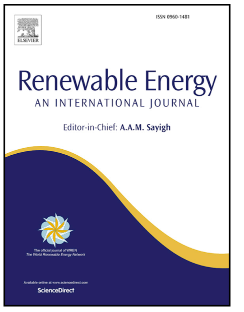

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THERMO-ECOLOGICAL COST OF ELECTRICITY FROM RENEWABLE ENERGY SOURCES

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Abstract

Nowadays, the society faces the challenge of continuous supply of electricity. Energy from two different sources of origin such as renewable and non-renewable is used to meet the needs of modern humankind. The paper presents the findings concerning the thermo-ecological cost assessment of renewable energy sources defining their total impact on the environment. Biogas, wind and photovoltaic power plants were evaluated to present the results of cumulative environmental impact based on the thermo-ecological cost methodology. Polish law regulations and the prediction of the future energy mix structure are described to emphasize the importance of selected technologies. The measurements data of real renewable energy units in Poland and the characteristics of components were used to calculate thermo-ecological cost of electricity originating from renewable sources. Moreover, different phases of the production chain are considered to present results in total life cycle of the respective technologies. In the calculations, continuous availability of conventional power plants for stabilizing the current electricity needs is taken into account. Finally, the results of this study prove that biogas power plants cause lower environmental impact than wind and photovoltaic technologies.

Keywords: renewable energy resources; thermo-ecological cost; biogas; wind power plant; combined heat and power plant; photovoltaic energy

1 Introduction

In this section, the statistical, economic and political background is presented for renewable and non-renewable resources. It is provided to show the importance of application of scientific methodology in the policy regarding renewable energy sources (RES). Continuous aspirations for further global economic growth accelerate the consumption of limited stock of non-renewable resources. Their lifetime defined as ratio of proven reserves of resources to their production, further referred to as R/P[1] ratio, in the case of fossil fuels is now significantly limited [1]: natural gas – 54.1 years, oil – 52.5 years in relation to total word resources. In the case of coal, during the last decade an extremely rapid decrease of R/P ratio has been observed: in the year 2000 the ratio was estimated at the level of 220 years; whereas after 14 years – in 2014, it was estimated as only at the level of 110 years [1]. These numbers are not precise as they depend on many changing factors, yet it is clear that sooner or later the resources of these fuels will deplete, and we should promote sustainable development to minimalize the risks tied to that depletion.

Electricity is one of the most important energy carriers for many manufacturing processes, for this reason power sector plays a significant role in consumption of resources. Moreover, electricity generation in fossil fuel based power plants is strongly connected with rejection of harmful wastes as well as greenhouse gases to the natural environment. Consumption of hard coal and lignite dominates in the fuel structure of Polish electricity generation. In the years 2006 – 2014, the share of chemical energy of hard coal was equal to 50 – 58%, while lignite consumption was equal to 36 – 40%. Fig. 1 presents the average (gross and net) energy efficiency of electricity generation in Polish fossil fuel based power plants within the years 2006 – 2014. Efficiency is defined as generated electric power (either gross or net) divided by the rate of chemical energy of fuel used in the power plant. Gross power is the output of electric generator. Net power is obtained by subtracting the power for own needs of the power plant.

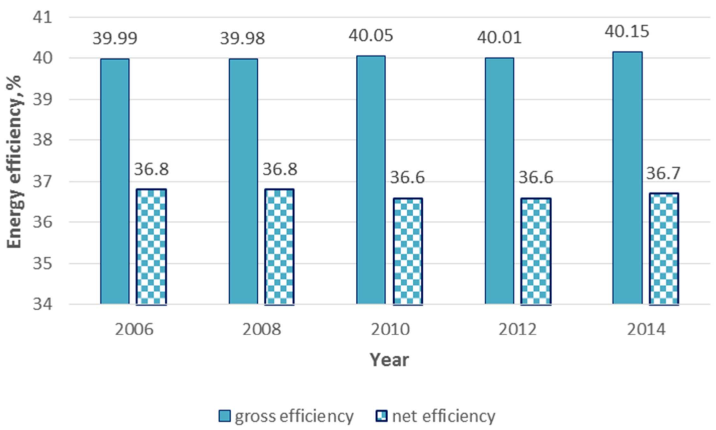

Figure 1: Energy efficiency of electricity generation by conventional power plants [2]

The improvement of electricity generation efficiency and the increase of RES in energy mix are crucial issues from the sustainability point of view. According to the Polish Energy Policy [3], a significant increase of renewable sources with simultaneous decrease of coal consumption are planned for electricity generation (Fig. 2). Energy mix based on both non-renewable and renewable primary energy resources requires consequent evaluation at the level of extraction of natural resources. The analysis should include interactions of non-renewable and renewable power plants within the national energy system. These interactions result mainly from the existing regulations, as well as from random accessibility of primary renewable energy.

In Polish conditions, due to the policy [4], renewable electricity has ensured the priority in the national energy market. With such regulations, random generation of electricity based on RES leads to changing operation of fossil fuel power plants, which finally leads to work with decreased efficiency. Concluding, random operation of RES induce specific losses in utility non-renewable power plants fed with fossil fuels. This effect has to be included in the evaluation of RES, however, very often it is

[1] Reserves-to-production (R/P) ratio – If the reserves remaining at the end of any year are divided by the production in that year, the result is the length of time that those remaining reserves would last if production were to continue at that rate.

neglected or ignored. These issues have been addressed in some international studies, in most cases with focus on the emission of carbon dioxide [5-10].

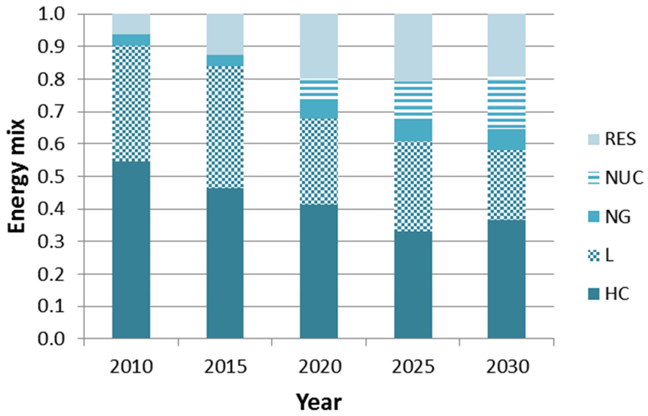

Figure 2: Structure of Polish energy mix according to Polish energy policy (based on [4])

(HC – hard coal; L – lignite, NG – natural gas; NUC – nuclear energy, RES – renewable energy sources)

