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# CONFIGURATION OF A PHOTOVOLTAIC POWER PLANT AND DETERMINATION OF PERFORMANCE

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**Abstract:** The work refers to the design of a photovoltaic plant that will be built near the city of Carbunesti (44.9580N; 23.5060E), a location that falls within the yellow zone of solar radiation. Based on the imposed power, the solar panels in polycrystalline silicon technology, the inverters and the connection transformer are chosen. Next, it is established the number of solar panels and how to connect them, so as to achieve both the required power and the voltage required at the input of the inverters. It also determines the required number of inverters, the structure and the number of independent energy fields, which are connected to the mains transformer by means of their own cells. The energy produced is also estimated, monthly and for one year, by using the dedicated application – JRC Photovoltaic Geographical Information System (PVGIS) – European Commission and by a calculation algorithm developed by the authors. The electrical structure of the plant is composed of 4 identical generating fields, consisting of 12 inverters and 1008 panels. Finally, some conclusions are summarized that highlight the positive impact on the environment, by reducing the amount of CO2 released into the atmosphere.
**Keywords:** Photovoltaic plant, Solar radiation

## 1. INTRODUCTION

The use of renewable energy has many potential benefits, including a reduction in greenhouse gas emissions, a diversification of energy supply and a reduction in dependence on fossil fuel markets (especially the oil and gas market). [15] Romania is located in a geographical area with good solar coverage, with 210 sunny days per year and an annual flow of solar energy between 1000 kWh/sqm/year and 1300 kWh/sqm/year. It is estimated that between 600 and 800 KWh/sqm/year can be captured from this amount of energy [5].

Compared to wind energy, where the wind potential is mainly concentrated in the area of Dobrogea and Moldova, the solar potential of Romania is spread almost throughout the country [3].

Romania is in the European sunshine zone B, which offers real advantages to obtain electricity by using solar energy. Depending on the geographical area, Romania is divided into three main areas according to the intensity of solar radiation (Hi) in the horizontal plane. The red zone (Hi>1650 kWh/sqm/year) includes the southern zone, respectively Oltenia, Muntenia, Dobrogea and the south of Moldova.

The yellow zone with Hi between (1300 – 1450) kWh/sqm/year, in which are found the Carpathian and sub–Carpathian regions of Muntenia and Oltenia, Transylvania, the middle and the northern part of Moldova and the whole Banat.

The blue zone in which the mountain regions are found and which corresponds to the radiation intensity between (1150 – 1300) kWh/sqm/year.

Although at present, in Romania, the installed capacity of photovoltaic power plants represents only 7.5%, ie 1388.15 MW, compared to 16.3% of the installed capacity in wind farms, solar energy is rated by many market specialists with good chances to transforms into the new boom of the green energy segment (Figure 1) [6].

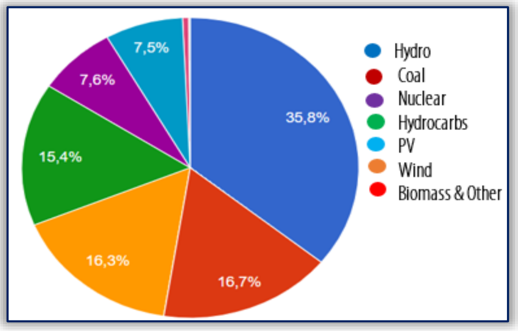

Figure 1. Power installed in Romania as percent from total of 18538,433 MW (04/04/2022)

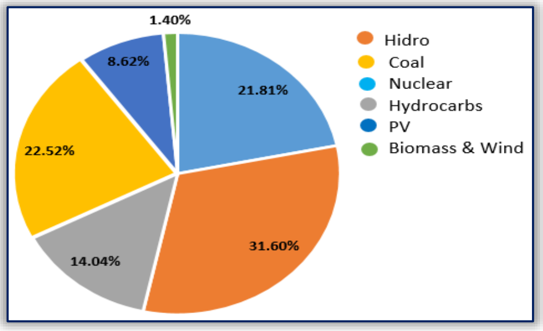

Figure 2. Energy consumption in Romania as percent from total of 7430 MW (04/04/2022 at h12:02)

The efficiency of the investments in the construction of photovoltaic power plants, compared to the wind ones, is proved by the share in the electricity consumption (Figure 2). For example, on 04/04/2022 at h12: 02, the energy produced in photovoltaic power plants represents 8.62% of the total consumption of 7430 MW, while the energy produced in wind farms represents about 1% [7]. As constructive solutions, solar panels can be fixed or mobile to permanently follow the trajectory of the sun in order to maximize the energy produced [1], [2].

