Energy efficiency index of industry in the conditions of energy transition in Bulgaria.

Dimitrina Koeva*

Department of Electric Power Supply and Electrical Equipment, Technical University of Gabrovo, Gabrovo, 5300, Bulgaria

Abstract. Regarding the energy transformation and the Net Zero Scenario, Bulgaria's effort is to maintain a coherent energy policy with the EU-28, in accordance with its geographical and climatic conditions and the current state of the energy intensive "Industry" sector. The general analysis of the current situation in the country, synthesised in this paper, is completed by an analysis of the specific technical features of the operation of nearly 1700 induction motors in two highly energy intensive enterprises: a chemical factory and a food factory. The energy losses on an annual basis can be determined by using several parameters and magnitudes. Recommendations and key factors for energy efficient investments are also presented.

1 Introduction

European Environmental Agency (EEA) defines „energy efficiency index of industry", (ODEX). This index is a weighted average of the specific consumption index of 10 manufacturing branches; the weight being the share of each branch in the sum of the energy consumption of these branches in year t and the sum of the implied energy consumption from each underlying industrial branches in year t (based on the unit consumption of the sub-sector with a moving reference year). For manufacturing industry, the evaluation is carried out at the level of 12 branches: 7 main branches: chemicals, food (beverage and tobacco), textile (and leather), wood, machinery (and metal products), transport vehicles and other manufacturing; 3 energy intensive branches: steel, cement, pulp and paper, mining and construction; 2 residual branches: other primary metals (i.e. primary metals minus steel) and other non-metallic minerals (i.e. non-metallic mineral minus cement). On this basis, the EEA prepares an energy profile for each country, [1]. This country profile summarizes key data related to industry: its relevance with respect to economic contributions, energy and water consumption, as well as air and water emissions and waste generation. Country profiles are available for EEA 33 member countries (Bulgaria is a member of group) and EU-28, Figure 1. In 2017, for example, industry in Bulgaria was responsible for 27.69% of energy consumed, 23.99% of gross value added and 83.76% of water use! The National Integrated Plan in the field of energy and climate of Bulgaria 2021-2030 has been prepared in accordance with the requirements of Regulation (EU) 2018/1999

* Corresponding author: dkoeva@abv.bg

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and formulates the goals, priorities and policies for increasing energy efficiency in the country, [2].

In this regard, national targets have been set to achieve a 27.89% reduction in primary energy consumption and a 31.67% reduction in final energy consumption by 2030, relative to the reference scenario PRIMES. In quantitative terms, the country's national goals until 2030, specified in this plan, are:

- Primary energy consumption (PEC) - 17 466 ktoe (in 2021 – 18 578.1 ktoe)
- Final energy consumption - 10 318 ktoe (in 2021 – 10 247.1 ktoe)
- Final consumption in the sector "Industry"- in 2021 –2 910.7 ktoe, which is 28.41% of the total for this year.

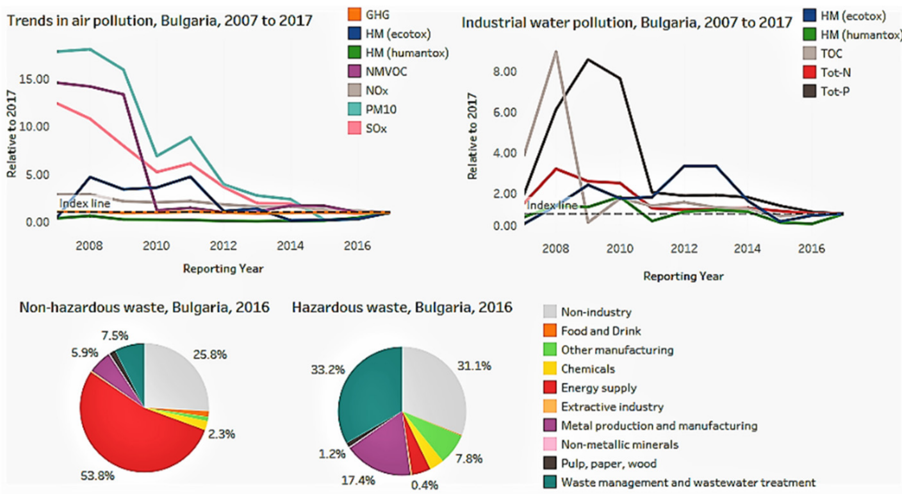

Fig.1. Energy profile of Industry sector in Bulgaria according to data of EEA.