The influence of any production technology, including power technologies, on the depletion of resources has to be evaluated using the methods that let to: 1) take into account the whole cycle, 2) evaluate the resources quality by one common measure, as well as 3) take into account the influence on the depletion resulting from generation of wastes. Such approach is possible due to the application of the Thermo-Ecology methodology [11]. The theory of the Thermo-Ecological Cost (TEC) has been presented e.g. in [12-16]. The evaluation by means of TEC, in other words the investigation of the technology's influence on the global non-renewable resources consumption is especially important in the case of renewable power technologies such as biomass, biogas, wind or solar energy. The comparison of these processes e.g. with non-renewable power plants is only possible at the level of primary resources. It is also proposed in simplified way e.g. by legal regulations devoted to RES supporting system [17] or to energy consumption in buildings [18]. To evaluate the influence on primary resources consumption the following approach is proposed:

$$E_p = w_i E_f \qquad (1)$$

where E_p and E_f denote consumption of primary and final energy and w_i denotes the coefficient of primary energy consumption necessary for final energy generation. Very similar coefficient c_i was used in proposal of Polish regulations [17]. Both coefficients for different power technologies are collected from the literature [18,19] and presented in Table 1. The coefficients c_i and w_i presented in Table 1 are not scientifically determined ecological costs of a given process. These values are just simple conversion factors used in current policy regulations to convert final energy to primary energy extracted from nature. One of the goals of this article is to propose methods to evaluate these factors based on solid scientific ground.

Table 1 Coefficients for RES

System	**c_i [17]**	**w_i [18]**	**w_i [19]**
Renewable Natural Resources			
PV	2.85	0.00	0.70
Biogas	1.40	0.50	N/A

Hydro	1.90	N/A	N/A
Wind	0.90	0.00	N/A
Biomass	N/A	0.20	0.20
Nonrenewable Natural Resource			
Oil	-	1.10	1.10
Natural gas	-	1.10	1.10
LPG	-	1.10	1.10
Hard coal	-	1.10	1.10
Lignite	-	1.10	1.10

These numbers are presented here to discuss the fact, that they are chosen arbitrarily and are lacking rigor in their definition. The lack of consequence seems to be evident. According to [18,19], in the case of photovoltaics (PV) once $w_{PV} = 0.0$ and 3 years later $w_{PV} = 0.70$. It seems also not justified that for all non-renewable technologies based on primary energy the coefficient is at the level of 1.1, while these fuels are extracted and processed with very different burden on the environment [20,21].

One of the proposals of Polish regulations towards RES support introduced "coefficients of support". The level of support in this proposal was directly proportional to the c_i coefficient. It is difficult to explain in physical ways why PV ($c_i = 2.85$) would be almost three times better than wind ($c_i = 0.9$) or about 2 times better than biogas ($c_i = 1.40$).

It can be concluded that the evaluation of RES as well as comparison with non-RES requires comprehensive, objective and based on physical laws methods. Such approach is possible thanks to the introduction of TEC indices for their comparison. Taking into account the random operation of RES, the classic TEC approach has to be supplemented with an additional part due to the compensation and induced losses.

2 Thermo-Ecological Cost (TEC) – fundamentals

The physical, as well as ecological cost of any product should take into account the total consumption of natural resources at the level of their extraction from nature. Moreover, it has to be calculated using the common measure of resources quality. Such cost can be expressed by the TEC index that is mainly affected by the consumption of exergy of non-renewable resources extracted directly from the nature, such as fuels, mineral ores, nuclear ores or fresh water [11-13].

TEC has been defined by Szargut [11,12] as: the cumulative consumption of non-renewable exergy connected with the fabrication of a particular product with additional inclusion of the consumption resulting from the necessity of compensating the environmental losses caused by the rejection of harmful waste substances to the environment.

Consumption of resources taken into account within TEC analyzes first of all appears in the production processes directly connected with the extraction of substances from the natural deposits, e.g. in a coal mine or a metal ores mine. However, even though not all branches of economy are directly connected to the nature, due to existing interconnections between production processes and systems each product is directly or indirectly linked to the natural resources. TEC is also generated by the consumption of semi-finished products exchanged between the branches of the system.

In some branches, a by-production can appear, which entails that the by-products replace main products in other branches, and therefore the value of TEC of a considered main product is reduced. TEC of useful by-products should be determined by means of avoided consumption of non-renewable exergy [14]. The balance of TEC includes also an additional consumption of resources necessary to compensate or to avoid the losses caused by the rejection of harmful wastes to the natural environment. TEC of pollution is calculated as the amount of exergy needed to prevent these discards from being released to the environment (i.e. use of exergy in abatement installations), or the amount of exergy needed to overcome the negative effects caused by the discards if they are released [22,23]. The balance of TEC is schematically presented in Fig. 3.

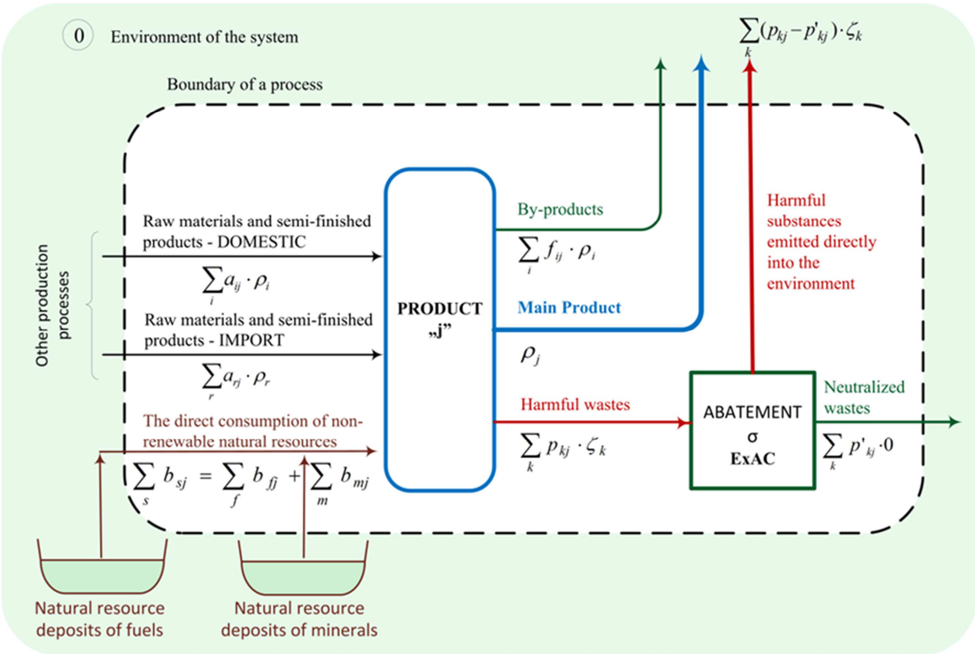

Figure 3: Idea of TEC balance equation

The balance of TEC of *j*-th production branch includes also an additional consumption of resources connected with waste rejection to the environment p_{kj}. This additional consumption is connected with maintenance and operation of abatement installations, as well as with the necessity of compensation of other losses in the environment. Under these assumptions, the index of operational TEC ρ_j can be determined by solving the set of thermo-ecological balance equations, which general form is presented by Eq. (2) [11-15]:

$$\rho_j = \sum_s b_{sj} + \sum_k p_{kj}\zeta_k - \sum_i (f_{ij} - a_{ij})\rho_i \tag{2}$$

where:

a_{ij} coefficient of consumption of *i*-th material per unit of *j*-th main product, e.g. in kg/kg or kg/MJ,
f_{ij} coefficient of by-production of *i*-th product per unit of *j*-th main product, e.g. in kg/kg or kg/MJ,
b_{sj} exergy of *s*-th non-renewable natural resource immediately consumed in the process under consideration per unit of *j*-th product, MJ/kg,
ρ_i specific thermo-ecological cost of *i*-th product, e.g. in MJ/kg,
p_{kj} amount of *k*-th harmful substance from *j*-th process, kg,
ζ_k thermo-ecological cost of *k*-th harmful substance, MJ/kg.

Besides the operational part, in the case of power technologies also other phases of the whole life cycle can be important. The general form of the equation to calculate the thermo-ecological cost in the whole life cycle has been formulated by Szargut and presented in [11]. This approach has been applied for example to investigate the exergetic life cycle of solar collector system in the work of Szargut and Stanek [15]. This function, expressing the yearly thermo-ecological cost has the following form:

$$\rho_j^{LCA} = \theta_n \left(\sum_i \dot{G}_i \rho_i + \sum_k \dot{P}_k \zeta_k - \sum_u \dot{G}_u \, \rho_j s_{ju} \right) + \frac{1}{\tau_j} \left(\sum_l G_l \rho_l \, (1 - u_l) + \sum_r G_r \rho_r \right) \qquad (3)$$

where:

θ_n average annual time of exploitation of *j*-th considered machine, device, installation or building, in other words annual operation time with nominal capacity, h/year,

τ_j nominal lifetime of *j*-th machine, device, installation or building, years,

$\dot{G}_i$ nominal stream of *i*-th material used in *j*-th production process, kg/h,

$\dot{G}_u$ nominal stream of *u*-th by-product manufactured simultaneously with *j*-th product within the production process, kg/h,s_{ju} replacement index of by-product *u* by main product *j*,

$\dot{P}_k$ nominal stream of *k*-th waste product released to the environment from *j*-th production process, kg/h,

G_l amount of *l*-th material used for the construction of *j*-th considered machine, device, installation or building, kg,

G_r amount of *r*-th material used for the maintenance of *j*-th considered machine, device, installation or building, kg,

u_l expected recovery rates of *l*-th material after the end of operation phase of *j*-th considered machine, device, installation or building, kg/kg.

The next part of this article presents some results of TEC calculations for fuels, electricity generation, as well as TEC evaluation of RES with the inclusion of whole life cycle.

3 Thermo-ecological cost of non-renewable fuels

Example values of TEC for non-renewable primary energy of fuels are presented in Table 2.

Table 2: TEC of energy carriers – operational part (Eq. 2) [20]

Energy carrier	**Lower Heating Value**	**Chemical exergy**	**TEC in relation to unit of the energy carrier**	**TEC in relation to LHV**	**TEC in relation to b_{ch}**
	LHV	b_{ch}	ρ	γ	R
	MJ/unit	**MJ*/unit**	**MJ*/unit**	**MJ*/MJ**	**MJ*/MJ**
Hard coal[1]	24.0	26.2	27.10	1.12	1.040
Lignite[1]	7.8	9.1	9.46	1.21	1.040
Natural gas[2]	790.0	821.6	835.70	1.06	1.020
Petrol[1]	44.8	48.0	49.30	1.10	1.027
Diesel oil[1]	43.3	46.3	47.40	1.10	1.025

[1] unit = kg, [2] unit = kmol

Using the values from Table 2 for fuels and knowing the structure of electricity generation in domestic energy mix (Fig. 2), the average operational TEC for electricity ρ_{el} can be estimated from the formula:

$$\rho_{el} = \frac{\sum_j E_{ch,j}\left(\gamma_j + \sum_k p_{k,j}\zeta_k\right)}{E_{el,Y}} \quad (4)$$

where $E_{el,Y}$ denotes annual amount of electricity generation by national energy system (in domestic system power plants) and $E_{ch,j}$ denotes chemical energy of j-th kind of energy carrier used in energy mix.

Figure 4 presents the results of TEC calculations (operational part) for electricity generated in domestic system power plants.

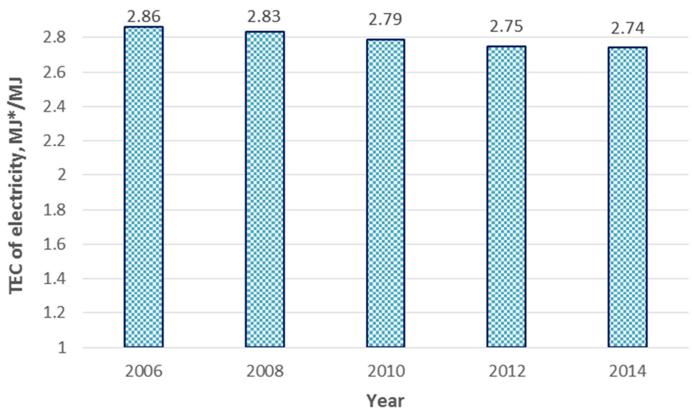

Figure 4: Average TEC of electricity generated in the whole Polish energy system

Figure 4 shows that in the considered period (2006 – 2014) the TEC of electricity generated in domestic system power plants has been decreasing despite the domination of hard coal and lignite within the whole considered period. The operational TEC decreased from the level of 2.86 MJ*/MJ in 2006 to 2.74 MJ*/MJ in 2014. The value of TEC significantly higher than 1 results from the domination of non-renewable fossil fuels in the energy mix.

4 Thermo-ecological cost of renewable fuels

In this section, the results of the TEC calculations based on the data of various RES installations in the European Union are provided [24-26]. Detailed algorithm for calculation of TEC for RES has been presented in [20,21]. Here, the TEC with the inclusion of LCA (see Eq. 3) results for biogas (10 plants), PV (26 plants) and wind (7 plants) are presented in Figs. 5-7, respectively.

