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DETERMINATION OF THE ENVIRONMENTAL IMPACT OF REACTIVE POWER COMPENSATION IN THE POWER GRID

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ABSTRACT: The article discusses the problem of the determination of savings on active energy as a result of a reactive power compensation. Statutory guidance on the required energy audit to obtain white certificates in the European Union was followed. The paper presents a detailed analytical method and an estimation method taking into account the impact on the line, the transformer and the generator. The effect of the reactive power compensation on the environment in accordance with relevant laws was estimated. Discussed method is particularly helpful in the calculations for simple network topology generator-network-receiver. The analysis was performed using the energy equivalent of reactive power. The effect of the reactive power compensation on the security of the power system has been omitted. The presented simplified method for determining the transmission loss is particularly useful in economic operations. It is useful when the electricity audit covers many connection points, and it is impossible the implementation of accurate calculations.

KEYWORDS: Energy management, environmental economics, power systems, power system economics, reactive power control, static VAr compensators, white certificates

1. INTRODUCTION

The system that grants and awards white certificates is a means to promote energy efficiency in Europe. In Poland, its activities began at the end of the year 2012. These are certificates that confirm energy savings as a result of investments in an improved energy efficiency. This is a certification of those investments that reduce power consumption by reducing the negative environmental impact. An entity that is required to settle the obligation to redeem the required number of white certificates may obtain these certifications by implementing projects to improve energy efficiency, or it may purchase them at the National Energy Exchange or the European Energy Exchange (EEX), or at any other international stock exchange. An energy audit is an element that makes the settlement of the actions undertaken possible [1, 2, 3, 4, 5, 19].

In the light of the current Polish legal regulations [1, 2, 3, 4, 5, 6, 22, 23], the activities under a selected project may relate to those investments that have already been realized, that is only the settlement of the previously found savings on primary energy, and to future measures to reduce energy consumption. However, according to [1 Art.18.2], those projects aimed at an improvement of energy efficiency that were completed before 1 January 2011 cannot be submitted to participate in tenders.

The numerous measures whose purpose is to improve energy efficiency [7, 21, 22, 23, 24, 25] and which offer the opportunity to apply for white certificates, include a reactive power flow reduction [2 p.7 § 5.2]. The Law on the detailed scope and method of the preparation of an energy efficiency audit [2] indicates that this activity is based on the measurements and analyses of the location of the compensator.

The legislature, however, does not specify how to perform analyses when determining final energy savings for a project whose objective is a reduction of the reactive power flow. As clarified by the Energy Regulatory Office [6], the subject of energy savings is always active electric energy that is saved as a result of efforts to reduce reactive energy consumption. Support in the form of energy efficiency certificates is addressed to projects in the area of savings on active energy, and a reduction of the reactive power flow constitutes a method to reduce losses on active power.

The relevance and significance of “white certificates” mentioned in the title and in the paper are energy savings certifications that are not in widespread use outside of Europe, but are used in some European countries.

The power factor correction procedure must be regarded as an auxiliary method of a reduction of transmission losses (lines, transformers) and of production losses (the generator). An engineering approach in this area will involve a determination of savings on primary energy (individually on each grid element) being the result of reducing reactive power flows. In this publication, this method will be referred to as a thorough audit.

An analysis in a detailed and simplified audit should be prepared by means of the balance method [2, 4]. The method presented below affects the most important elements in the power distribution system by choosing the shortest route which connects the generator with the reactive power compensation location.

2. POWER LOSS AT A SECTION OF THE TRANSMISSION LINE

A total compensation of reactive power flows in the grid is practically impossible. These flows cause the following to occur in a section of the line:

- an increase of active power losses,
- a limitation of the active power transfer,
- an increase of current and voltage drops,
- an increase of investment outlays,
- difficulties in the work of grid elements (increased overvoltages).

Limitations of the bandwidth consumption by power equipment are the result of rated current values, which causes heating of devices. The ratio of active power P transmitted to power factor cosφ is constant (when $U = const$) [8, 9, 18]:

$$\left.\frac{P}{\cos\varphi}\right|_{U=const} = const. \tag{1}$$

This condition means that when the power factor on the grid has been reduced, the power equipment throughput decreases.