The papers refers to design a photovoltaic plant that will be built near the city of Carbunesti (44.9580N; 23.5060E), a location that falls within the yellow zone and is structured on three sections of background.
In the first section, starting from the location of the panels, the intensity of the solar radiation and the facilities of connection to the national electricity distribution network are analyzed. Next, based on the imposed power, the solar panels in polycrystalline silicon technology, the inverters and the connection transformer are chosen. Section 2 is intended to determine the number of solar panels and how to connect them, so as to achieve both the required power and the voltage required at the input of the inverters. It also determines the required number of inverters, the structure and the number of independent energy fields, which are connected to the mains transformer by means of their own cells. The calculation of the main quantities and the estimation of the energy produced is the subject of section 3.
The configuration of the electrical structure of the power plant and the necessary verifications are performed in section 4.
Finally, some conclusions are summarized that highlight the positive impact on the environment, by reducing the amount of $CO_2$ released into the atmosphere.

## 2. LOCATION CHARACTERIZATION AND SELECTION OF SOLAR PANELS AND MAIN NETWORK CONNECTION EQUIPMENT

— Location characterization

The photovoltaic plant will be built near the town of Carbunesti (44.9580N; 23.5060E), at an altitude of approx. 300m and must meet the following conditions: Rated voltage on the side of a.c. ($U_N$) 400 V; Total peak power required ($P_{tvi}$) 1000 kW; Annual energy produced ($E_{an}$) 1200 MWh.
In the location area there is a medium voltage network (20 kV OHTL) located on the public domain. The connection of the plant is made through a 20 kV overhead connection with a 24kV/400A load separator and 2 line cells, for the connection to the National Energy System (NES) and for the connection of the plant transformer.
The maximum estimated current, debited by the photovoltaic power plant in the MT line, is:

$$I_{maxOut} = \frac{P_{tvi}}{\sqrt{3}U_N} = \frac{10^6}{\sqrt{3}\,400} = 29\text{ A}. \quad (1)$$

— Choice of solar panels, inverters and NES connection transformer

When choosing solar panels, the quality of the panel must be taken into account, which is of overwhelming importance and is determined by two main parameters: efficiency and reliability. At the same time, there must be a balance between reliability and accessibility [10]. A high–performance and competitive solar system is built with quality polycrystalline photovoltaic panels that have, at the same time, an affordable price. Last but not least, solar systems must have guarantees of at least 25 years, and the reduction of the efficiency must be of maximum 20%, in the last 5 years of life.
Taking into account these aspects, was chosen the AC–250P/156–60S panels that have electrical data from Table 1. They correspond to the standard conditions (STC), respectively, irradiance 1000 watts/m2 and spectrum AM 1.5 at a cell temperature of 25°C [11].

Table 1. The main electrical data of the AC–250P/156–60S panels

| Nominal output (Pmp) | Nominal voltage (Ump) | Nominal current (Imp) | Short circuit current (Isc) | Open circuit voltage (Uoc) | Module conversion (Eff) |
|---|---|---|---|---|---|
| 250 Wp | 30,70 V | 8,18 A | 8,71 A | 37,80 V | 15,37 % |

Limit values: System voltage – 1000 VDC; NOCT (Nominal Operating Cell Temperature) – 45°C +/–2K; NOCT irradiance – 800W/m2; AM 1,5; Minim output voltage (at – $30^0$C) – 26 V.
Panel dimensions: (L x W x H) = (1640 x 992 x 40) mm.
In a first stage, the necessary number of panels results, based on the relation:

$$N_{pi} = \frac{P_{tvi}}{P_{mp}} = \frac{10^6}{250} = 4000. \quad (2)$$

— Choice of inverters

There are many brands, types and sizes of inverters on the market, and therefore, some important aspects must be taken into account when choosing inverters.

≡ The capacity of the inverter to be able to manage the maximum power that the photovoltaic system can produce.
≡ The inverter display should provide as much information as is displayed directly on the inverter. In addition, there may be a remote monitoring option (console or phone). Some of the information that should be displayed directly on the display refers to: the number of hours the system has been operating;

instantaneous electric power; the amount of energy (kilowatt–hours) produced in a predefined time interval (daily, monthly, etc.); the amount of electricity produced from the installation.