Table 3: Average TEC of electricity from RES

	Range	Average value
TEC of electricity from biogas, MJ*/MJ	0.021 – 0.260	0.082
TEC of electricity from PV, MJ*/MJ	0.194 – 0.364	0.294
TEC of electricity from wind, MJ*/MJ	0.055 – 0.147	0.081

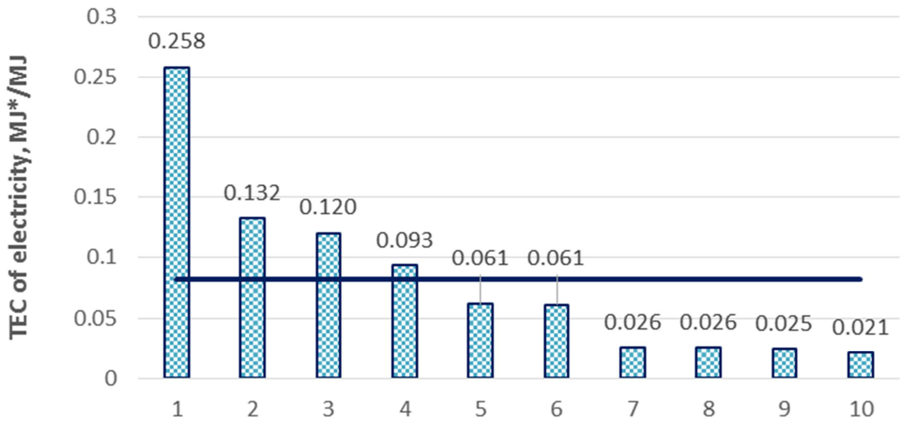

Figure 5: TEC of electricity generated by biogas power plants [24]

Figure 5 presents the TEC of electricity produced by using the following biogas [24]:

1. bio-waste at agricultural co-fermentation plant,
2. mix at agricultural co-fermentation plant,
3. fat and oil at agricultural co-fermentation plant,
4. slurry at agricultural co-fermentation plant,
5. agricultural digestion not covered,
6. agricultural co-digestion,
7. bio-waste,
8. whey digestion,
9. grass digestion,
10. sewage sludge.

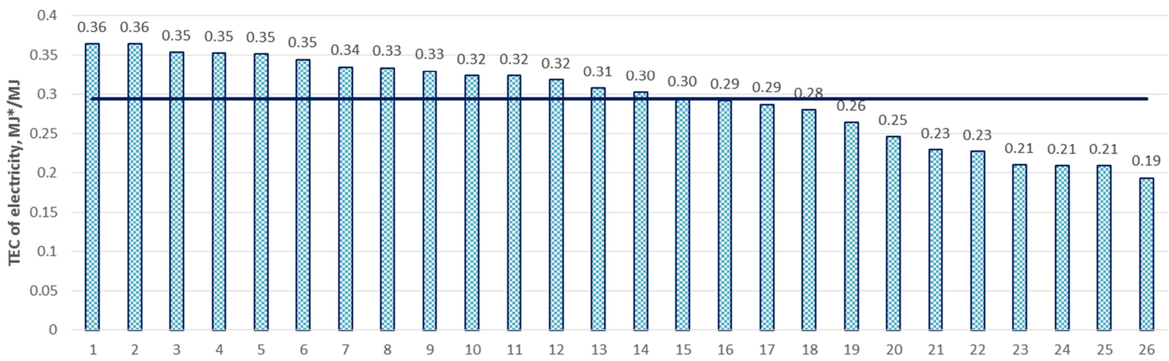

Figure 6: TEC of electricity generated by photovoltaic power plants [25]

Figure 6 presents the TEC of a mix of flat roof, slanted-roof and facade installations made of different compositions such as Si and CdTe, located in various countries in Europe [25]. Since the amount of solar energy reaching the ground varies between countries, TEC takes the lowest values for sunny countries such as Portugal and Spain, and the highest for countries such as Great Britain and Norway.

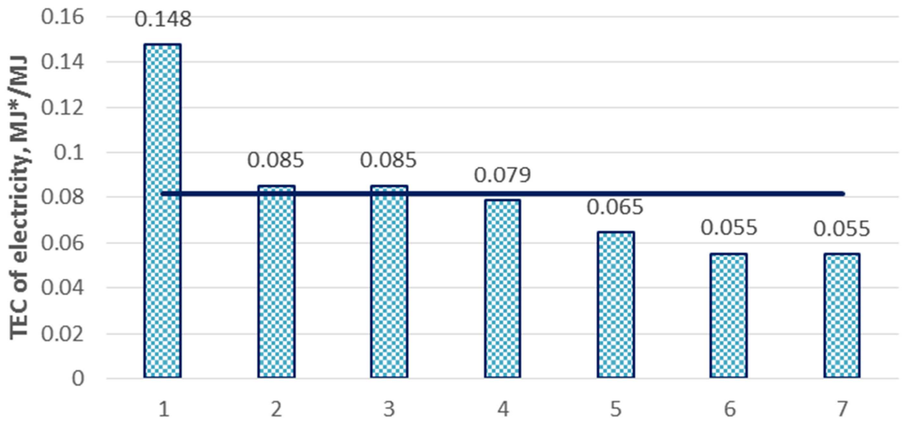

Figure 7: TEC of electricity generated by wind power plants [26]

Figure 7 shows the TEC of electricity from various wind power plants [26]:

1. Grenchenberg 150 kW power plant in Switzerland,
2. 600 kW power plant in Switzerland,
3. average in the Oceanic region,
4. 800 kW power plant in Switzerland,
5. 2 MW offshore power plant,
6. average in Switzerland,
7. average in Europe.

Relatively large differences between the TEC of listed plants are caused by the type of installation or the region where the installation is located. Based on the presented results, the average TEC for considered power technologies has been determined. It is included in Table 3. The average values of TEC will be taken into account in the TEC analysis of induced losses caused by random operation presented within the next part of the paper.

The presented values concern the operation, as well as the investment part of TEC (see Eq. 3). In the next section of the paper, the characteristic of the investigated RES systems is presented. In the case of random operation of renewable power plants, the classic approach of TEC given by means of Eq. (3) has to be supplemented with an additional part resulting from induced losses in non-renewable power plants used for compensation of RES plants operation.

