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Economic assessment of gas-steam systems taking account of variable loads

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Abstract

Increasing competition from high-power gas technologies on the energy market depends on many factors. Apart from the requirement to meet ecological criteria, the most important are: improvement in thermal flexibility, favorable characteristics of performance at variable loads and the related economic efficiency. The adaptability of gas technologies to changes in loads in the 24-hour cycle is now attracting special interest. This paper focuses on issues related to adapting the methodology of economic calculations to the changing roles of gas technologies in the electricity generation subsector. In the new market environment, an economic model which comprises a certain number of parameters (which usually characterize the base load) and takes account of revenues coming from this type of operation does not provide a full picture. First and foremost, it does not indicate additional revenues that could potentially be earned from new market possibilities related to rendering system services and reducing the environmental impact. Generally speaking, a more accurate approach to the assessment of gas-steam systems has to factor in basic parameters that determine thermal flexibility (start-up and shutdown times), issues related to maintaining availability, changes in efficiency at variable loads and emissions characteristics.

Keywords: Gas-steam combined cycle, Cost of electricity, Load profile

1. Introduction

The national electricity generation sector is expected to witness an increase in the share held by gas turbine technologies. This forecast is related to the new requirements that power generation technologies have to face in connection with developments in the energy market, new emissions goals and the rise in wind and solar technologies. Compared to coal technologies, standalone gas turbine sets and gas-steam systems are much better at coping with requirements related to the rise in thermal flexibility (understood as the dynamics of changes in load and maintaining the durability of main modules) and improvements in efficiency and reliability. Ecologically, one important advantage of gas fuel is the smaller amount of carbon dioxide generated in the combustion process per unit of chemical energy contained in the fuel compared to other fossil energy sources. In the process of carbon combustion 0.112 kg CO_2/MJ is produced, whereas in the case of methane combustion – the unit emissions are equal to 0.055 kg CO_2/MJ. Moreover, taking account of the difference in electricity generation efficiency between coal and gas technologies, there is a substantial ecological advantage to be obtained from gas-based technologies, which is expressed in much lower carbon dioxide emissions per unit of generated energy. Also, for currently applied TIT (Total Inlet Temperature) values [1] the standard levels of NOx emissions can generally be achieved without any serious problems. An important reason for the rising significance of gas technologies in the Polish power sector is the anticipated increased availability of gas in Poland (shale gas, new exploration of conventional gas, import) [2, 3]. An increase in competition from high-power gas technologies on the energy market depends on many factors. Apart from the requirement to meet eco-

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logical criteria, the most important of them are: an improvement in thermal flexibility, favorable characteristics of performance at variable loads and the closely related economic efficiency. The adaptability of gas technologies to changes in load in the 24-hour cycle is now gaining special importance. This paper focuses on issues related to adapting the methodology of economic calculations to the changing roles of gas technologies in the electricity generation sub-sector.

2. General characteristics of the computational method used in the economic analysis of electricity generation based on gas technologies

The economic analysis of a given type of technology is usually conducted using conventional discount methods which determine different measures of an investment project profitability assessment (e.g. [4–7]). In contrast to simple methods, discount methods make it possible to compare expenditures and effects for projects completed in different periods of time. Determination of the net present value is the basis for drawing further conclusions. It should be stressed here that this concerns periods of project completion (construction) and operation. The measures used in the analysis are the following: Net Present Value (NPV), Internal Rate of Return (IRR), Modified Internal Rate of Return (MIRR), Discounted Pay Back Time (DPBT), Break Even Point (BEP) and others. In order to determine these quantities, net cash flows CF need to be defined:

$$CF = -J_0 + J_k + S_n - K + A - R - P_d + L \tag{1}$$

where: J_0—investment expenditures in total, J_k—the amount of taken up loan, S_n—sold output (net), K—production cost, A –depreciation, R—loan repayment installments, P_d—income tax, L—liquidation value.