Bulgaria's national goal in terms of energy savings is defined in the Integrated Energy and Climate Plan of the Republic of Bulgaria 2021-2030. The country uses the opportunity under Directive (EU) 2018/2002 to gradually increase the goal by reaching the defined cumulative goal of 4,357.55 ktoe in 2030. The national cumulative target is met by introducing a duty scheme for energy traders and alternative measures. All this is happening under the conditions of energy transition and activities part of the REPowerEU plan, [3]. In the Industry sector, a significant decrease of the GVA (8.6%) was observed in the crisis year 2020, as well as minimal growth in 2021. After a minimal decrease in 2020, the energy consumption grew significantly in 2021. However, the energy intensity grew in the last two years with the total growth being almost 12%. The effect of the crisis in 2020 lead to a decrease in the energy consumption, due to a decrease in the economic activity in the industry, but this decrease has been compensated by a decrease in the efficiency in production due to the crisis. In 2021, compared to 2020, the GVA grew with only 1.7%. At the same time, the energy consumption has increased by almost 10%, leading to a significant increase in the energy intensity with 8.1%.

International Renewable Energy Agency (IRENA) presents data for Bulgaria in terms of generating capacity according to the type of technology used, energy losses and electricity consumption by sector, Figure 2. [4]. The data are summarized in Table 1. When it comes to the beginning of the energy transformation period, the primary energy consumption has the main objective of limiting the use of electrical energy from non-renewable sources and increasing its efficient use in general. A major contribution to the reduction of the energy consumption is the accelerated implementation and absorption of the potential of renewable energy sources. [3, 5].

Table 1. Bulgaria energy balances, 2020.

Supply by Technology, 2020, MWh	Electricity	- 625 138.89
	Pellets	-400 277.78
	Solar Thermal	318 722.22
	Renewable Waste	487 638.89
	Other Renewable	1 297 888.89
	Geothermal	415 277.78
	Wind	1 477 138.89
	Solid Biofuels	19 114 111.11
	Solar PV	1 480 861.11
	Liquid Biofuels	2 001 027.78
	Hydropower	2 820 388.89
	Biogas	619 916.67
Total Transformation Losses, 2020, MWh	CHP	-1 908 750
	Own Use	-1 436 666.67
	Distribution	-771 333.33
	Electricity	-479 888.89
	Heat	-29 027.78
Consumptions by Sectors, 2020, MWh	Transport	2 077 194.44
	Industry	4 968 000
	Residential	12 683 472.22
	Commercial	4 403 166.67
	Other	159 944.44

The increase of the energy consumption in the industry is caused by the increase in the consumption of electricity and heat. The energy intensity decrease in the industry is due to the replacement of low-efficiency fuels (coal) with high-efficiency energies (electricity and heat). In Bulgaria, the levels of final energy intensity in the industry (FEI) are defined as high (this is a ratio of the consumed energy to GVA, created in the industry). In the last five years, there has been an increase in the GVA created in the industrial sector, under the conditions of decreasing energy consumption (Figure 3). The actual reduction of the industry's FEI is equally due to the improvements in energy efficiency and internal restructuring, concentrated on industries with lower energy intensity. Despite this downward trend, the FEI of the industry remains relatively high – about twice as high as the average for EU countries, Figure 4, [4].