5 Characteristics of analyzed power plants

The analysis of induced losses of exergy of natural resources is presented for three kinds of renewable power technologies: cogeneration fed with biogas, wind power plant and photovoltaic power plant. In the case of biogas-fired power units, two plants have been analyzed which differ in the stability of biogas generation. Figs. 8-10 present the changes in accessibility of energy from analyzed renewable systems. In presented Figs. 8-10, one of the variables is reduced time for which the value of 1 represents the total number of hours in selected period. Similarly, the relative power is equal to hourly power divided by the maximum power in the analyzed period. Selected factors for these characteristics are summarized in Table 4 .

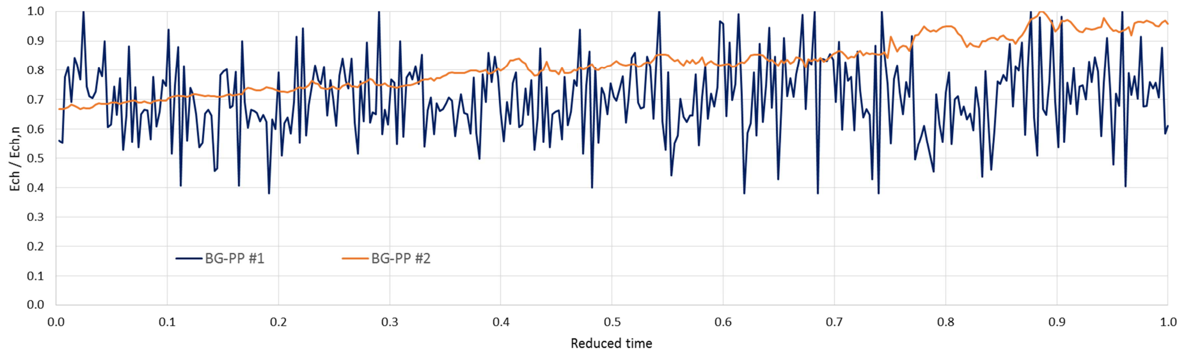

Figure 8: Biogas production through the year

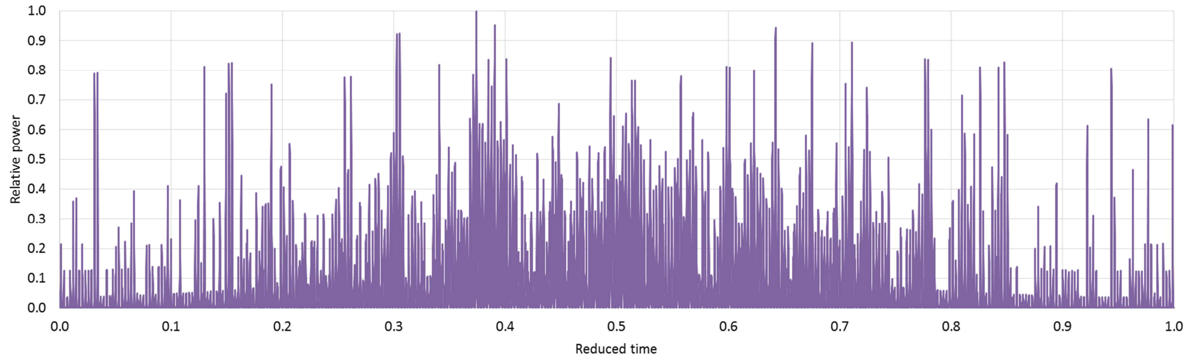

Figure 9: Annual electricity generation by photovoltaic power plant (PV-PP)

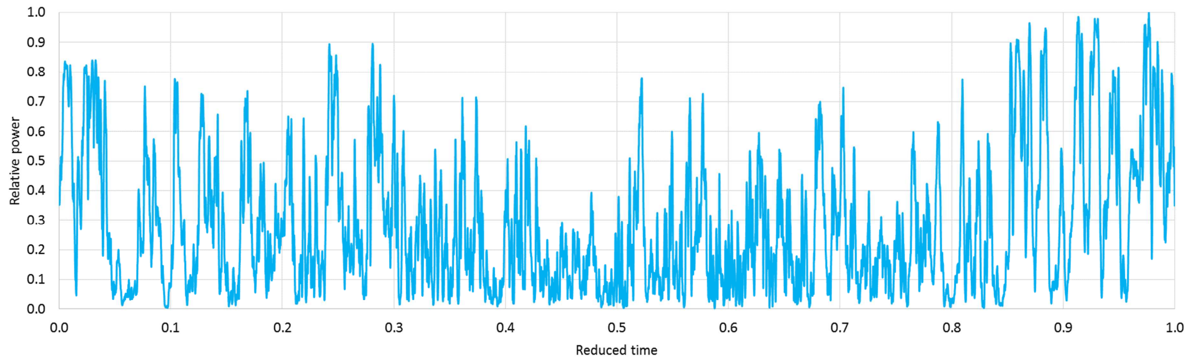

Figure 10: Annual electricity generation by wind power plant (Wind-PP)

Table 4: Characteristic of considered RES plants

Indicator	BG-PP #1, kW	BG-PP #2, kW	Wind-PP, MW	PV-PP, kW
Min. capacity	699.40	760.70	8.91	0.00
Max. capacity	2047.80	1206.70	4251.94	340.00
Average capacity	1378.50	956.20	1215.57	32.65
Standard deviation	280.70	114.00	990.39	55.97

It can be noticed that biogas plants are the type of technology that provides the most stable output. In comparison to biogas plants, PV and wind power plants change their production much more randomly. In the case of BG-PP #2 plant, the average chemical energy output is not significantly lower than the maximum power output. In the case of BG-PP #1 plant, the production within the majority of time is higher than 50% of maximal capacity; what is more, in the case of BG-PP #2 plant the output during the whole season is between 70-100%. In the case of PV-PP and Wind-PP the majority of operating points are located below 50% of maximum capacity. It can be expected that the annual utilization of nominal capacity will be high in the case of biogas and relatively small in the case of wind and PV. Furthermore, it can be expected that the mentioned effects would have significant influence on results of TEC analysis.

5.1 Biogas Power Plant

Figure 11 presents the time distribution curve of relative production of chemical energy of biogas during the year for both analyzed biogas plants. Based on the presented data, it can be concluded that the ratio of utilization of nominal power for both plants is as follows: BG-PP #1 – 70.5%; BG-PP #2 – 81.6%. For further TEC analysis, it has been assumed that biogas is applied for electricity production in a combined heat and power (CHP) unit with an internal combustion engine (ICE). Selected energy characteristics are presented in Figs. 12, 13 and 14 [22]. Figure 12 shows the total energy efficiency (produced heat and electricity divided by used chemical energy) as a function of engine's relative load. Figure 13 depicts the relation of electricity production and chemical energy input. Figure 14 shows the ratio of produced electricity and power as a function of the engine's load.