The cost of production may be written as:

$$K = K_{op} + F + A \tag{2}$$

where: F—costs of financial services, and operating costs are understood as:

$$K_{op} = K_E + K_p + K_{or} + K_{pr} + K_e \tag{3}$$

K_E—costs of energy (including fuel), K_p—pay costs, K_{or}—servicing, maintenance and repair costs, K_{pr}—costs related to other materials, K_e—other operating costs (including fees for using the environment).

Production costs can also be expressed using the notions of fixed and variable costs:

$$K = K_f + K_v \tag{4}$$

Fixed costs are independent of the output volume. They comprise costs related to the capital service and a part of K_e (the plant overhead costs, costs of management, etc):

$$K_f = K'_e + \rho J_0 \tag{5}$$

where: ρ—rate of the investment capital service. Variable costs K_v will be approximately be equal to K_{op}.

Assuming annual output of electricity generation as E, the unit cost of production is found:

$$k = \frac{K_f + K_v}{E} = k_f + k_v \tag{6}$$

Formula (6) allows a clearer assessment of cost tendencies in the case of more complex operating scenarios.

3. Selected aspects of adaptation of economic models for a power plant operating with variable demand for electricity

The effectiveness of the power engineering installation operation depends on operating algorithms. In traditional economic models it is determined using the nominal load data (power output capacity, efficiency), the time of operation being treated as a parameter. This method of calculating unit costs of production and other economic indices for installations operating in substantially changeable conditions may lead to errors. If the technological structure of power generation systems becomes diversified (due to the growing share of low energy density technologies in electricity generation), many installations (including gas-steam systems) operate on a daily start-stop cycle basis with a two-time start-up process in every 24 hours. In such conditions, which may become even more complex in future, tasks related to improving the gas installation characteristics gain special importance. The tasks should aim to:

- increase operating flexibility (improved dynamics of the change in load without affecting durability of components, fast start-ups and shutdowns).
- reduce operating costs (high efficiency at variable loads, fuel flexibility),
- improve reliability and availability.

These factors will determine the choice of gas technologies and their competitiveness on the energy market in the near future. A discussion of these issues is central to creating rational technological structures of gas-steam systems, taking account of the turbine available, series of types and indicating directions for improving characteristics of individual modules of the gas-steam system (the gas turbine set, the waste heat boiler, the steam turbine, automation and control systems).

In the new market environment, an economic model comprising a certain number of parameters (which usually characterize the base load) and taking account of revenues coming from this type of operation does not provide a full picture. First and foremost, it does not indicate additional revenues that could potentially be earned from new market possibilities related to rendering system services and reducing the environmental impact. Generally speaking, a more accurate approach to the assessment of gas-steam systems has to take account of the basic parameters that determine thermal flexibility (start-up and shutdown times), issues related to maintaining availability, changes in efficiency at variable loads and emissions characteristics.

In order to discuss selected aspects of the impact of some operating parameters on making the economic model more realistic, let us write the unit cost of electricity generation in a gas-steam system in the following form:

$$k = \frac{\rho J_0 + K_e'}{E} + \frac{K_p}{E} + \frac{K_e''}{E} + \alpha \frac{K_{op} - K_p - K_e' - K_e''}{E} \quad (7)$$

$$k = \frac{\rho J_0 + K_e'}{\bar{\tau}\bar{N}} + \frac{k_p}{\bar{\eta}} + k_e'' + \alpha k_{eks} \quad (8)$$

where: k_p—fuel energy unit cost; $\bar{\eta}$, $\bar{N}$—equivalent efficiency and power output of an installation operating at a variable load; $E = \bar{\tau}\bar{N}$, $k_e'' = \sum_i C_i e_{pi}$, $\bar{\tau}$—total operating time of the power unit in operation (taking account of start-up and shutdown times, i.e. ignoring the latter as they are small compared to the former):

$$\bar{\tau} = \tau_0 + \sum_1^U n_i t_i \quad (9)$$

τ_0—total operating time at different loads, n_i—number of start-ups with time t_i, U—total number of start-ups, C_i—costs of emissions of the i-th substance (per mass unit), e_{pi}—emissions of the i-th substance per generated unit of electricity, α—measure of the increase in operating costs in specific events of operation (base load $\alpha = 1$), k_{eks}—costs for the base load.