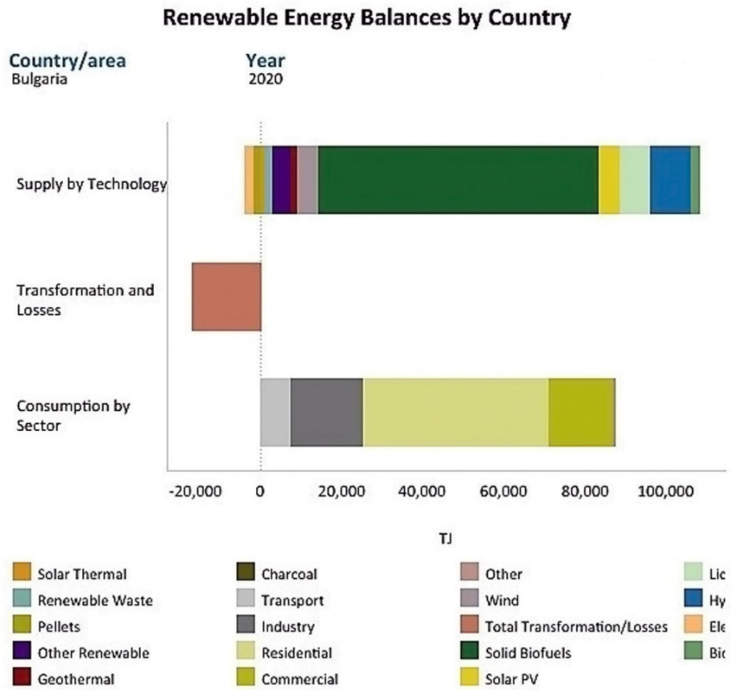

Fig. 2. Bulgaria energy balances. (https://www.irena.org, last update: 09 August 2022).

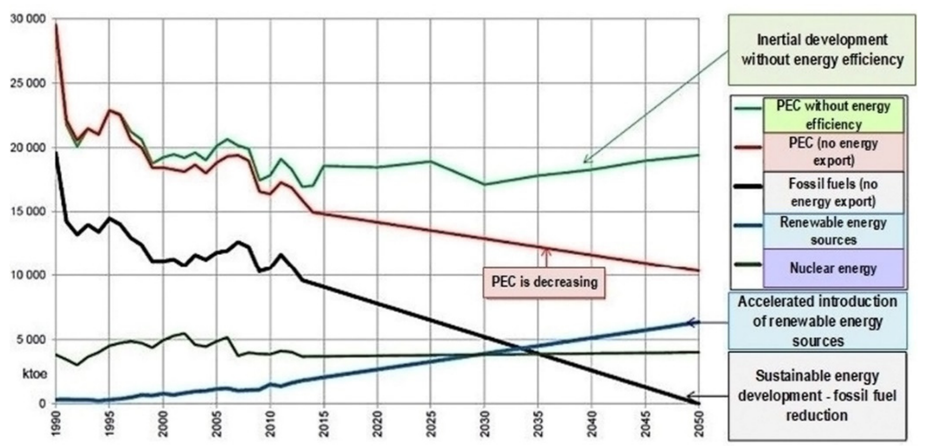

Fig. 3. PEC according to Integrated plan in the field of energy and climate of Bulgaria.

The most frequently recommended measures for increasing energy efficiency are:
- Combined production of heat and electricity (cogeneration) – 1%;
- Use of RES – 2%;
- Reduction of energy costs for buildings – 11%;
- Energy-saving lighting – 12%;
- Energy efficient transformers – 5%;
- Introduction of highly energy efficient electric drives and motors – 6%;
- Changing the used fuel – 5%;
- Increasing the energy efficiency of boiler plants - 8%;
- Improvements in thermal insulation (14%) and steam transferring systems (8%);

- Improvement of technologies (11%) and/or replacement of technological equipment (10%);
- Energy monitoring systems – 6%.