≡ The efficiency of a solar inverter connected to the SEN by the transformer is at least 95% and can reach 98% for premium category inverters.

≡ The warranty is that most grid–connected inverters have a lifespan of 10–20 years, with some expansion options for an additional cost. The need for an extended warranty is a criterion that must be considered in order to rely on a lifespan of at least 15 years.

≡ The price depends on the characteristics of the inverter, but also on how much you are willing to invest in an inverter. On the market there are inverters similar in characteristics, but at significantly different prices. It is certain that the cheapest option may not be the best. Ideally, information could be obtained from equipment that has been in operation for at least 5 years.

For high flexibility and maintenance, several inverters of appropriate power will be used, which are connected in parallel, in the secondary of the transformer. Thus, the TRIO–20.0/27.6–TL–OUTD inverter is chosen, which has the dual input section containing two independent Maximum Power Point Tracking (MPPT) and allows optimal energy harvesting from two sub–arrays oriented in different directions [13]. In addition, the main features are very good in meeting the above criteria (Tab. 2).

Table 2a. Input side

| Absolute maximum DC input voltage ($V_{max,abs}$) | Rated DC input voltage ($V_{dcr}$) | Rated DC input power ($P_{dcr}$) | Number of independent MPPT | Maximum DC input power for each MPPT ($P_{MPPTmax}$) | Maximum DC input current ($I_{dcmax}$) / for each MPPT ($I_{MPPTmax}$) |
|---|---|---|---|---|---|
| 1000 V | 620 V | 20,75 kW | 2 | 12 kW | 50.0 A / 25.0 A |

Table 2b. Output side

| Rated AC power (Pacr @cosφ=1 ) | Rated AC grid voltage (Vac,r) | Maximum AC output current (Iac,max) | Nominal power factor and adjustable range | Total current harmonic distortion | Weighted efficiency (EURO/CEC) |
|---|---|---|---|---|---|
| 20 kW | 400 V | 33 A | > 0.995 | < 3% | 98% |

The number of panels connected in series must ensure the necessary voltage on the DC side of the inverters, respectively:

$$N_{ps} = \left|\frac{V_{dcr}}{U_{mp}}\right| + 1 = \left|\frac{620}{30.7}\right| + 1 = 21. \tag{3}$$

The power of one serial branches is:

$$P_{rs} = P_{mp}N_{ps} = 250x21 = 5,25\ kW. \tag{4}$$

The number of serial branches connected in parallel to an MPPT input is obtained as:

$$N_{ps} = \left|\frac{V_{dcr}}{U_{mp}}\right| + 1 = \left|\frac{620}{30.7}\right| + 1 = 21. \tag{5}$$

On this basis, the number of necessary inverters is obtained:

$$N_{inv} = \left|\frac{N_{pi}}{2N_{rpi}N_{ps}}\right| + 1 = \left|\frac{4000}{2x2x21}\right| + 1 = 48. \tag{6}$$

But, each inverter is connected to:

$$N_{rpinv} = N_{ps} \times 2 \times N_{rpi} = 21 \times 4 = 84, \tag{7}$$

thus, in the end, the required number of solar panels is corrected:

$$N_p = N_{inv} \times N_{rpinv} = 48 \times 84 = 4032 \tag{8}$$

In this way, the structure of the photovoltaic generator is completely determined, and the final value of the total peak power is:

$$P_{TV} = N_p \times P_{mp} = 4032 \times 250 \times 10^{-3} = 1008\ kW \tag{9}$$

— Choice of NES connection transformer

Considering the rated voltages of the MT line and at the output of the photovoltaic generator, but also the power to be transferred, it is necessary to use a lifting transformer. The main parameters of power transformer are: type Dy11 0,40/20kV; S= 250 kVA; Short circuit voltage = 6%; Rated efficiency = 98,75 (cosfi=1); 98,4% (cosfi=0,8).

## 3. CALCULATION OF THE MAIN QUANTITIES AND ESTIMATION OF THE ENERGY PRODUCED

For the estimation of electricity produced by the photovoltaic plant, monthly and for one year, the dedicated application – JRC Photovoltaic Geographical Information System (PVGIS) – European Commission [8] and a calculation algorithm developed by the authors were used. The algorithm takes into account that the panels are fixed.

