Improving the methodology of main power equipment choice for the gas turbine plants

Evgeny Lisin, Wadim Strielkowski, Ivan Komarov, Ivan Garanin

Abstract - **Our paper considers the problem of economic substantiation of the choice of the main power equipment at the stage of functional studies of investment projects in conditions of uncertainty and incompleteness of initial data. As a solution to the designated problem we suggest using the method of the best equipment for gas turbine power plant choice. The method is based on an optimality criterion of power equipment choice which allows us to determine the best solution for the gas turbine from the perspective of capital and operating costs minimizing.**

Index Terms - **Gas Turbine Power Plant, Main Power Equipment, Investment Project, Statistical Analysis, Capital Cost, Operating Cost.**

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I. INTRODUCTION

THE investment project in the energy sector can be defined as an endeavor focused on creation, development of power facilities, representing a system of objectives, resources, organizational and managerial activities for their implementation. The life cycle of a typical investment project in the energy sector (IEP) consists of 3 main stages: pre-investment, investment, and operation.

The pre-investment stage is a preparatory stage of IEP, during which the investor gets detailed information about the feasibility and economic efficiency of the energy project. According to the results of pre-investment studies, the decision on expediency of the project realization is made. The key document of pre-investment studies is a feasibility study (FS).

Feasibility study represents the document containing reliable information about technical, financial, commercial, social, environmental assumptions of the investment project implementation, as well as evaluating the viability and economic efficiency of the project. The feasibility study is typically composed of 10 chapters. Each Chapter focuses on critical aspects of the project without consideration of which the answers to key questions, including the feasibility and economic viability of the project will not be received. Some of the most important aspects of the project, which are analyzed in the feasibility study of the IEP can be highlighted:

- power sales: electricity supply planning, forecasting the dynamics of changes in tariffs for electricity supply, the study of the possibility of the station connection to the power grids, a preliminary production schedule;
- fuel supply: determination of the possible volume of fuel and lubricants, forecasting fuel prices, the study of the possibility of generation facilities connection to the fuel source;
- description of the selected energy technologies: defining technical and economic parameters of equipment, estimating costs associated with the equipment operation, evaluation of the required volume of investments for the acquisition, installation and commissioning of the equipment;
- description of the location of the object: determination of the environmental situation at the construction site of the power plant, estimation of costs related with the preparation of the construction area;
- human resources: an analysis of the possibility of attracting qualified staff for the operation of power station, determination of the wages level in the region, assessing the costs of salary fund;
- preparation of investment and operational plans of the project;
- financial analysis and economic evaluation of investment.

According to guidelines for the development of industrial feasibility study prepared by the United Nations Industrial Development Organization (UNIDO), the accuracy of the estimates given in the feasibility study should not be below 10% [1, 2]. It is not possible to obtain such precise estimates without significant labor and financial resources costs.

According to UNIDO, the share of costs for development of feasibility study of the total cost of the investment project may

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be 1-3% [1, 2]. At an average cost of 6 MW gas turbine power plant of 4.4 million euros, the investor will need at least 0.44 million euros to conduct the feasibility study.

If the feasibility study shows that the investment project will not provide the expected return to the investor according to its rate of return or the payback period is too large, then the investor will have to make adjustments to an existing project or to develop a new project. A negative result obtained by the results of the feasibility study, is aggravated by the fact that the feasibility study is conducted at the stage of investment feasibility study, which is preceded by a significant number of costly stages of preparation of the investment project.

In order to reduce the cost of preparing the investment project, it is necessary to conduct justification of the choice of the best initial parameters for the investment object that requires the solution of optimization problem. [3]

Final economic assessment of IEP is formed from two sides:

- assessment of the external environment of the project;
- assessment of the internal parameters of the project.

The assessment of the external environment of the project includes macroeconomic indicators, indicators of electric power market, the level of life of population, characteristics of tax and environmental legislation.