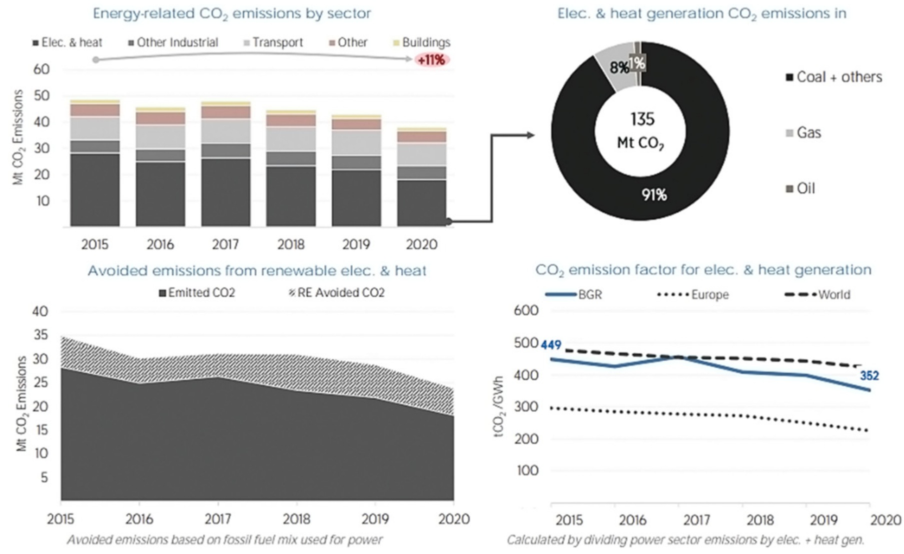

Fig. 4. Energy related CO2 emissions by sector in Bulgaria.

Energy efficiency measures in the industry do not go out of focus. On the contrary, energy efficiency management in all enterprises and industrial systems becomes mandatory. This measure has been regulated in Art. 63 of the EE Law, according to which EE management should be carried out. The main object of one of these measures is industrial systems, which annual energy consumption is over 3000 MWh. For 2022, 57 industrial systems have been inspected. Energy saving measures (ESM) for lighting installations and replacement of technological equipment have been marked as the ones that have been used the most. In 2022, the largest amount of energy was saved by applying the ESM measure on technological aggregates and equipment and by the replacement of technological equipment. According to the assessment of the effect of energy efficiency management for the past year (2022) in enterprises and industrial systems the saved energy is GWh/y 449.6; the saved carbon emissions CO2 ktCO2/y are 187.2; the investments are 130.9 million lv/y, as 78% of them are own investments.

2 Technical considerations

The EE measures that have to be taken under consideration are focused in two directions. The first is requiring large investments and optimizing electricity consumption in the long run and it includes identifying and implementing measures, related to limiting electricity consumption. With the second alternative, the industrial site maintains its current consumption, but uses all the opportunities provided by the liberalization of the energy market. The choice of specific measures is strictly individual and fully compliant with the specifics of each enterprise. The development of an effective program begins with an objective and accurate analysis of the consumption of energy resources. In order to analyze, it is necessary to provide information on the actual consumption of all capacities, included in the relevant production. In order to provide this information, comprehensive systems are being built to measure the consumption in all key locations – aggregates, transformers, substations, production lines, etc., as well as the industrial facility itself as a whole.

The second stage includes the development of the program itself, as here a very important element is the analysis of the current consumption structure. This is essential in order to predict future consumption. It is also necessary to analyze the technical condition of the existing technological equipment, as well as to build a system for measuring and controlling the consumption at all critical points. The analysis is both technical and economic, as it takes into account the profitability of the planned investments, considering the expected electricity savings. Another approach, that specifically refers to the optimization of electricity costs, involves selecting the most attractive price tariff for the payment of electricity.

The electricity consumption of the industrial users is mostly measured with three-tariff electricity meters, due to the large amounts of energy that they consume. In order to reduce the costs that the enterprise has to pay, it is necessary to precisely calculate the peak consumption of day and night electricity. The ultimate goal is to manage the load schedule so that the most energy-intensive activities are concentrated in the periods of cheapest energy. Therefore, it is possible to impose a non-standard mode of operation of the enterprise in order to reduce the costs. However, managing the load schedule by trying to load the production capacities in the hours of cheaper energy is not always technologically possible. On the other hand, switching to a non-standard mode of work is associated with higher wage costs. For these reasons, the implementation of this type of event is recommended after expert analysis has been carried out.

When talking about the optimization of electricity costs, the liberalization of the electricity market should not be overlooked, i.e. using the lowest possible electricity price. Another approach to reduce the costs of electrical energy in enterprises without limiting the consumption is to implement measures that are directed towards reaching compliance between the regulated and the actually achieved power factor. This will save the allowances that is paid every month depending on the registered deviation between the prescribed and the achieved power factor.