The transmission line on one phase can be described with impedance $R + \mathrm{j}X$ [10]. The phenomena for one phase are presented below. For a real three-phase system, in each phase are similar relationships.

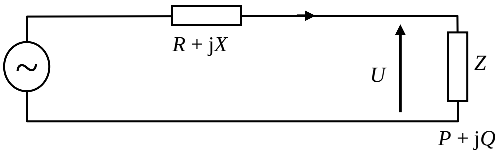

Figure 1. Circuit power model

Active power losses on element $R + \mathrm{j}X$ can be described with the following equation [20]:

$$\Delta_L P = \frac{P^2 + Q^2}{U^2} R, \tag{2}$$

where: P, Q – active and reactive power respectively that flows through the grid element, R, X – the resistance and reactance respectively of the grid element, U – voltage on the grid element.

In the remainder of this publication, the symbol Δ_L is a power or energy dissipation.

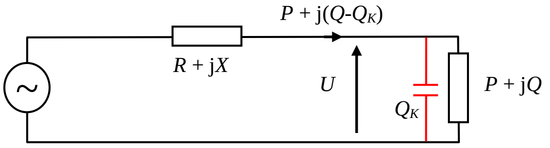

Figure 2. Circuit power model with compensator

As a result of a power factor correction, the reactive power flow through the line is reduced. With partial compensation, the remaining reactive power continues to load the flow. The difference between the active power loss (2) determined prior and after compensation is a profit on active power in the m^{th} section of the transmission line:

$$\Delta_\$ P_{Pm} = \frac{2QQ_K - Q_K^2}{U_m^2} R_m, \quad \Delta_\$ A_{Pm} = \Delta_\$ P_{Pm} \cdot T_p, \tag{3}$$

where: Q_K – power of compensator, T_p – work time of compensator Q_K, $\Delta_\$ A_P$ – profit on active power.

In the remainder of this publication, the symbol $\Delta_\$$ is the profit which was due to a reduction of power or energy dissipation.

The auditor, when using Formula (3), needs to know the network topology, the length of the m^{th} section of the line, the conductor cross-section area and the conductivity of the conductive material. When determining the savings on active energy by reactive power compensation, one needs to know the operation time T_p of compensator Q_K.

3. POWER LOSSES IN A TRANSFORMER DUE TO REACTIVE POWER FLOW

In the physical sense, Equation (2) applies to the lines and transformers. Reactive power flows through the transformer cause an increase of active power losses in the transformer. Load losses $\Delta_L P_{oT}$ are the result of the flow of current I through the winding; hence, they can be described as losses in lines:

$$\Delta_L P_{oT} = 3 I^2 R_T \tag{4}$$

where: R_T – resistance of a single phase of the transformer.

Load losses $\Delta_L P_{onT}$ at nominal current flow I_{nT} will be as follows:

$$\Delta_L P_{onT} = 3 I_{nT}^2 R_T. \tag{5}$$

By dividing both sides of Equations (4) and (5), a dependence is obtained which allows one to determine losses at any transformer load with nominal power S_{nT}, depending on load losses at nominal load $\Delta_L P_{onT}$ (from the transformer's datasheet).

$$\Delta_L P_{oT} = \Delta_L P_{onT}\left(\frac{I}{I_{nT}}\right)^2 = \Delta_L P_{onT}\left(\frac{S}{S_{nT}}\right)^2, \tag{6}$$

where: $\Delta_L P_{onT}$ – nominal load power dissipation, S_{nT} – nominal power of the transformer.

As a result of the compensation, reactive power will be reduced:

$$Q_{1K} = Q - Q_K, \tag{7}$$

where: Q_{1K} – reactive power after compensation, Q – reactive power before compensation, Q_K – power of the compensator.