— Calculation of the useful solar radiation depending on the trajectory of the sun

The correction factor refers to one month. Let the contour of the horizon at the location of the plant, with the highlighting of the average trajectory of the sun in that month (dashed line – Figure 3). It was considered that the photovoltaic panels are oriented (vertically and horizontally), so that when the sun is in the middle of its trajectory (at point M), the sun's rays are perpendicular to the horizontal location of the panels. The point C coresponds to the location of the plant (approximately $45^0$ north latitude), and α is the angle made by the projection of the sun's rays with the N–S axis passing through point C. The angles made by the projection of the sun's rays with the parallel passing through point C, to the east and respectively sunset, are assumed to be equal ($\alpha_0$).

The solar irradiance has the reference value ($I_0$) when the sun is at point M, respectively when the sun's rays fall perpendicular to the tangent to the parallel $45^0$, at the point where the plant is. For another point on the path of the sun, the value of the radiation is:

$$i_\alpha = I_0 \cos\alpha \tag{10}$$

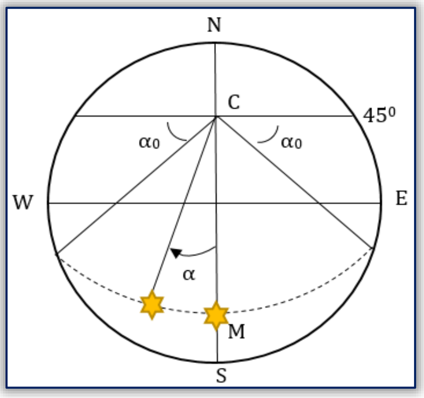

Figure 3. Explanatory note on calculating the average value of solar irradiance

The average value during a day will be:

$$I_{av} = \frac{1}{\pi - 2\alpha_0} \int_{-\left(\frac{\pi}{2}-\alpha_0\right)}^{\left(\frac{\pi}{2}-\alpha_0\right)} i_\alpha d\alpha. \tag{11}$$

After processing it get:

$$I_{av} = 2I_0 \frac{\cos\alpha_0}{\pi - 2\alpha_0}. \tag{12}$$

Thus, the expression of the correction coefficient is:

$$k_c = 2\frac{\cos\alpha_0}{\pi - 2\alpha_0}. \tag{13}$$

— Estimated electrical energy

If the Daily/Monthly in–plane irradiation (Hid/Him) are known, the Daily/Monthly output electric energy are obtained as:

$$\begin{gathered} E_d = H_{id} \times N_p \times S_p \times \eta_p \times k_c \\ E_m = H_{im} \times N_p \times S_p \times \eta_p \times k_c \end{gathered} \tag{14}$$

In the PVGIS application was used the solar radiation databases PVGIS–SARAH2 (0.05º x 0.05º) produced by CM SAF that covers Europe, Africa, most of Asia, and parts of South America. Temporal range: 2005–2020.

It is specified that, in the case of fixed solar panels, the application allows the use of an imposed arrangement of them, or the optimization of the position [4]. In the case of the power plant that is the object of the work, the measurements performed at the location led to the identification of the positioning of the solar panels at $2^0$ E from the meridian of the place and an inclination of $30^0$ from the horizontal. In comparison, the application indicates, as an optimal positioning, $0^0$ E and a slope of $37^0$, which leads to an increase in annual energy estimated by only 0.58%. In this situation, it chosen the first option of orienting the solar panels.

The monthly in–plane irradiation is shown in Figure 4 and the monthly energy output of PV system in Figure 5. The numerical values of the in–plane irradiation (daily and montly) and of electric output energy are given in Table 3. The values from the last two columns are obtained by the relations (14).

It can be observed that the rezults are very close, that confirm the correction of above relations. Thus, the anual produced energy obtained by the relations (14) is lower about 1.54% (1235.12 MW versus 1254.385).