Assessment of internal parameters of the project is carried out from the perspective of the following factors:

- feasibility: the efficiency of the main equipment, the cost of equipment, fuel consumption, the level of automation of the production process, the cost of electricity for its own needs, the life of the equipment;
- environmental: the choice of flue gas cleaning system, the choice of work of the equipment (open or closed loop);
- financial: the use of the cheapest sources of financing, the choice of the financing scheme, the selection of reliable partners (project participants);
- geographic: selection of the most successful location of the object in terms of proximity to the fuel source, proximity to the point of generation object technological connection and sufficient distance from residential areas [1, 2].

In contrast with the external factors which are given and characterize the economic environment of the project, the internal parameters of the IEP are determined at the stage of pre-investment studies. The cost of investment planning and future economic effect depend on their optimal choice.

Technical and economic parameters of the project are largely determined by the choice of the main power equipment from the position of operational and capital costs minimum.[4]

There are many varieties of gas turbines which differ both in terms of efficiency and cost. Fuel component of gas turbine power plants costs ranges from 65 to 75% of the cost of electricity, the value of the specific fuel consumption is a function of the efficiency of gas turbines [6]. Assessment of the fuel component in the cost can be obtained from the following dependence [4]:

$$C^{FC} = K_n N_T G_{ic} P^{FC} \frac{1}{\eta_{GTU} Q^{FC}}, \qquad (1)$$

C^{FC} - the value of fuel costs;

P^{FC} - the price per cubic meter of natural gas;

Q^{FC} - heat of combustion of natural gas (kJ/m^3);

G_{ic} - installed generation capacity (KW);

η_{GTU} - gas turbine efficiency, %;

K_n - conversion factor of units of electrical energy (KWh) into units of heat of combustion (kJ);

N_T - the number of working hours in a year.

It should be noted that, in general, the lower the cost of installation is, the less perfect the technology of production and larger specific fuel consumption per 1 KWh of electric energy are, the cost of electricity production increases. However, the production cost of energy products is also affected by the cost of the installation through the depreciation of the main power equipment [5, 6, and 7]. Optimization problem of selection of generating equipment from the perspective of capital and operating costs minimizing occurs.

Based on the above, one can draw some conclusions and formulate requirements to the method of the equipment choice, which would allow us to justify the choice of the main power equipment at the stage of pre-investment studies:

- choice of the best options for power equipment should be conducted prior to the formation of a feasibility study for the project in order to reduce the cost of preparation of the investment project;
- choice of power equipment must be a solution of the optimization problem according to the principle of minimizing capital and operational costs;
- versatility, sufficient simplicity of the calculations and the possibility of their automation, low time costs should be peculiarities of the methodology.

II. The Choice of the Main Power Equipment for the Gas Turbine Power Plant

Gas turbine power plant (GTPP) is a high-tech generation object that allows to produce electricity and heat. Gas turbine power plant may have an electric capacity of twenty KW to hundreds of MW. A variant of GTPP, which provide combined heat and power, is called GTPP-CHP (combined heat and power). GTPP-CHP differs from GTPP via gas-water heat exchanger (GWHE) and additional pumps for pumping the water. Hereinafter, we will consider only the power plant with electric power, due to the complication of development of a selection methodology for the GTPP-CHP equipment due to the enlargement of the power equipment.

Gas turbine power plants use natural gas and operate on the basis of thermodynamic Brayton cycle. As part of the gas turbine, typically runs one unit of the main power equipment - gas-turbine unit (GTU), which, in turn, comprises a compressor, a combustion chamber, a gas turbine and an electric power generator. A gas turbine (GT) plant is based on Brighton's open thermodynamic cycle. For normal operation of the main power equipment GTPP includes additional (auxiliary) equipment [6]:

- electrical equipment unit;
- booster compressor for fuel;
- automated process control system (APCS);
- integrated air-cleaning device;
- Emergency Power Supply Unit;
- firefighting unit;
- ventilation unit of GTU container.

According to the calculations made by the software package PEACE, total capital cost on ancillary equipment does not exceed 12% of GTPP total capital costs. Tables 1 and 2 show the estimates of the cost of GTPP based on GTU of different manufacturers and capacities.