Savings on active power losses in the w^{th} transformer using reactive power compensation in the receiver are equal to the difference of losses before and after compensation:

$$\Delta_\$ P_{Tw} = \Delta_L P_{onT}\left(\frac{P^2+Q^2}{S_{nT}^2} - \frac{P^2+Q_{1K}^2}{S_{nT}^2}\right) = \Delta_L P_{onT}\frac{Q^2-Q_{1K}^2}{S_{nT}^2}. \tag{8}$$

The following value is a profit on active energy generated in the transformer under examination that is lost as a result of a reactive power compensation:

$$\Delta_\$ A_{Tw} = \Delta_\$ P_{Tw}\cdot T_p = \Delta_L P_{onT}\frac{Q_K(2Q-Q_K)}{S_{nT}^2}T_p, \tag{9}$$

where: Q – the total reactive power of all receivers that operate on the secondary winding of the transformer.

4. POWER LOSSES IN THE GENERATOR DUE TO THE FLOW OF REACTIVE POWER

A reactive power flow through the windings of a generator causes a reduction of the possibility of active power generation. Apparent power, which is supplied to the network, causes heating of the generator windings. The power of the turbine which works with the generator is matched to the active power of the generator that is to operation at a nominal power factor. When the power factor is less than nominal, it is impossible to use the full power of the turbine due to the thermal load of the generator. Moreover, an increased reactive power flow causes a demagnetization of the rotor and a reduction of the electromotive force of the generator. The control system, which controls the voltage of the synchronous generator, must increase the excitation current. The permissible value of the current cannot be exceeded, as when the generator returns reactive power that is greater than nominal, in order to maintain the nominal voltage and not to exceed the thermal load of the rotor, it is necessary to reduce the active power generated.

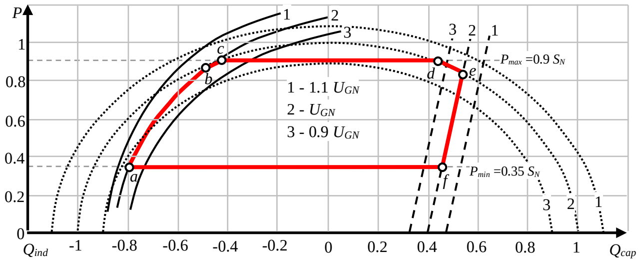

Figure 3. Pie chart that shows the acceptable area of the generator’s activity, where: U_{GN} – nominal voltage, S_N – rated power generator, 1, 2, 3 curves correspond to the value of the voltage at the generator terminals: 1.1 U_{GN}, U_{GN}, 0.9 U_{GN}

For large synchronous generators, any additional power losses caused by the generation of reactive power are negligible. They consist of small losses in the winding, which has a low resistance, and of additional losses in the coil winding.

In the case of asynchronous generators, reactive power must be supplied from the network or from the compensator with an individual compensation.

Apart from limitations associated with the thermal conditions of the operation point, the synchronous generator is additionally subject to restrictions that result from the following: permissible currents of the stator and the rotor, the shaft power available and the limit balance conditions of cooperation between the generator and the power system. These restrictions are presented in a pie chart of the generator in Figure 3 [13]. The work area for the nominal voltage is marked with the “*a-b-c-d-e-f-a*” outline. The change area of the reactive power ratio in the power system is limited with the “*a-b*” section of the permissible operation of the generator, which represents the limit of the maximum excitation current of the generator.

It is difficult to recount the impact of reactive power generated in the receiver to the balance of active power in the generator.

A simplification of this task is based on similarities in the electrical properties between the transformer and the generator. Equations (4), (5) and (6) are used and a formula is substituted in accordance with Equation (9), in order to determine savings on active power in the generator as a result of reactive power compensation in the receiver:

$$\Delta_\$ A_{bG} = \Delta_\$ P_{bG}\cdot T_p = \Delta_L P_{onG}\frac{Q_K(2Q-Q_K)}{S_{nG}^2}T_p, \tag{10}$$

where: $\Delta_L P_{onG}$ – load losses at a nominal current flow through the generator, S_{nG} – nominal power of the generator.

The production costs of reactive power in generators are substantially smaller than in receivers. However, the production of reactive power in the generator increases the transmission costs of reactive power in the network. Therefore, from an economic point of view, the production of reactive power in the generator and its transmission to customers is unprofitable.