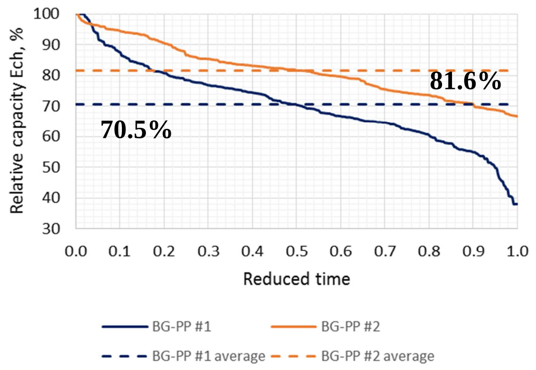

Figure 11: Yearly production of biogas

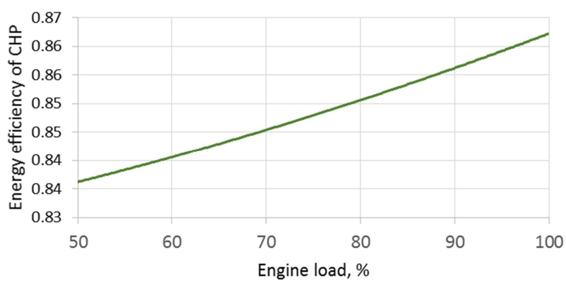

Figure 12: Energy efficiency of biogas CHP

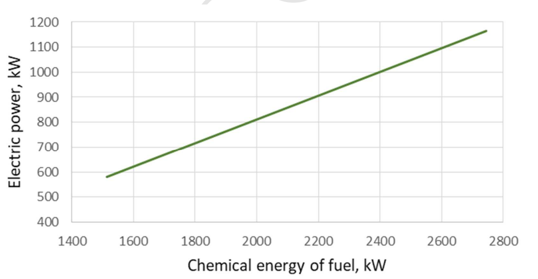

Figure 13: Electricity production in CHP

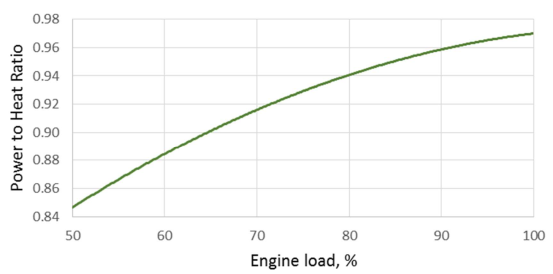

Figure 14: CHP Power to Heat ratio

To determine the TEC of electricity produced from biogas, the total consumption of fuel in CHP has to be divided between products (heat and electricity). In the presented analysis the exergy allocation has been applied. The following steps of the procedure are explained by the formulas presented below.

Total consumption of fuel (chemical energy) in CHP plant:

$$\dot{E}_{F,\mathrm{CHP}} = \frac{\dot{Q}_{\mathrm{CHP}} + N_{\mathrm{CHP}}}{\eta_{E,\mathrm{CHP}}} \tag{5}$$

where:
$\dot{Q}_{\mathrm{CHP}}$ heat produced in CHP unit, kW,
N_{CHP} electric power of the engine, kW,
$\eta_{E,\mathrm{CHP}}$ energy efficiency of CHP unit.

Exergy efficiency of the CHP plant is defined as:

$$\eta_B = \frac{\dot{Q}_{\mathrm{CHP}} \frac{T_m - T_0}{T_m} + N_{\mathrm{CHP}}}{\alpha \dot{E}_{F,\mathrm{CHP}}} \tag{6}$$

where:
α ratio of chemical exergy of fuel per unit of lower heating value ($b_{\mathrm{ch},F}$ / LHV),
T_m mean thermodynamic temperature of the heat carrier,
T_0 ambient temperature.

The expression in denominator specifies the total exergy of fuel feeding the CHP system, whereas the expression in numerator specifies the total exergy of useful products of the CHP system. It should be noted that in CHP two useful products are generated, for this reason the distribution of the environmental burden on heat and electricity must be determined. The analysis starts with identifying the main product with its impact on environment, and then the rest of the environmental burden is designated to the by-product. Consumption of chemical energy of fuel burdening the fabrication of electricity in CHP is calculated as:

$$\dot{E}_{F,\mathrm{el}} = \dot{E}_{F,\mathrm{CHP}} - \dot{E}_{F,\mathrm{Q}} = \dot{E}_{F,\mathrm{CHP}} - \dot{Q}_{\mathrm{CHP}} \frac{T_m - T_0}{T_m} \frac{1}{\alpha \eta_B} \tag{7}$$

Using the algorithm presented by Eqs. (5) – (7) and making use of CHP characteristic given by Figs. 12-14, the characteristic of partial energy efficiency of electricity production can be determined. This characteristic is presented in Fig. 15. Note that due to the above described methodology, the results are different from those that could be derived from Fig. 13. Using this methodology, a simulation of the influence of random access of biogas on the energy and exergy efficiency, as well as TEC can be performed. The presented procedures will be applied further in the methodology of calculation of TEC resulting from compensation. Fig. 15 shows partial efficiency of electricity generation in the ICE.

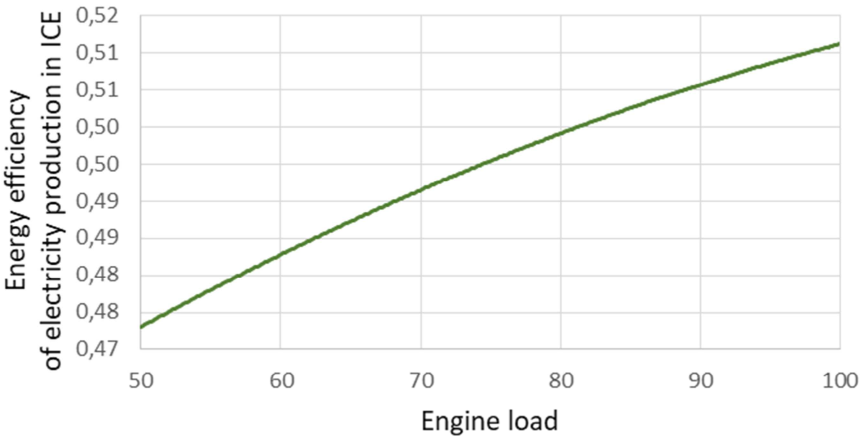

Figure 15: Partial energy efficiency of electricity generation in ICE

5.2 Photovoltaic power plant

In the case of the photovoltaic power plant, the TEC analysis has been performed assuming the energy and exergy characteristic of PV presented in Fig.16 and real data on solar radiation (Fig. 9). Fig.16 shows the energy ($\eta_{E,PV}$) and exergy ($\eta_{B,PV}$) efficiency in relation to solar radiation flux ($I\beta$). Based on the data presented in Fig. 9, the time distribution curve of solar radiation, which is presented in Fig. 17 has been determined.