Table 1: Estimates of the cost of GTPP based on GTU of different capacities

GTU	Ca-pacity, MW	Effi-ciency	GTU price, mln $	The cost of auxiliary equipment, mln. $	Cost of installation and commission-ing work, mln. $	GTPP total cost, mln. $
Alstom TB 5000	3,809	25,2	2,4	0,41	0,75	3,56
Siemens SGT-200-1S	6,25	30,3	3,6	0,62	1,13	5,35
Mitsubishi MF 111A	12,83	30,6	6,2	1,13	1,96	9,29
GE LM2000	17,64	34,9	7,9	1,35	2,48	11,73
Siemens SGT-700	29,06	36	11,9	2,03	3,73	17,66
GE 6561B	40,34	32,4	14,2	2,43	4,45	21,08
Siemens SGT-800-50	50,5	38,3	18	3,07	5,64	26,71
RR TRENT 60 WLE	64	41	22,5	3,85	7,05	33,4

Table 2: Consolidated cost structure at GTPP of different capacities

GTU	GTU, %	GTPP auxiliary equipment, %	Installation and commissioning work, %
Alstom TB 5000	67,42%	11,52%	21,07%
Siemens SGT-200-1S	67,29%	11,59%	21,12%
Mitsubishi MF 111A	66,74%	12,16%	21,10%
GE LM2000	67,35%	11,51%	21,14%
Siemens SGT-700	67,38%	11,49%	21,12%
GE 6561B	67,36%	11,53%	21,11%
Siemens SGT-800-50	67,39%	11,49%	21,12%
RR TRENT 60 WLE	67,37%	11,53%	21,11%
Average	67,29%	11,60%	21,11%

From the tables above one can conclude that the most of the capital costs of GTPP is the main power equipment (67,3%). It should also be noted that the share of expenses for ancillary equipment, construction, installation and commissioning does not depend on the manufacturer and GTP capacity. This fact is an important feature as it will allow us to ensure comparability condition of the results of the selected power equipment using the developed methodology.

The most common way of comparing two gas turbines with each other in order to solve the problem of choosing the main power equipment is to conduct identical feasibility studies for different GTU. This approach assumes that a change in the brand and the model of the equipment may affect not only the capital cost of the gas turbine, but other articles of the forecasted cost. However, according to the data shown in the Table 2, the cost structure of units of different manufacturers remains unchanged. Therefore, free choice of equipment will not distort a comparative assessment of equipment.

The second important aspect is the operational efficiency. Operational efficiency is the difference in operating costs arising as a result of the choice of the more efficient equipment.

Selection of equipment for the procedure of comparison should be made from the power equipment of comparable installed capacity. The desire of the investor to build a GTPP of a certain power is based on the analysis of the electricity market and the load schedule. The project power should be required, and the equipment should be loaded. Equipment of comparable capacity will be served by the same number of industrial production personnel (IPP). The number of IPP for GTPP of 12 to 150 MW capacity can be defined according to the regulations of the number of industrial production personnel [2, 8] The feature of the standards is quite a big step in power, within which the number of employees remains the same. The step size is from 10 to 30 MW. This implies that the permissible range of values of GTP capacities should be less than a given range.

As it was shown above, other costs also do not actually change when one changes the brand of comparable capacity equipment. In assessing the cost of energy products other costs are determined by the regulatory method. Other costs are usually 5-7% of the total cost of electricity.

As for the repair costs, then it is necessary to start with two basic parameters of repair of the equipment: the duration of the interval between repairs and the cost of repairs. The analysis of GTU revealed that the installation of similar capacity have identical service life and require the same number of repairs which means that regardless of the choice of equipment repairs will be carried out in a comparable time. This can be explained mainly by corrosion processes in the metal caused by high gas temperatures inside the plant – a property shared by all gas turbine designs. The common term "oxidation" refers to high-temperature oxidation of rotor vanes. The cost of repair of GTU doesn't differ greatly. The fact is that manufacturers of gas turbine equipment operate on the world market in conditions of tough competition. As the power equipment is largely identical, increasing the cost of repairs by the manufacturer leads to lower competitiveness [9, 11].