It is not an easy task to determine the quantities included in Equations (7–8) and use them in the analysis of the NPV, IRR or other functions.

From the point of view of the accuracy of analysis, finding the equivalent power and efficiency of an installation operating at variable loads is an important step. Various methodological approaches can be adopted here. If the load algorithm and the gas-steam system technological structure are known, it is relatively easy to determine equivalent efficiency. Otherwise, load coefficient β can be estimated using the following formula (e.g. [8, 9]):

$$\beta = \frac{E}{\bar{\tau}} \frac{1}{P_0 \gamma_0 (1 - \delta)} = \frac{\bar{P}}{\bar{P}_\delta} \quad (10)$$

based on it, $\bar{P}$ is found. In (10) P_0 denotes nominal power, γ_0—is a correction factor of the impact of ambient temperature on the volume of generated power, δ—index of power degradation depending on the method of operation. For γ_0 and δ known from (10), $\bar{P}$ is found. It is more difficult to determine the installation equivalent efficiency corresponding to the assumed operating mode. In [8, 9] it is proposed that this quantity should be calculated from the following formula:

$$\bar{\eta} = \eta_0 \gamma_1 (T_{ot}) \gamma_2 (\beta) \left(1 - \delta_\eta\right) \quad (11)$$

Calculating equivalent efficiency from (11) requires the determination of the impact of ambient temperature (T_{ot}) on efficiency (coefficient γ_1) and the effect of variable loads (γ_2) and that account of efficiency degradation in the process of operation (δ_η). Once in possession of the values under consideration, it is possible to determine the volume of annual electricity generation and related emissions. The computational process requires modeling the installation in different load states and at different parameters of the surroundings. In [10], variants of the reference installation are proposed. Analysis of it could be decisive when selecting the technological structure with respect to the specific market model and expected economic profits at the design stage. Discussion of the interrelations between technological structures and operating strategies facilitates decisions leading to a minimization of k determined according to (7–8).

4. Discussion

4.1. *Configuration of power plants with gas-steam installations*

Apart from quantitative measures of thermal flexibility, works on gas-steam installation (GSI) optimization

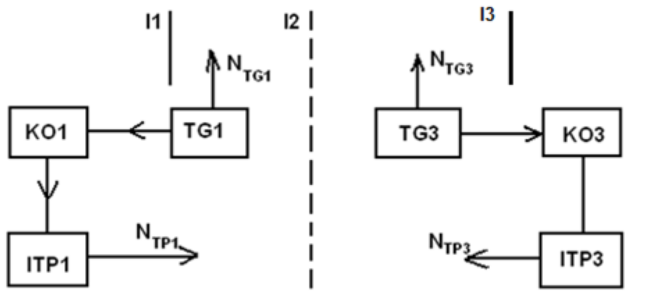

Figure 1: Configuration composed of several (i=1–3...) double-shaft systems: TG (the gas turbine set) + KO (waste heat boiler) + ITP (steam turbine installation)

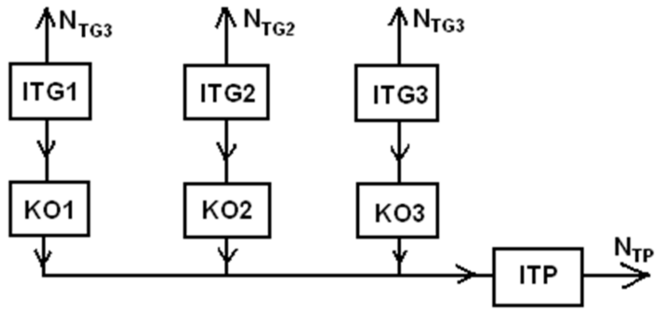

Figure 2: Configuration composed of several (i=1–3...) TG + KO systems combined with a single ITP

should take account of the installation's efficiency at variable loads, the technical minimum and the emissions characteristics, including the unit value of carbon dioxide emissions. Therefore, the first essential step in the process is to select the technological configuration of the gas-steam power plant. The systems that can be analyzed are presented in Fig. 1–3 [9].

