer to linear, i.e. wind turbines consume more energy at higher wind speeds.

The resulting fluctuations for energy production and consumption may be explained by wind turbine efficiency [1-3, 33] as well as actual climate conditions of analyzed wind turbines/farms location.

Evaluating according to Building Climatology Building Code of the Republic 156-94 (the dotted red line) in Fig.10 is not enough due to actual wind speed in real time.

DISCUSSION

In order to meet the requirements, set forth in the Directive 2010/31/EU, the primary energy factor value for wind turbines is calculated following the methodology described in EN 15603:2014. However, studies of wind turbines operated in Lithuania have shown that f_{Pnren} and f_{Ptot} values calculated according to the aforementioned methodology are imprecise (Tab.4).

Table 4. Comparison of wind turbine capacities and f_{Pnren}, f_{Pren}, f_{Ptot} values

Indicators	Values of wind turbines operated in Lithuania, kWh: (>1) MW capacity	(<1) MW capacity	Weighted average	Values according to EN 15603:2008
f_{Pnren}	0.012	0.009	0.010	0.300
f_{Pren}	1.000	1.000	1.000	1.000
f_{Ptot}	1.012	1.009	1.010	1.300

Data presented in the table above shows that the values of non-renewable primary energy factors in (> 1) MW and (< 1) MW capacity wind turbines operated in Lithuania are similar (the average f_{Pnren} = 0.010).When these values are compared to the values given in EN 15603:2014, the value of non-renewable primary factor for wind turbines operated in Lithuania is 97% lower than the value given in the standard. EN 15603:2014 does not give any reference conditions and criteria used to determine the value of non-renewable primary energy factor.

The calculated total primary energy $f_{P,tot}$ of a wind turbine is also imprecise. The test results of wind turbines operated in Lithuania are presented in Tab.4 which show that this imprecision is about 22 % of the rated capacity of a wind turbine.

The test results revealed the importance of declaring precise primary energy values in energy policy making, in defining energy saving goals or energy consumption efficiency in international and national energy statistics, scenarios, environmental impact assessments, directives and standards.

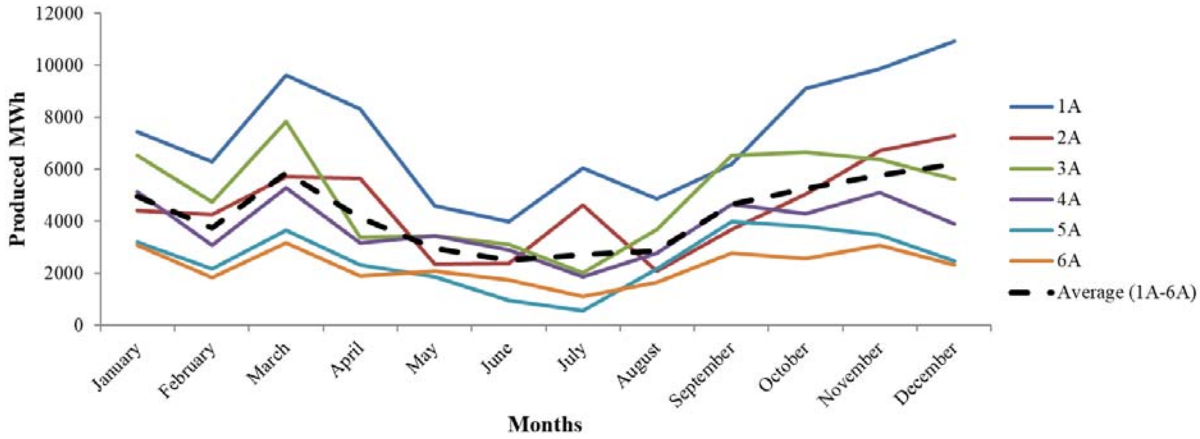

Fig.8. Electricity production performance of (>1) MW capacity wind turbines/farms