The second major approach to reduce the energy costs involves developing and implementing a program to limit the consumption. This could be achieved by technological optimization, loss limitation or by a very good knowledge of the technology specifics. It usually works both ways. Among the largest consumers of electrical energy in the field of industry are electric motors, as a predominant share of them have IM. It is considered that if the average load of the engine is 45% of the nominal, it is economically feasible to replace it with a model with less power. In applications where the motor load is higher than 40% and at the same time lower than 70% , the decision to replace it is made after a thorough analysis. Initially, the calculation of the real load factor depends on the operation mode of the engine - with a relatively even loading, with cyclic loading without switching off the engine between cycles, with cyclic loading with switching off the engine at the end of the cycles and with non-periodic and non-cyclic loading. After the load factor has been calculated and depending on the so-called power losses, it can be determined how appropriate the investment in a new engine is.

3 Power and energy losses in IM with industrial application

The electrical equipment of industrial units, and in particular their electrical drives, are the main consumers of electrical energy in the industry. Electric drives are included in the electrical equipment of mass-used fans, pumps, conveyors, cranes, elevators, machine tools, etc. The development of electric drives does not exclude but anticipates the development of other types of industrial drives (hydraulic, pneumatic, internal combustion engines, etc.). In some cases, combined drive systems are used, e.g. electric and hydraulic drives for electric trucks, high-lift trucks and machine tools, etc. By using an established mode of operation of the electric motors, the losses of active energy ΔW_a in them can be determined as the sum of the losses in the windings in the steel and also the mechanical losses:

$$\Delta W_a = 3.k_{fi}^2.I_{cp}^2.R_e.T_p\,, \tag{1}$$

where R_e for IM is the sum of the stator resistance and resistance of the rotor: $r_1 + r_2^{`}$.

Steel losses are determined by measurement only for wound-rotor IM:

$$\Delta W_{steel} = T_{act}(P_0 - 3.I_{10}^2.r_1), \tag{2}$$

where P_0 - idle power; I_{10} - idle current, T_{act} - actual working time; k_{fi} - form factor of the load schedule by current.

For all motors (except for wound-rotor induction motors), steel losses should not be separated into a different part of the energy balance. Like the mechanical losses, they also depend on the load of the electric motor, and therefore they are combined with them.
The mechanical losses in the units and the electrical losses in the steel of the AC drive motor are determined by the equation:

$$\Delta W_{mech} + \Delta W_c = (P_{id} - 3.I_{id}^2.r_1).T_{act}, \tag{3}$$

where: P_{id} - no-load power of the electric motor coupled to the drive mechanism; I_{id} – idle current.

Losses in transient modes of electric motors are determined as follows:

- startup process $\Delta W_п \approx k.h_п.\frac{GDn_0^2}{2620}.10^{-6}$, [kWh];
- when stopping by switching $\Delta W_{тп} \approx 3кh_т\frac{GD^2n_0^2}{2620}.10^{-6}$, [kWh];
- in reverse braking mode $\Delta W_{рев} \approx 4k.h_p.\frac{GDn_0^2}{2620}.10^{-6}$, [kWh];
- in dynamic braking mode $\Delta W_{тп} \approx \Delta W_п$,

where: $h_п, h_т, h_p$ - number of starts, stops, reversals for 1 hour; n_0 – speed of the electric motor at ideal idle speed; k=1+$\frac{r_1}{r_2}$ for IM; GD^2 - motor and mechanism torque.

4 Calculation and results

The subject of the study is the operation of IM in two industrial enterprises whose production is defined as energy-intensive (chemicals and food - two of the main 7 branches). The losses in the electric motors of these enterprises, which for technological reasons work from 9 to 22 hours a day and 335-348 days in the year (in three-shift operation mode) are calculated. The form factor of the load current schedule k_f is determined as follows: for IM operating from 9 to 12 hours - k_f = 0.86; operating from 12 to 15 hours - k_f=0.88; operating from 15 to 21 hours - k_f=0.9 and operating until 22 hours - k_f=0.92. In order to determine the losses in detail, we have previously defined the parameters and magnitudes of the IM that drive the industrial systems in both enterprises using ANSYS MotorCAD motor design software, [6, 7, 8]: the resistance of one phase of the stator winding r_1, rotor resistance reduced to stator winding $r_2^{`}$, idle power P_{id} and the idle current I_{id}, Table 2.