Each of the proposed configurations has advantages and disadvantages, and not all of them are available for each class of gas turbine. The strong point of the system presented in Fig. 1 is the possibility of constructing

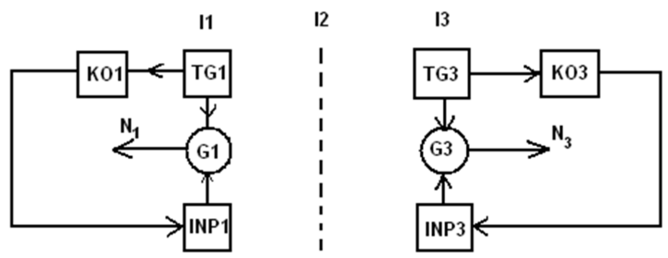

Figure 3: Configuration composed of several (i=1–3...) single-shaft systems: TG + KO + ITP

installations with a high power output capacity. The investment process can be spread over time. Individual installations can be viewed as modules made with the use of not necessarily the same classes of gas turbine. The power plant technical minimum is the same as the technical minimum of a single module. A configuration like this allows a reduction in efficiency losses at small loads. The system can operate with a cyclical change in power output at evening shutdowns and morning start-ups from the hot state of each module. The system shown in Fig. 2 is more "rigid" technologically. It should be used to operate at base load. Its initial configuration cannot be changed without fundamentally affecting electricity generation efficiency. One of its advantages is high efficiency for the nominal load (a high power steam turbine has greater internal efficiency than a low power turbine) and a reduction in the required number of generators. The technical minimum corresponds to the technical minimum of a single gas turbine set (it may be conditioned by a minimum mass flow of steam through the steam turbine). Efficiency at variable load largely depends on the steam turbine characteristics. The installation with the configuration presented in Fig. 3 has the same advantages as the one shown in Fig. 1. However, it is only available for single-shaft UPGs. The power plants included in this configuration class usually consist of one module. During the assessment of individual configurations, apart from technical characteristics, the results of a thorough economic analysis should be considered. Beside typical cost components, the economic analysis should take account of the anticipated nature of operation (its variability in individual periods of operation), the number of start-ups and emissions characteristics.

4.2. Investment costs

The share of investment expenditures in production costs is defined by the first term of the right side of equations (7–8). Its value can be determined by the anticipated operating strategy to the effect that strategy realization may require an appropriate technological structure, which has an influence on expenditure. Another element is the time of making investment decisions. Fig. 4 presents information on changes in the prices of gas turbine installations. Similar relations will apply to gas-steam systems.

4.3. Carbon dioxide emissions

An analysis of costs related to carbon dioxide emissions may in some cases be important when selecting procedures and methods of operation. The analysis of this

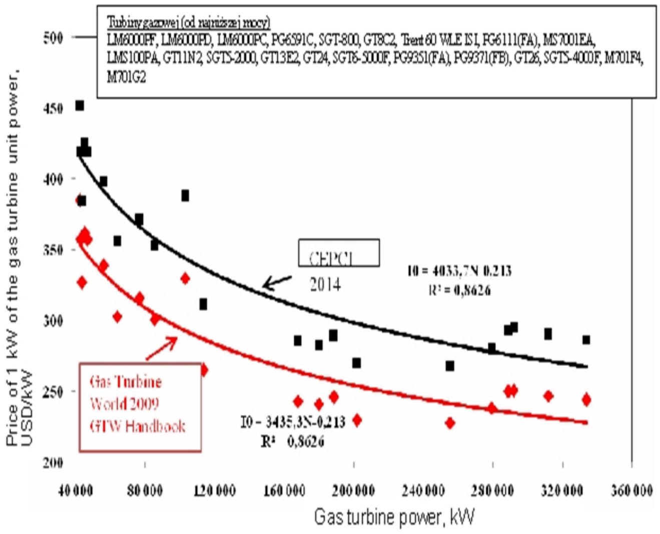

Figure 4: Price of gas turbines depending on power capacity

cost component justifies the option of installation shutdown for the night period (low load) rather than continuing operation at a small load. The cost effect of such an action can be estimated using the following formula:

$$\Delta k = \Delta\varepsilon\,(CO_2)\,C\,(CO_2) + \Delta c_p k_{jp} - \Delta E k_{jel} - \Delta\delta_{INS} \quad (12)$$

where: Δk—reduction in operating costs, $\Delta\varepsilon$—change in CO_2 emissions, C(CO_2)—unit cost of CO_2 emissions, Δc_p—reduction in fuel consumption, k_{jp}—cost of fuel mass unit, ΔE—reduction in electricity generation, k_{jel}—unit selling price of electricity, $\Delta\delta_{INS}$—difference in costs of start-ups and of the installation degradation resulting from them compared to degradation due to operation at a small load. Works [11–14] present the estimate for the SCC5-4000F 1S gas-steam system, which indicates that everyday shutdown of the installation may generate savings in the order of €5 million throughout the entire year (fuel price: 20.2 €/MWh, CO_2 emissions price: 2.88 €/MWh, electricity price in the shutdown period: 29.4 €/MWh).

4.4. Start-up time

Table 1 presents basic data concerning thermal flexibility, efficiency and emissions for conventional technologies.

The values point to significant progress in developing start-up processes and improving indices related to load variability dynamics. Progress has been made in all technologies but it is most visible for the UGP. From the point of view of the 24-hour load structure, the data concerning the start-up time from the hot state (downtime <8 h) are essential. A significant step forward has been made lately to increase the share of gas technologies in the stabilization of the electrical power system.

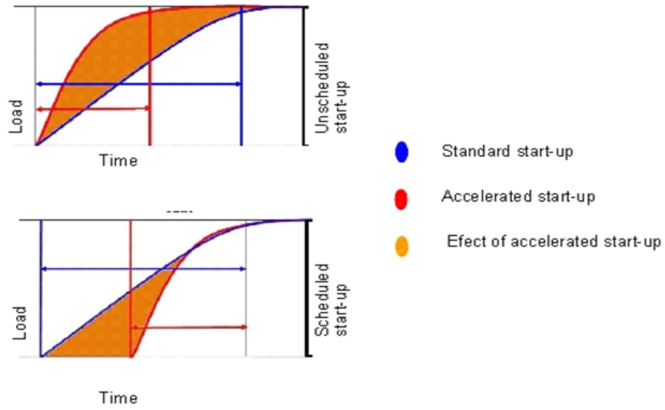

Figure 5: Accelerated start-up vs. standard start-up in the range of load and electricity generation

Planning the load strategy must take account of technological limitations (allowable start-up time, life reduction, minimum time of operation, minimum load, capability to operate effectively at peak loads). These parameters make it possible to calculate electricity generation costs depending on the selected start-up system. Taking the curve illustrating changes in electricity prices into consideration, the information can be optimized to maximize the internal rate of return.

The following data are required to perform the calculations:

- reduction in the start-up time, min
- fuel mass flow during start-up, MWh/min
- electricity generation during start-up, MWh/min
- variable cost of the start-up process (mainly fuel costs that have to be considered), €/GJ)
- costs and charges for life reduction (factor α in Equations (7–8))
- costs and revenues from of balancing energy market, €/MWh (important for the market participants)
- costs or revenues from CO_2 certificates, €/t_{CO_2}

Fig. 5 illustrates the impact of using accelerated start-ups for the gas-steam system generating electricity. State-of-the-art gas-steam systems are characterized by the time of start-up from the hot state of 30 minutes. In the case of an unscheduled start-up, the desired load is achieved in

Table 1: Data characterizing thermal flexibility and emissions for nuclear technology, coal-based power engineering and gas-steam installations (e.g. [15–17])