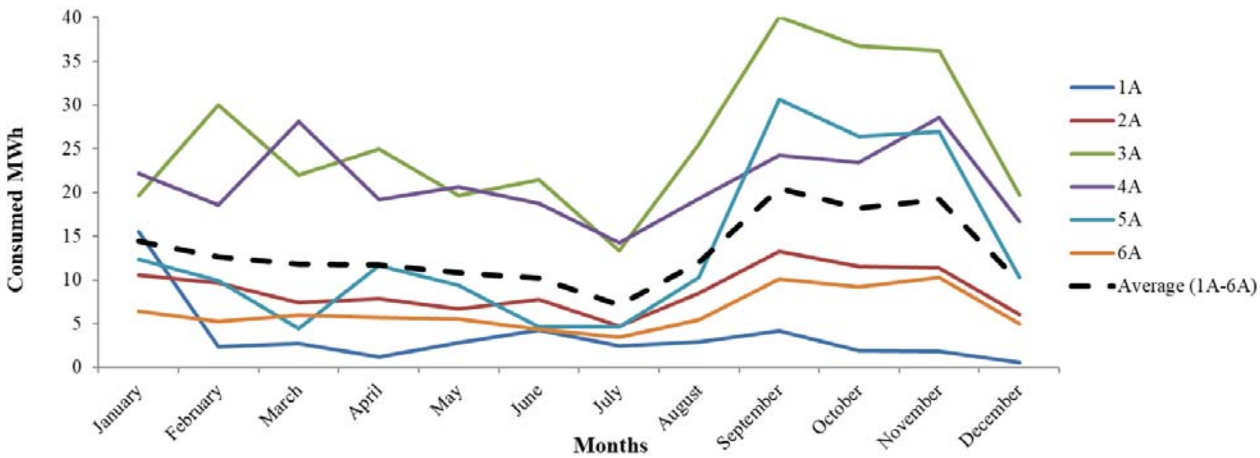

Fig.9. Electricity consumption performance of (>1) MW capacity wind turbines/farms

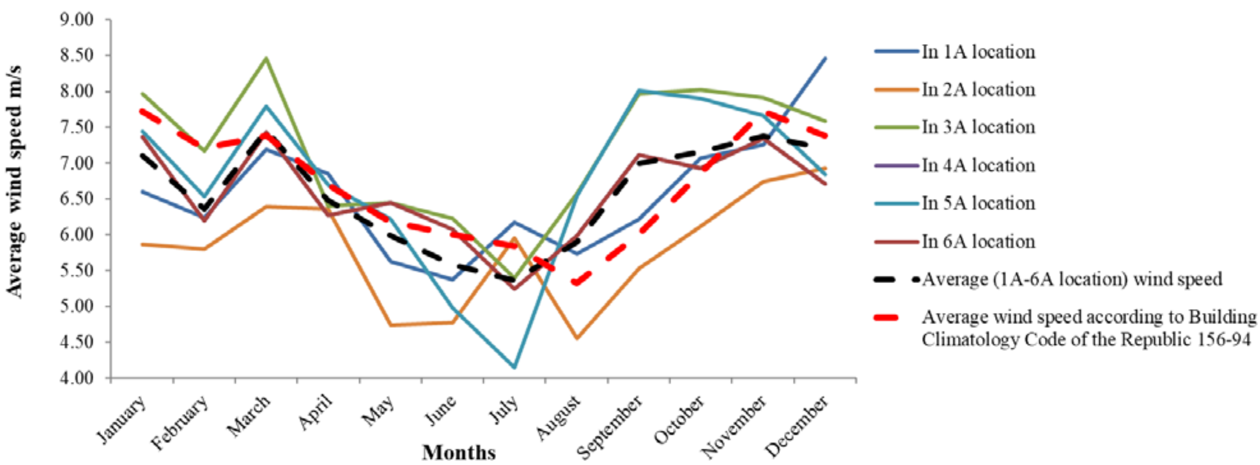

Fig.10. Wind speed in (>1) MW capacity wind turbines/farms

Every European Union member state should define the methodology for the calculation of primary energy in wind turbines as well as the statistical parameters of wind turbines and climate (wind speed, wind turbine capacity, conversion efficiency, turbine-power consumption etc.) for the calculation of PEF value. The progress of wind turbine technologies requires regular recalculation of these values.

The results of this study were used in drafting the national Technical Regulation for Construction Works STR 2.01.09:2012 Certification of Energy Performance of Buildings, which shall ensure the implementation of the provisions and goals of Directive 2010/31/EU in Lithuania.

CONCLUSIONS

The values of non-renewable primary energy factor f_{Pnren} for wind turbines operated in Lithuania and calculated according to EN 15603:2014 methodology is 97 % lower than the numeric indicator from the same standard used for calculations.

Calculations of non-renewable energy factor f_{Pnren} revealed that wind turbine capacity has no effect on the value of non-renewable energy factor f_{Pnren}. The value of non-renewable primary energy factor f_{Pnren} is 0.010 (kW·h) for (> 1) MW and (< 1) MW capacity wind turbines operated in Lithuania.

The results of the study revealed that in (>1) MW capacity wind turbines the turbine-power consumption increases with lower wind speeds, whereas in (<1) MW capacity wind turbines it is on the contrary, i.e. the turbine-power consumption increases with higher wind speeds.

In order to achieve the goals set forth in EU energy efficiency and renewable energy directives and regulations all EU member states should use the same or very similar methodology for the calculation of primary energy factor of renewable and non-renewable energy sources.

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