Table 2. Parameters and dimensions of the considered IM.

IM rated power, kW	**0.4**	**0.8**	**1.1÷2.2**	**4**	**7.5**	**11**	**13**	**15**	**17**	**18.5**	**22**	**75**	**up to 180**
r_1, Ω	35.1	20.13	8.39	1.7	1.37	0.52	0.36	0.402	0.318	0,261	0.22	0.123	0.071
$r_2^`, \Omega$	21.55	6.3	3.97	0.942	0.57	0.41	0.245	0.196	0.158	0,153	0.14	0.01	0.088
P_{id}, W	38	73.87	109.48	275.75	243.6	402	392	435.8	362.8	618,2	754.5	927	1537
I_{id}, A	0.5	0.77	0.48	0.42	5.6	6.2	7.24	7.8	6.95	9.24	12.75	33.5	39.75

The total number of drive motors in the Chemical factory is 1047, and in the Food factory – 664 as they have been listed according to their rated power and presented in Table 3. The active energy losses in the motors in the Chemical factory are 7.65% of the total annual active electrical energy consumed, and the active energy losses in the motors from the technological production in the Food factory – 11.5%, Figure 5. Reactive energy losses in engines in the Chemical factory are 4.85% of the annual amount of reactive energy consumed, and for the Food factory - 9.03%, Figure 6. Almost twice as many engines, which have a significant share in the energy losses of the Food factory! What could be the reason for that?

Table 3. IM according to rated power and application.

IM rated power, kW	**0.4**	**0.8**	**1.1÷2.2**	**4**	**5.5**	**7.5**	**11**	**13**	**15**	**18.5**	**22**	**30**	**55**	**75**	**up to 180**
Chemical factory	434	18	216	4	134	154	23	6	6	2	10	4	19	3	14
Food factory	344	10	157	38	18	13	22	-	18	10	11	6	6	7	4

Obviously, the assessment of purely technological options for reducing the consumption is a complex process that requires a profound knowledge of the currently available technologies. Each production is characterized by the so-called theoretical minimum in energy consumption. In order to make a precise analysis of the opportunities for savings, the consumption in the process of implementing the technology and the consumption in the process of its operation must be known. The lower the energy consumption of a given technology, the greater the opportunities for energy savings. On the other hand, it is also true to say that the less energy-intensive a given technology is, the more expensive and difficult it will be to implement the measures for further reduction of the energy consumption. Usually, the specific consumption of electricity in the process of implementation of a given technology has the highest value. In the process of operation and due to a number of factors (among which is the knowledge of the technology specifics by the personnel) the specific cost decreases. Eventually, the main question which technology to choose and whether to keep the old one by trying to increase the energy efficiency, or to initiate a complete replacement with a lower energy-intensive technology is purely economic.

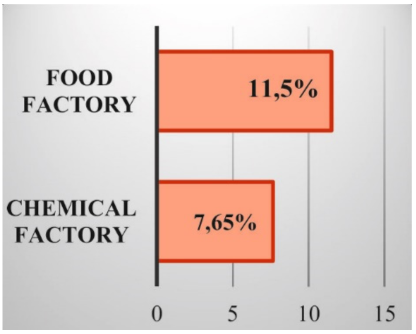

Fig. 5. Active energy losses.

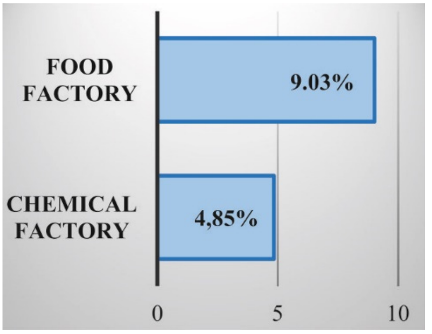

Fig. 6. Reactive energy losses.

That is one more reason to emphasize on the great importance of some key economic evaluation indicators, when it comes to investing in energy efficiency, [9]. These indicators are static and dynamic. For example: a simple redemption period (PB) is static and does not reflect the moment when the investments are made; O/M – maintenance costs, etc. The relation between them is described by the following equations:

$$B_b = S.E; \tag{4}$$

$$B = S.E - \frac{O}{M}; \tag{5}$$

$$PB = \frac{I_0}{B}, \tag{6}$$

where: $B -$ economy of energy saving activities, [kWh/year, kWh/lv]; E- average price, [lv/kWh/year]; S - saved energy for 1 year; B_b - gross annual savings; B - net annual savings; PB - simple redemption term; I_0 - initial investment; $\frac{O}{M}$ - maintenance costs.