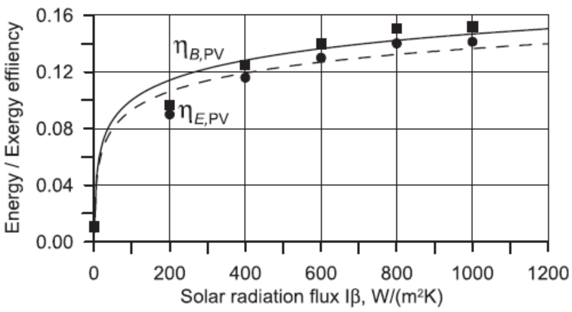

Figure 16: PV energy and exergy characteristic

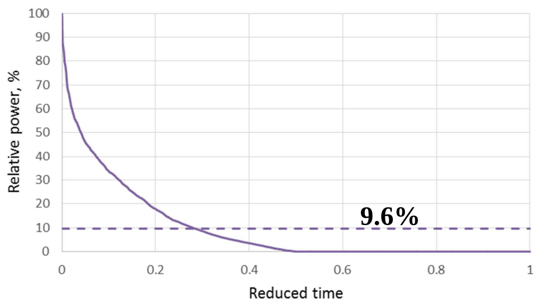

Figure 17: Power distribution curve - PV

Based on the distribution curve (Fig. 17), the average nominal capacity utilization ratio of PV plant can be determined. For the assumed plant (Fig. 16) and solar data (Fig. 9), average relative power is equal to 9.6% (see Fig. 17), this is significantly lower than the average relative power of both biogas plants.

5.3 Wind Power Plant

Fig. 18 presents time distribution curve of electricity generated in wind farms in Poland (these are data of all Polish wind farms in 2015). For the case of wind, the annual capacity utilization ratio is at the level of 28.6%. Rapid changes in production with relatively high maximum power reaching 4 300 MW in 2015 influence the electricity grid balance more than installed PV or biomass plants.

Additionally, Fig. 19 presents the time distribution of number of power units with gross nominal capacity of 260 MW that are necessary to compensate random production of wind farms. The numbers were determined using the procedure described in the next paragraph.

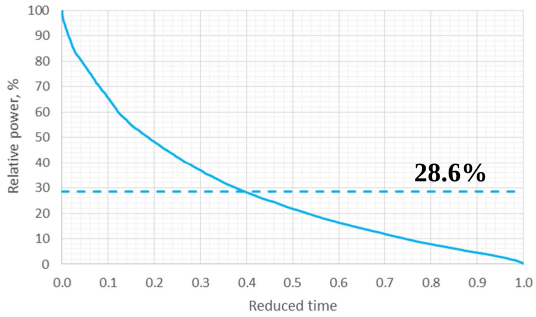

Figure 18: Power distribution curve - wind

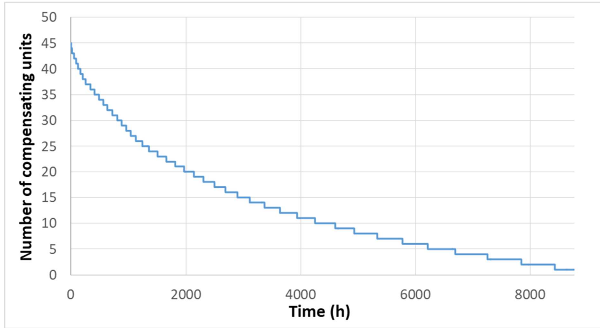

Figure 19 Compensation scenario – wind

6 Calculation of TEC of compensation

Having in mind the data characterizing random accessibility of renewable technologies (Table 4 and Figs. 8-10) it is necessary to extend the TEC approach by losses resulting from the compensation of random operation of renewable technologies. The losses result from the characteristic of RES, which induce work of non-RES with non-nominal capacity (generally lower capacity) and varying load of power units. Efficiency of the unit is lower when it works with non-nominal capacity. So in the case of analyzing RES, the total TEC has to consist of three components:

$$TEC_T = (TEC_{OP} + TEC_{INV}) + TEC_{COM} = TEC_{LCA} + TEC_{COM} \tag{8}$$

While Eq. (2) consists of two parts of TEC which are operational part TEC_{OP} and investment part TEC_{INV}, Eq. (8) is extended by compensation part TEC_{COM} to calculate the total cost TEC_T. The TEC_{COM} resulting from compensation should be calculated as following:

$$TEC_{\mathrm{COM}} = \frac{\rho_F}{E_{el,Y}} \int_{\tau=1}^{8760} \Delta E_{ch,F}(\tau)\mathrm{d}\tau \tag{9}$$

$$\Delta E_{ch,F}(\tau) = \left(\frac{1}{\eta_{\mathrm{el}}(\tau)} - \frac{1}{\eta_{\mathrm{el},0}}\right) \cdot n(\tau) \cdot N_{com}(\tau) \tag{10}$$

where:

$E_{el,Y}$ electric energy produced by the RES installation throughout the year, GWh,
$n(\tau)$ hourly number of counterbalancing conventional power plants,
$N_{com}(\tau)$ hourly power of a counterbalancing conventional power plant, MW,
ρ_F TEC of fuel used in conventional power plants (1.12 for hard coal),
$\eta_{\mathrm{el},0}$ nominal energy efficiency of compensating power plant,
$\eta_{\mathrm{el}}(\tau)$ current energy efficiency (for decreased output) of compensating power plant.

The number and power output of compensating power plants were determined using the methodology expressed by Eqs. (11) and (12).

$$n(\tau) = \text{int}\left[\frac{\Delta N_{RES}(\tau)}{N_{nom} \cdot (1 - LF_{min})}\right] + 1 \tag{11}$$

$$N_{com}(\tau) = N_{nom} - \frac{\Delta N_{RES}(\tau)}{n(\tau)} \tag{12}$$

where

ΔN_{RES} difference between current RES generation and minimal RES generation, MW

N_{nom} nominal net power of a counterbalancing unit (assumed as 238 MW),

LF_{min} minimal load factor of the unit (assumed as 60%).

If the current generation of power from RES is greater than their minimum output, thermal units need to drop with their load to balance the grid. Thermal power plants' base load is assumed to be 100%, and as the RES power increases, they reduce their output and more units are needed for counterbalancing. To properly compare the selected RES technologies, the data from Table 4 was scaled to 100 MW of average power through the year (~100 MW being the actual installed power of PV systems in Poland; installed power of biogas and wind installations is higher).