5. CUMULATIVE IMPACT ON THE ENTIRE NETWORK

Energy saving that results from the reduction of active power losses in all the parts of the network by using the reactive power compensation of the receiver requires knowledge of the network topology and the determination of Relationships (3), (9) and (10).

$$\Delta_{\$}A_b = \Delta_{\$}A_{bG} + \sum_w \Delta_{\$}A_{bTw} + \sum_m \Delta_{\$}A_{bLm}, \qquad (11)$$

where: $\Delta_{\$}A_{bTw}$ – active energy saved in the w^{th} transformer, $\Delta_{\$}A_{bLm}$ – active energy saved in the m^{th} section of the line.

Apart from the knowledge of the network topology, the determination of value (11) requires the measurement of power Q at each point in the network. This information is not available for every point in the network.

Moreover, in those cases where the reactive power in Z recipient (fig. 1) is not equal of the total reactive power which flow through w and m network element (considered in eq.11), formulas (3, 9, 10) are not real.

A solution to this problem might be the use of the ratio which was determined in the mid twentieth century: *the energy equivalent of reactive power* [17]. This ratio is defined as the differential of the active power losses in relation to reactive power. When counting it in relation to equation (2), the following is obtained:

$$k_e = \frac{\partial(\Delta_L P)}{\partial Q} = \frac{2Q}{U^2}R \left[\frac{kW}{kVAr}\right]. \qquad (12)$$

The value of coefficient k_e strongly depends on reactive power, and it varies with changes to this power. This quantity permits one to calculate the change of active power losses caused by changes to reactive power that is collected at a given point in the network. The value of this factor depends on the value of reactive power and the distance of the point analyzed to source, whose measure is resistance R. According to the literature [11, 12], the value of this coefficient is determined for the minimum and maximum reactive power loads.

Table 1. Example Values of k_e

Type of grid	$k_{e\,min}$	$k_{e\,max}$
220 *kV*, 400 *kV*	0.04	0.08
110 *kV*	0.06	0.1
1 ÷ 60 *kV*	0.08 ÷ 0.1	0.12 ÷ 0.15
to 1 *kV*	0.12 ÷ 0.14	0.18 ÷ 0.22

In order to estimate how much power losses are reduced in the grid that supplies a given network point as a result of the installation of a battery of condensers, it is enough to multiply the value of the reactive power energy equivalent for this point by the power of the battery installed. Due to the variability of the load, the average value of the reactive power energy equivalent in a given network node is accepted in calculations. The reduction amount of losses is calculated from the following formula:

$$\Delta_{\$}P = \frac{k_{e\min} + k_{e\max}}{2} Q_K = k_{e\,Sr} \cdot Q_K. \qquad (13)$$

The reduction amount of the energy loss is calculated by multiplying the value of the power loss reduction by the operating time of capacitor battery T_P:

$$\Delta_{\$}A = \Delta_{\$}P \cdot T_p = k_{e\,Sr} \cdot Q_K \cdot T_p. \qquad (14)$$

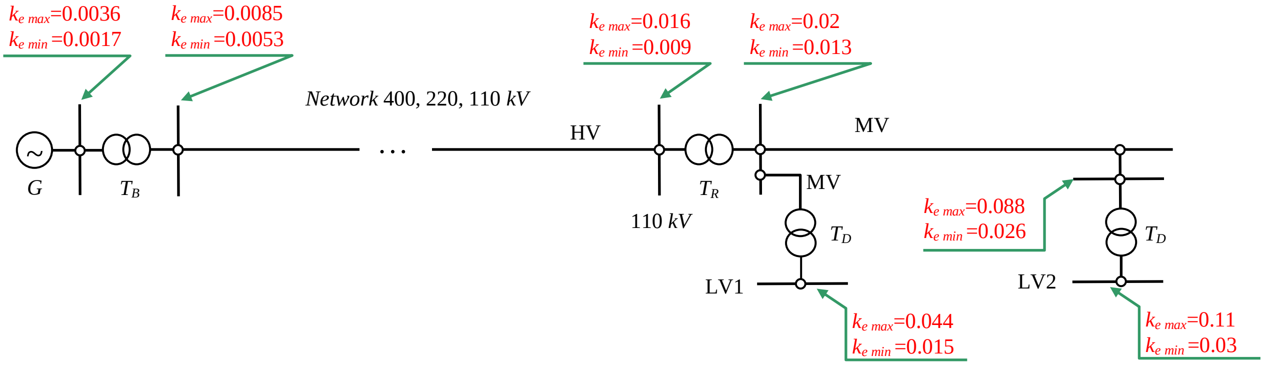

Figure 4. The values of the energy equivalent of reactive power estimated in 2007 [10]