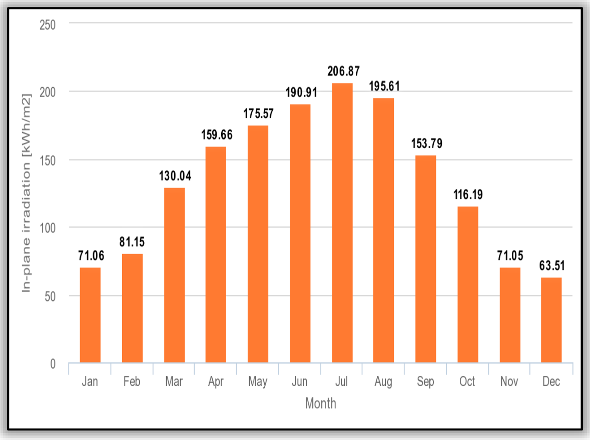

Figure 4. Monthly in–plane irradiation

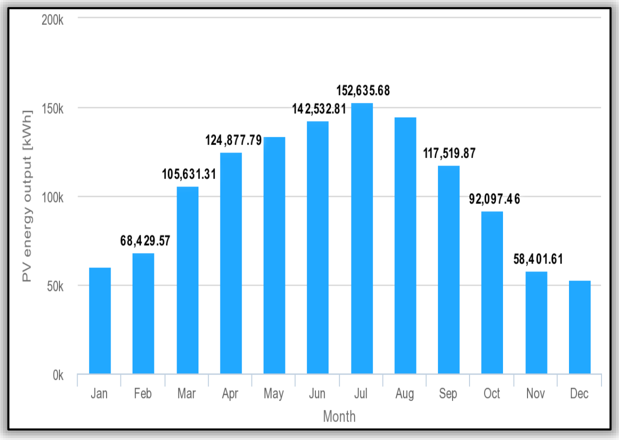

Figure 5. Monthly energy output of PV system

Table 3. Daily and monthly in–plane irradiation and daily and monthly output electric energy from PVGIS and appling above relations

| PVGIS | | | | Algorithm | |
|---|---|---|---|---|---|
| $H_{id}$ [kWh/m²] | $H_{im}$ [kWh/m²] | $E_d$ [kWh] | $E_m$ [MWh] | $E_d$ [kWh] | $E_m$ [MWh] |
| 2.29 | 71.06 | 1879.07 | 60.472 | 1920.97 | 59.550 |
| 2.90 | 81.15 | 2355.55 | 68.43 | 2404.20 | 67.318 |
| 4.19 | 130.04 | 3285.64 | 105.631 | 3351.48 | 103.896 |
| 5.32 | 159.61 | 4012.1 | 124.878 | 4097.76 | 122.933 |
| 5.66 | 175.57 | 4157.45 | 133.578 | 4240.98 | 131.470 |
| 6.36 | 190.91 | 4583.71 | 142.533 | 4676.56 | 140.297 |
| 6.67 | 206.87 | 4748.14 | 152.636 | 4844.19 | 150.170 |
| 6.31 | 195.61 | 4505.46 | 145 | 4608.54 | 142.865 |
| 5.13 | 153.79 | 3779.38 | 117.52 | 3857.09 | 115.713 |
| 3.75 | 116.19 | 2862.1 | 92.097 | 2929.26 | 90.807 |
| 2.37 | 71.05 | 1873.17 | 58.402 | 1919.78 | 57.593 |
| 2.05 | 63.51 | 1651.5 | 53.208 | 1693.82 | 52.508 |
| Average values | 1615.36 | | 1254.385 | | 1235.12 |

## 4. CONFIGURING THE ELECTRICAL STRUCTURE OF THE PLANT AND NECESSARY VERIFICATIONS

### — Configuring the electrical structure of the plant

To obtain a high degree of flexibility and maintenance, the structure of the plant is configured in four identical fields that can operate independently. Each generation field consists of 12 inverters and 1008 photovoltaic panels. Each inverter is powered at each MPPT input from 2 strings of photovoltaic panels connected in parallel. Each string contains 21 panels connected in series, so that at each MPPT input the energy generated by 42 photovoltaic panels is received. Table 4 gives the energy quantities related to a field / inverter, but also the useful electricity that is sent to the NES.