Performance characteristics	Nuclear power units	Coal-fired power units	Gas-steam systems
Load changing capability	10%/min (80–100% of the load) 5%/min—in the range of 50–100% of the load 2%/min—in the range of 20–100% of the load	3–6%/min (40–100% of the load)	4–9%/min (40–100% of the load)
Minimum loads (% of the nominal load)	20–30	35–40 20–25 (in the system with flue gas recirculation)	30–50 (for a single-shaft installation with an inlet air heating system), 15–25 (for a configuration of 2 GTs and 1 ST)
Start-up time -from the hot state downtime <8 h -from the warm state downtime <48 h -from the cold state downtime <120 h	 60–120 min 2–3 h 15–20 h	 80–150 min 3–5 h 5–10 h	 30–60 min (<30 min—potentially) 1–1.5 h (<50 min—potentially) 2–3 h (depending on the configuration)
Efficiency, % -nominal load -50% nominal load	 36–3 (EPR reactor) 33–35 (EPR)	 45–47 42–44	 >60–61 54–57 (1 GT + 1 ST) 60 (for a higher number of GTs)
CO_2 emissions, g/kWh	none	740	330
SO_2 emissions, mg/m^3_N	none	100–200	~0
NO_x emissions, mg/m^3_N	none	75–100 (SCR)	30–50

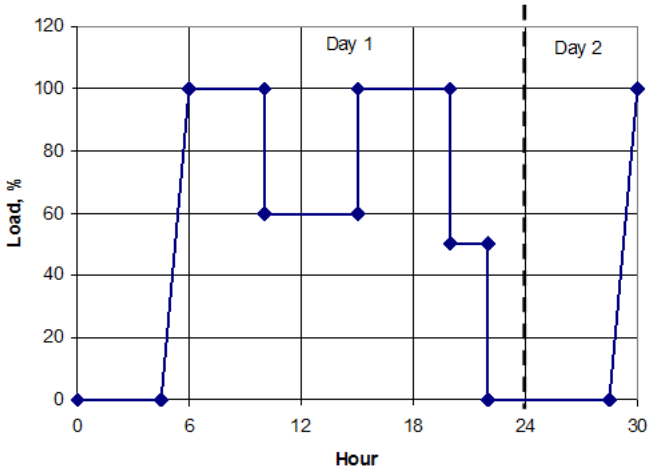

Figure 6: Gas-steam system 24-hour load profile

a shorter time. Consequently, more electricity is generated and with greater efficiency in periods when a higher price is obtained. If the start-up is a scheduled one, it can be commenced later and, as a result, less electricity is generated in the low price period.

4.5. Economic assessment of a gas-steam system operating at partial load

One of an economic index used to assess the power plant economic efficiency is the minimum selling price of electricity. This particular index is the same as the unit cost of electricity production k and it is determined using the following formula:

$$NPV\left(C_{el}^{gr}\right) = 0 \tag{13}$$

The most important technical parameters needed to find C_{gr}^{el} are: annual fuel consumption and the amount of electricity generated per year.

In order to determine these parameters, considering the cyclical operation of the gas-steam system, it is necessary to define the system load profile throughout the year. It is assumed in the analysis that the system will operate 50 weeks a year. Two one-week breaks in the operation are anticipated for servicing and overhauls. Every week the system will operate for five days: Monday to Friday. The 24-hour load profile of the gas turbine is presented in Fig. 6.

Based on the assumptions mentioned above, it can be stated that during the year there are two start-ups from the cold state (after the one-week breaks), 48 start-ups from the warm state (after 48-hour downtimes) and 4x50=200 start-ups from the hot state. The time of operation at constant load (without start-up and shutdown times) thus total 4,000 h. Ignoring the shutdown time and assuming that the time of start-up from the cold state is 3 h and from the warm state—1.5h, the total time of gas turbine operation is obtained: $\overline{\tau}$=4178 h.

It is assumed in the calculations that the gas-steam system was constructed based on a class F gas turbine operating in the configuration presented in Fig. 1. The system net electric power is 423 MW and the electricity generation efficiency—58.4%.