The value of the energy equivalent of reactive power k_e depends on the following:

- the load of the network - an adoption of the arithmetic average of the minimum and maximum values is only a partial correction of an error in estimation;

- the distance of the point analyzed in the network (the resistance path from the generator to the point analyzed in the network);
- k_e coefficient varies greatly in different areas. In some 110 kV stations, in certain load conditions, it may accept negative values.

This means that an estimation of the reduction of losses based on the energy equivalent of reactive power is burdened with significant errors. In addition to this, there are no real values of k_e. The values (presented in table 1) reported in the literature are derived from Soviet literature from before the mid-twentieth century. The values of k_e has been updated in 2007 [10]. This value has been determined on the studies of a typical Polish power system. The study was performed by analyzing the various components of a typical transmission line. The final results were determined by the sum of the k_e coefficients for all elements of the energy system between the source and the network endpoint. The results are shown in figure 4.

Collected values are several times lower than those of the table 1. The development of the power system (i.e.: increase power ratings of generators and transformers, increasing the voltage of the transmission and the number of connections between nodes) causes a decrease in the value of the energy equivalent of reactive power. In the medium-voltage network increased nominal voltage and cable cross-sections, and shortened the length of circuits.

The individual variables in the equation (14) have random distribution of errors.

$$\Delta_x(\Delta_\$ A)=\sqrt{\begin{array}{l}\left(\frac{\partial(\Delta_\$ A)}{\partial Q}\right)^2\cdot\Delta_x^2(Q)+\left(\frac{\partial(\Delta_\$ A)}{\partial R}\right)^2\cdot\Delta_x^2(R)+\\+\left(\frac{\partial(\Delta_\$ A)}{\partial Q_K}\right)^2\cdot\Delta_x^2(Q_K)+\left(\frac{\partial(\Delta_\$ A)}{\partial T_p}\right)^2\cdot\Delta_x^2(T_p)\end{array}} \tag{15}$$

where: $\frac{\partial(f)}{\partial X}$ - partial derivative equation f with respect to variable X, $\Delta_x(X)$ - error on variable X.

For the function shown in equation (14) and (12), error limit of energy savings is:

$$\Delta_x(\Delta_\$ A)=\frac{2}{U^2}\sqrt{\begin{array}{l}R^2Q_K^2T_p^2\cdot\Delta_x^2(Q)+Q^2Q_K^2T_p^2\cdot\Delta_x^2(R)+\\+Q^2R^2T_p^2\cdot\Delta_x^2(Q_K)+Q^2R^2Q_K^2\cdot\Delta_x^2(T_p)\end{array}} \tag{16}$$

In equation (16) error on voltage U has been omitted.

The value of the energy equivalent of reactive power is used in the economic calculations when selecting the transformer (taking into account the effect of reactive power dissipated in the transformer active power losses in the power supply), and in assessing the effectiveness of reactive power compensation in order to determine the profit resulting from the reduction of active power losses due to reactive power compensation [10].

6. POWER ENGINEERING AUDIT WITH ESTIMATION METHOD

Methods for determining power losses, which are presented in sections II, III and IV require use of the calculation of power values measured at each point in the network. In practice, the auditor does not have as accurate information.

In the absence of the required data, the auditor will have to use estimation methods. For a network for which energy equivalents of reactive power were determined, estimation will come close to real values. For the remaining networks, the average values of coefficient k_e (13) need to be accepted as shown in Figure 4 and Table 1.

In fact, the operating time of the bank of capacitor T_p (14) is difficult to estimate. However, by using the power values averaged over the period (for example, taken from the invoices billing), you can tell the time T is the number of days in this period.