Table 4. Structure and useful energy sent by a field and total

| Field | Inv. No | Panels No/Inv | Total panels No | Pinv. [kW] | Ppanels [kW] | Degree efficiency | Solar rad [kWh/m^2]/an | En [kWh] | En/Inv. [MWh] | Losses [%] | E_util [kWh] |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
| 1–4 | 12 | 84 | 1008 | 240 | 252 | 105 | 1615.36 | 314592 | 26216 | 22.4 | 244123 |
| Total | 48 | | 4032 | 960 | 1008 | 105 | | 1258369 | 26216 | 22.4 | 976494 |

On the sizes in Table 4, the following specifications are made:

≡ The degree of efficiency (column 7) is calculated as the ratio between the power of the panels and the power of the inverters;
≡ Solar radiation (col. 8) is calculated in Tab. 3;
≡ The electric energy produced by solar panels (col. 9) is calculated by relations (14);
≡ The electric energy from column 10 corresponds to one inverter;
≡ The useful energy sent to the NES by a field and the photovoltaic plant is calculated with the relation:

$$E_{\_util} = (1 - \text{Losses})E_n. \quad (15)$$

### — Necessary verifications

Checking the correct choice of component equipment will be done for an equivalent generator (one inverter) in a field, becase the structure of the panels that supply the 48 inverters is identical. Four checks are required on the compatibility between the output parameters of the photovoltaic panels, including how they are connected and the parameters of the inverters.

1. The minimum voltage at the inputs of the inverters must be in the range in which they can operate properly. The minimum value of the voltage at the output of one string (of the panels connected in series) is determined by the minimum value of the voltage given by a photovoltaic panel during operation in load ($U_{pmin}$ = 26 V for $T_{min}$ = –30$^0$C) and the number of panels connected in series:

$$U_{dcmin} = N_{ps} \times U_{pmin} = 21 \times 26 = 546\ \text{V}. \quad (16)$$

Since the minimum voltage allowed at the input of the inverters is 252 V, it turns out that they work properly (546 V> 252 V).

2. The maximum voltage at the input of the inverters must be less than the maximum permissible value (1000 V). The maximum value of the voltage at the output of the series of panels connected in series is determined by the maximum value of the voltage given by a photovoltaic panel, in idle operation, ($U_{pmax}$ = 44.66 V for $T_{max}$ = 45$^0$C) and the number of panels connected in series:

$$U_{cpmax} = U_{cp0} \times (1 + \propto_T \Delta T) = 37.8 \times (1 + 0.0033 \times 20) = 44.66\ \text{V}. \quad (17)$$

$$U_{dcmax} = N_{ps} \times U_{pmax} = 21 \times 44.66 \cong 938\ \text{V}. \quad (18)$$

The significances of the quantities that intervene in relation (17), are:

$U_{cp0}$ – the voltage at the terminals of a panel when idling and the temperature of 250C;

$\alpha_T$ – voltage variation coefficient with temperature (0.33% / K);
$\Delta T$ – panel temperature variation, from 250C (test temperature) to –300C (minimum working temperature).
The safe operation condition is met because:

$$938\ \mathrm{V} < 1000\ \mathrm{V}. \qquad (19)$$

3. Maximum input short circuit current for each MPPT ($I_{scMPPT}$) must be lower than the maximum admissible value (30 A). Because two strings are connected in parallel at the input of each MPPT, it follows that $I_{scMPPT}$ is twice the sc current of a panel:

$$I_{scMPPT} = N_{rpi} \times 8.71 = 17.42\ \mathrm{A} < 30\ \mathrm{A}. \qquad (20)$$

4. The degree of efficiency must be between 80% and 120%. This condition is met because:

$$80\% < 105\% < 120\%. \qquad (21)$$

## 5. CONCLUSIONS

The designed photovoltaic plant uses high performance photovoltaic modules made by polycrystalline Si technology. The configuration mode consisting of four identical fields, each field having 12 independent elementary generators (inverters), provides a high degree of flexibility and maintenance. Moreover, each inverter has two independent inputs each with two series branches, of 21 panels, connected in parallel.

The estimated annual electricity production is approx. 1258 MWh which is equivalent to saving: 108.2 tons of oil, or 118,938 m3 of natural gas, or 155 tons of coal [17].

The positive impact on the environment is illustrated by the CO2 equivalent of approx. 1070 tons [16], which is no longer produced.

**Note**: This paper was presented at XX$^{th}$ National Conference on Electric Drives – CNAE 2021/2022, organized by the Romanian Electric Drive Association and the Faculty of Electrotechnics and Electroenergetics –University Politechnica Timisoara, in Timisoara (ROMANIA), between May 12–14, 2022 (initially scheduled for October 14–16, 2021).

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