7 Results of TEC calculations

Results of TEC calculations with and without necessity of compensation are presented in Table 5 and Fig. 20. Total TEC of electricity generated by technologies fueled by renewable resources is presented with the decomposition of TEC between LCA part resulting from Eq. (3) and the additional component of TEC, which includes compensation. The TEC in the full life cycle (TEC_{LCA}) is calculated based on the data given in [21]. The calculations of TEC take into account the annual utilization factor of nominal capacity and the assumption that in the periods of lower than nominal capacity of renewable technologies, the lack of generated power is provided by conventional power plants. The results are presented in Table 6.

Table 5: TEC for analyzed RES power plants

	Unit	BG-PP #1	BG-PP #2	Wind-PP	PV-PP
Time of operation, t_{op}	h/year	8760	8760	8760	4394
TEC in full life cycle, TEC_{LCA}	MJ*/MJ	0.082	0.082	0.081	0.294
TEC of compensation, TEC_{COM}	MJ*/MJ	0.154	0.046	0.340	0.362
Total TEC, $TEC_{LCA\text{-}COM}$	MJ*/MJ	0.236	0.128	0.421	0.656
Share of compensation in total TEC	%	65.2	35.9	80.8	55.2

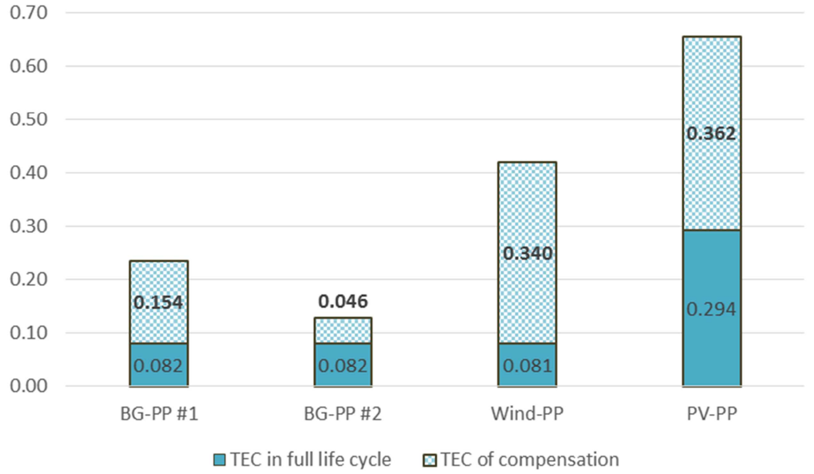

Figure 20: TEC of electricity from analyzed RES power plants

Table 6 presents the following information:

- TEC_{RES} thermo-ecological cost of electricity generated by power technologies based on renewable resources,
- $TEC_{pp\text{-}sys}$ thermo-ecological cost of electricity generated by average power plant based on nonrenewable resources (conventional power plants fueled by coal),
- TEC_{mix} thermo-ecological cost of electricity generated in Polish energy mix,
- S_{sys} share of electricity produced by conventional power plants (equal to 100% minus annual utilization ratio of nominal capacity of RES),
- nc compensation not taken into account,
- comp compensation taken into account.

Table 6: Average TEC of electricity

Indicator	Unit	BG-PP #1		BG-PP #2		Wind-PP		PV-PP	
		nc	comp	nc	comp	nc	comp	nc	comp
TEC_{RES}	MJ*/MJ	0.082	0.154	0.082	0.046	0.081	0.340	0.294	0.362
$TEC_{pp\text{-}sys}$	MJ*/MJ	3.052							
S_{sys}	%	33.04		20.60		71.4		90.4	
TEC_{mix}	MJ*/MJ	1.063	1.111	0.694	0.665	2.202	2.276	2.787	2.794

Figure 20 shows that the compensation part is significantly higher in the case of wind and PV power plants than the case of biogas plants. For wind, TEC_{COM} is over four times higher than the TEC_{LCA} calculated by formula (3), and for PV it is at the same order of magnitude. This is caused by high variability of energy production from these types of power plants, compared to biogas plants. High variability results in greater and more frequent changes in the operation of compensating thermal units and worsens their efficiency The exact values depend on the assumed power of RES units (and become greater the higher the RES power), but the results of comparison are similar regardless of that. The total TEC of PV is higher than total TEC of other considered renewable power plants. It mainly results from high use of natural resources and energy during the investment phase. Regarding the results of TEC of energy mix, biogas plants are also better than the other analyzed technologies. Wind and PV plants do not significantly decrease the TEC_{MIX}, because of their low nominal capacity utilization ratio. Here, the TEC_{MIX} was calculated in a local balance boundary (i.e. consisting only of the analyzed RES unit and the conventional thermal units needed for compensation). For a global balance boundary, the TEC_{MIX} would be the lower, the higher the installed power of RES would be.

8 Summary and conclusions

The variability of electricity production from technologies based on nonrenewable fossil fuels strongly influences efficiency of these power plants. The requirements set by the European and national regulations facilitate work of renewable technologies at the expense of conventional plants that actually maintain primary demand for electricity. Despite the fact that continuous changes related to renewable technologies rule the electricity production, the TEC of electricity is slowly decreasing each year (Fig. 4).

The obtained results confirmed that the current administrative regulations discussed in section 1 have no physical or ecological fundamentals. From the point of view of sustainability expressed by TEC, biogas CHP plant is more ecological than PV or wind power technologies.

When RES power plants are present in the national power system, the conventional plants need to play the role of compensating units. The procedure of calculating the compensation of lack of power generation by renewable technology is presented in the paper.

The TEC of electricity of three different renewable power plants in the full life cycle is calculated based on literature data as well as measurement data from four different plants. The results are presented for two biogas plants (BG-PP #1 and BG-PP #2), wind plant (Wind-PP) and photovoltaic plant (PV-PP). In the case of biogas plants, the characteristics of combined heat and power plant are presented, with inclusion of internal combustion engine.

In both biogas cases, the TEC of electricity generated by biogas plants is significantly lower than in the case of PV or wind. Even in the case of biogas plant with higher changes in production, which is assumed in the BG-PP #1, the total TEC is almost 2 times lower than in the case of wind power plant and 3 times lower than in the case of PV plant. The share of compensation in total TEC is significant for all analyzed technologies. Despite the negative effect of intermittent renewable energy sources on utility thermal power units, they still have a significant positive impact on the overall thermo-ecological balance of the power system.

Acknowledgements

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