The balance is prepared for one calendar year by making adequate measurements and calculations [2, section 5 § 5.2]. The values of the average power / energy determined in billing invoices can be used as input data. This can be determined when using advanced electronic energy meters, which possess separate individual records with a division into inductive and capacitive reactive power. For this purpose, it is best to accept the entire billing year in an analysis, including all the seasons, and which consists of n-billing periods. Before the power compensation, the average power factor for the inductive and capacitive components, respectively, is as follows:

$$\tan\varphi_{0Ln}=\frac{A_{Q0Ln}}{A_{P0n}},\quad \tan\varphi_{0Cn}=\frac{A_{Q0Cn}}{A_{P0n}}, \tag{17}$$

where: A_{Q0Ln}, A_{Q0Cn} – inductive and capacitive reactive energy respectively, read out from n^{th} invoice, A_{P0n} – active energy.

Index "0" describes the variables that occur before compensation, and "1" describes the variables that occur after compensation.

When carrying out an audit for a project that has already been realized, in analogy to (17), the values of the power factor after compensation $\tan\varphi_{1L}$ and $\tan\varphi_{1C}$ need to be determined taking readings from subsequent invoices. Otherwise, it must be assumed that the compensation will be done correctly when $\tan\varphi_1$ power factor is less than or equal to the contractual power factor.

The remaining reactive energy compensation is as follows:

$$A_{Q1Ln} = \tan\varphi_{1L} \cdot A_{P0n},$$
$$A_{Q1Cn} = \tan\varphi_{1C} \cdot A_{P0n}. \tag{18}$$

Therefore, reactive power reduced by the compensator in the n^{th} billing period is equal to:

$$A_{kLn} = A_{Q0Ln} - A_{Q1Ln},$$
$$A_{kCn} = A_{Q0Cn} - A_{Q1Cn}, \tag{19}$$

where: A_{kL} – reactive inductive energy reduced by the bank of capacitors, A_{kC} – reactive capacitive energy reduced by the bank of coils.

Taking the energy equivalent of reactive power determined for the point being the closest to compensation according to Equation (14), the value of active power reduction in the network caused by compensation A_{kL} and A_{kC} in the n^{th} billing period is as follows:

$$\Delta_{\$}A_{Ln} = \frac{k_{e\min} + k_{e\max}}{2} \cdot A_{kLn},$$
$$\Delta_{\$}A_{Cn} = \frac{k_{e\min} + k_{e\max}}{2} \cdot A_{kCn}. \tag{20}$$

Losses should be taken into account on all the elements of the network in the area between the compensation point and the point of k_e factor determined. Assuming that in this area there is only a line segment, the resistance value of the line is to be determined (neglects the skin effect):

$$R = \frac{l}{\gamma \cdot s}, \tag{21}$$

where: l – length of the line, s – cross-sectional area, γ - conductivity of the material, and use Equation (3); therefore:

$$\Delta_{\$}A_{PL} = \frac{A_{Q0L} \cdot A_{kL} - A_{kL}^{\ 2}}{T \cdot U^2} R, \tag{22}$$

$$\Delta_{\$}A_{PC} = \frac{A_{Q0C} \cdot A_{kC} - A_{kC}^{\ 2}}{T \cdot U^2} R, \tag{23}$$

where: $\Delta_{\$}A_{PL}$ – active energy savings on the section of the line through the inductive reactive power compensation, $\Delta_{\$}A_{PC}$ – active energy savings on the section of line through the capacitive reactive power compensation, T – total number of days of the invoices analyzed, i.e.:

$$T = \sum_n T_n.$$

In the formulas (22) and (23), all parameters are values averaged throughout the period. Thus, the variable T corresponds to the length of the period.

The measurement of reactive power collected and given back is conducted in the energy meter. It records these two parameters at different moments and in separate registers. This is due to the fact that at a given moment of time, reactive energy cannot flow in two directions simultaneously. It is permitted to totalize active energy savings through the reactive power compensation, which has an impact throughout the billing period.