There are also dynamic indicators: n - asset utilization period; r- real rate of interest, %, (software that estimates energy savings consider this a real estimate, as it is adjusted for inflation).

$$r = \frac{r_n - b}{1 + b}; \tag{7}$$

$$PV_i = \frac{B_i}{(1 + r)^i}; \tag{8}$$

$$NPV = B.\frac{1 - (1 + r)^{-n}}{r} - I_0, \tag{9}$$

where: r_n - nominal interest rate, %; b – inflation %; i - year being observed; PV_i- present value of net savings, [lv]; $\frac{1}{(1+r)^i}$ - the discount factor; NPV - net present value of the investment, [lv], (if $NPV > 0$, then the investment has been successful).

The difference between the two energy-intensive enterprises in this polar example comes down to:

- responsible and practical use of the ISO: 50001 - Energy management standard;
- use of secondary energy sources;
- use of the above-mentioned key dynamic indicators for energy efficient investments;
- consideration of the fact that the investment risk assessment includes technical, economic, administrative and management indicators. A simplified assessment of the energy efficiency can be carried out when production growth is maintained. Then the energy efficiency matches the energy intensity, [6].

If the production parameters are changed (a frequently observed situation during an energy crisis and energy transition), a recalculation of the average annual, initial and expected consumed electrical energy is required. If it is necessary to determine the ecological footprint of an average economy on an annual basis, then for saved energy $EF = 1.039\ kgCO2/kWh$ and for generated energy $EF = 0.833\ kgCO2/kWh$, [10].

Industrial activity in 2021 was directly responsible for emitting 9.4 Gt of CO2, which is equal to a quarter of the global emissions (without including the indirect emissions from electricity used for industrial processes). In the Net Zero Emissions by 2050 Scenario, industrial emissions fall to about 7 Gt CO2 by 2030, despite the expected industrial production growth. Modest improvements have already been made in the energy efficiency and also in renewable energy uptake, as well as some positive policies and innovation steps [5, 10].

Every EU country has its own strategy according to the level of its economic development. In our country, a new energy strategy must be built along with the development of an industrial strategy, given the forecast for an increase in the consumption of the energy-intensive industry. But before that it is necessary to make a detailed and realistic analysis of both the supply of electricity and the consumption. An important condition is to guarantee the provision of electricity at such a price that will preserve the competitiveness of the Bulgarian industry and will promote our native production.

It is important to point out the difference between energy amplification and energy intensity. Energy amplification is when a lot of energy is consumed in general, and energy intensity is when a lot of energy is consumed per unit of product due to the characteristics of the technological processes - electrolysis, melting of metals, synthesis of chemical products, etc. Energy-intensive industries are efficient, but they require a lot of energy and therefore the needed resources form a major component of their costs.

For many years the industry in Bulgaria has been the most energy efficient sector by constantly improving its performance. All large enterprises are continuously working towards improving their energy efficiency, because it is of major importance to good competitiveness and high export potential. Moreover, energy efficiency does not always lead to the reduction in electricity consumption. This is the so-called Jevons paradox - when the energy consumption per unit of product is reduced and the energy efficiency is increased, its production can be expanded by producing more units of the final product more efficiently and eventually increasing the energy consumption in absolute units. Despite the temporary calming of the energy markets, there is still a certain level of concern regarding the further increase in gas and electricity prices, as it cannot be determined whether the period of free and unpredictable formation of these prices has finished. Another challenge is the revival of long-term electricity deliveries to industrial end-users, as the risks arising from the high proportion of spot trading over the past 18 months have become clear.

However, what is Bulgaria's plan and isn't it too late to react? Bulgaria needs to increase the investments for energy transition. Smooth decarbonisation must be combined with very good predictability of electricity and energy resources also for the industry. Of course, with an increasing share of the energy mix of wind, solar and biomass.

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