The amount of generated electricity in the periods of operation at a constant load is affected by ambient temperature. In order to find exact values of the amount of generated electricity, it was necessary to determine the time of the gas turbine operation at a specific load at a specific ambient temperature. In preliminary calculations related to the gas-steam system operation, the system average power output capacity is often determined using the annual average temperature. Such calculations are justified due to the fact that the dependence of the gas turbine maximum power output on temperature is often linear. In order to calculate the amount of generated electricity in the periods of system operation at a constant load, it is assumed that temperature has no impact on the value of generated power. The production of electricity is thus:

$$\begin{aligned} E' &= 50 \times 5 \times 423\,\mathrm{MW} \times (100 \times 9\,\mathrm{h} + 60 \times 5\,\mathrm{h} + 2 \times 50) \\ &= 1,374,750\,\mathrm{MWh} \end{aligned}$$

The energy generated in the period of variable loads should be added to the value of produced electricity. Despite the fact that the change in the load is marked in the diagram with a straight line, depending on the start-up method, the amount of generated electricity is in fact smaller compared to what the calculations based on the diagram might suggest. Based on reference literature, it can be assumed that the amount of generated electricity is 30% for the start-up from the warm state and 55% for the start-up from the hot state compared to the linear change in the system load [9]. Electricity generation taking account of start-ups and shutdowns increased by about 2% and totals E=1406 GWh.

In simplified analysis, the fuel chemical energy consumption can be determined based on the corrected value of system efficiency.

In order to find parameter g_1, the characteristics of the SCC 5 4000F gas-steam system were used. For the average ambient temperature of 8.6°C it was 1.01. The value of g_2 was determined based on [9] and it can be defined using the following approximating formula:

$$\gamma_2 = -0.9 \cdot \beta^2 + 2 \cdot \beta - 0.1667 \qquad (14)$$

Based on the formula presented above, it can be determined that the efficiency value is 51.78% and the fuel chemical energy consumption totals 9,781,000 GJ.

A number of assumptions were made for detailed economic calculations. The most important ones are as follows: the time needed for the gas-steam power unit to be constructed—3 years, service life—20 years. The investment expenditures were as follows: Polish PLN 1,324,545,455 (unit expenditures—1000 \$/kWe). The share of own resources in financing—20%, the balance was covered by a commercial credit.

Real interest on the commercial loan was assumed at 7%; the loan repayment period—10 years. The allocation of investment expenditures to be incurred in subsequent years of construction was 20%, 40% and 40%, respectively. Moreover, it was assumed that the average depreciation rate was 9%, the excise tax—20 PLN/MWh, the income tax rate—20%. The calculations ignore the change in working capital and the value at liquidation. The price of the gas fuel was 1.29 PLN/m_n^3. The minimum selling price of electricity is 388 PLN/MWh.

Assuming continuous operation of the turbine set for a period of 50 weeks at a full load, the amount of generated electricity is 3,553,200 MWh (2.52 × E), the consumption of fuel chemical energy is 21,687,000 GJ (2.22×Bwd) and the resulting minimum selling price of the fuel chemical energy is 286 PLN/MWh. The minimum selling price of electricity in cyclical operation is thus by about 36% higher than the price at continuous operation.

5. Conclusions

The gas technologies implemented in the power system are characterized by numerous features which make them more competitive. These features are as follows: high electricity generation efficiency, ecological advantages, the dynamics of changes in load, high reliability and availability. The factor limiting their popularity is the low economy of operation at present prices of electricity and gas and high sensitivity to changes in gas prices. These limitations can be eliminated through detailed analysis and selection of technological structures of gas systems and taking account of the scenario of technological diversification in the electricity generation sector and the progress made in controlling the operation process. An important task for the future is to correct the methodology of the economic assessment of implemented technologies so that it takes different aspects of the technology operation in the power system into consideration, including the real time of operation and the real efficiency of the installation at different stages of operation. The example of the determination of economic effects of the gas-steam system cyclical operation presented in this paper indicates that the rise in the minimum selling price of electricity may be 36% compared to the system operating continuously.

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