The total final energy savings (within the meaning of the Act [1 Art.3, section 5]) constitute the sum of active energy savings resulting from compensation:

$$\Delta_{\$}A = \sum_n^N \Delta_{\$}A_{Ln} + \sum_n^N \Delta_{\$}A_{Cn} + \Delta_{\$}A_{PL} + \Delta_{\$}A_{PC} \quad [kWh/year]. \tag{24}$$

In accordance with the guidelines of the International Energy Agency (IEA) and the Organisation for Economic Co-operation and Development (OECD), the value of (24) expressed in the tons of oil equivalent (*toe*) is:

$$\Delta_{\$}A_{toe} = \frac{\Delta_{\$}A}{11630} \quad [toe/year]. \tag{25}$$

The average annual primary energy savings referred to in [1 Art.3, section 3] in accordance with [2, Annex 2, eq.29] are equal to:

$$\Delta_{\$}A_p = \Delta_{\$}A \cdot w_i, \tag{26}$$

where: $\Delta_{\$}Ap$ – the amount of primary energy savings expressed in primary fuel [kWh / year] or [GJ / year], $\Delta_{\$}A$ – final energy savings, expressed in [kWh / year] or [GJ / year], w_i – effort ratio of non-renewable primary energy which depends from the final energy carrier (Table 2).

Table 2. Effort Ratio of Non-Renewable Primary Energy for the Production and Supply of Electric Energy

Source of electric energy	w_i
mixed-mode production	3.0
production of electricity from solar energy	0.7

The w_i factor is defined according to the fuel or energy source used in a given country, which according to [14, Appendix 5, Table 1] should be one of the values (for example, in Poland):

Table 3. Example W_{ECO2} Reference CO_2 Emission Factors for Fuels [16] in Accordance with the Guidelines of the Intergovernmental Panel on Climate Change (IPCC) from the Year 2006

Fuel type	CO_2 emission factor [$MgCO_2$/TJ]
petroleum	73.3
shale oil	73.3
gas / diesel oil	74.0
ethane	61.6
solvent naphtha	73.3

petroleum coke	97.5
refinery gas	51.3
coking coal	94.5
lignite	101.1
bituminous coal	94.2
natural gas	56.1
industrial waste	142.9
waste oils	73.3
peat	105.9

By analogy to (26), primary energy can be represented in *toe*:

$$\Delta_{\$}A_{p\,toe} = \Delta_{\$}A_{toe} \cdot w_i. \tag{27}$$

For a specified value of $\Delta_{\$}A_p$ expressed in [*kWh / year*], the reduction of CO_2 emissions in a year is determined according to [15, Appendix 1, Table 2]:

$$\Delta_{\$}E_{CO2} = \Delta_{\$}A_p \cdot 3.6 \cdot 10^{-3} \cdot we_{CO_2} \quad [kg / year], \tag{28}$$

where: we_{CO2} – CO_2 emission factor for fuels.

The quantity of the reduction of CO_2 emissions is calculated using CO_2 emission factors contained in [15] and under the EU Emissions Trading System (EU ETS) for a given year.

White certificates are purchased as a result of a tendering procedure. A project aimed at an improvement of energy efficiency, as a result of which energy savings in (26) are obtained in an amount being an equivalent to at least 10 *toe* on average over the year, can be included in a tender [1, Art.18.1]. Several projects of the same type aimed at an improvement of energy efficiency, as a consequence of which the total energy savings are achieved in the amount being an equivalent to at least 10 *toe* on average over a year, may be brought together.

7. CONCLUSION

The methods proposed for the determination of savings on active energy as a result of the reactive power compensation carried out (which were presented in sections II, III and IV) possess some errors and inconvenience. The detailed method requires knowledge of the network topology and a determination of reactive power Q at each point of the network. This method of analysis is easy in execution, especially if the consumer of energy is the main or the most significant purchaser of electricity in the network.

In other cases, an estimated method (section VI) can be used, which requires the knowledge of the values of k_e factor: *the energy equivalent of reactive power*. The disadvantage of this method is the inaccuracy of calculations, which is dependent from the error in the determination of k_e coefficient. This is the only way of making an energy audit, particularly in countries where the energy grid is not fully measured, although the calculation error is large. In the absence of k_e coefficient, it may be assumed approximate values which are shown in Figure 4 - according to the literature [10].

The presented method for calculating losses is useful for economic analysis. In the event that a complex audit covers many terminal nodes in the network (for a large company with many subsidiaries), the resultant error committed in this method will be less than for a single consumer. The use of approximate methods for the designation of white certificates is justified because other audits (non-electric), also based on the approximate coefficients.

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