The remaining cost items - fuel costs and depreciation - characterize operational efficiency. Each installation of the selected capacity interval has different costs depending on efficiency and specific fuel consumption. In turn, the cost of the equipment affects the production cost of energy products through depreciation.

Next, let us make the selection criterion of the main power equipment for GTPP on the basis of parametric functions, characterizing the cost of equipment and its operational efficiency.

III. DEVELOPMENT OF SELECTION CRITERIA OF THE MAIN POWER EQUIPMENT FOR GTPP

In order to develop methods of choice of the main power equipment statistical analysis of technical and economic characteristics of GTU included in the database CAD Thermoflex was performed in program Statistica. The database consists of 232 units with the capacity from 0.5 to 60 MW (the most common power GTPP in Russian Federation). The study was conducted for the following parameters of power equipment: power, efficiency, shaft speed, compression of air in the compressor, the temperature difference in the turbine, air flow. The correlation analysis has allowed to reduce the number of variables and to establish the main cost factors of this type of power equipment: capacity and the number of shaft revolutions.

After normalization [10] the function of the cost parameter takes the following form:

$$CC'_{GTU} = CC_{GTU}\frac{1}{\sigma}, \qquad (2)$$

CC'_{GTU} - capital costs parameter,

CC_{GTU} - GTU cost of the selected interval capacity,

$\sigma = 6{,}3082$ mln \$ - standard deviation of cost GTU, calculated for a sample of the database Thermoflex.

To obtain the operational efficiency parameter function we will analyze expression 1. Most of the parameters of this function when changing GTU to unit of another manufacturer will remain unchanged. Installed capacity utilization rate, the price of fuel, calorific value, conversion coefficients, the number of work days do not depend on the main power equipment, so equipment changes are not reflected. Only two parameters will change - capacity (within a given interval) and efficiency. Changing the capacity in this case is not important, because it is assumed that the unit will work with a given load, which was originally founded in the IEP as an input. Efficiency remains. It will characterize the change of the fuel component of costs compared to other GTU. Hence, the function of the operational efficiency parameter determination can be written as follows:

$$C'_{GTU} = \frac{1}{\eta_{GTU}}, \qquad (3)$$

On the basis of the given parametric functions will form the selection criteria of the best equipment:

$$Z = \mu CC'_{GTU}(C'_{GTU} + \mu CC'_{GTU}) \rightarrow \min, \qquad (4)$$

C'_{GTU} - GTU efficiency parameter,

μ - the share of depreciation,

The criterion of selection of the best equipment consists of two factors: the first factor characterizes the amount of GTU capital costs, the second characterizes operational efficiency of GTU in comparison with other units, taking into account the relationship between the cost of GTU and operating costs through depreciation.

The proposed method for choosing the best power equipment involves cost and operational efficiency calculations, finding the optimization criteria for power equipment of given capacity selection. Equipment with minimum value of the optimization criterion will be economically feasible. To expand the sample in order to compare maneuverable energy equipment, it is proposed to produce calculation on interval data at a given capacity range:

$$[G_{nom}; 1{,}25G_{nom}] \qquad (5)$$

G_{nom} - required nominal generation capacity of the plant.

This range assumes that GTU, the capacity of which can exceed the nominal value for 25%, can provide the required capacity. It is also considered that at 80% the load of the nominal capacity and efficiency does not change. This assumption is partly justified by high maneuverability of GTU, which may reduce the capacity up to 60% of the nominal value without significant losses [11].

For units operating at decreased power, lower GT unit efficiency will translate into a higher operational savings factor which in turn will increase the Z parameter. A higher Z will automatically push the GT unit away from the optimum equipment choice frontier in a specific investment project. Thus, in order to make the primary power plant equipment selection technique more relevant, the operational savings parameter will have to be adjusted to reflect GT unit operating mode. An addendum to the described technique to account for GT utilization pattern is laid out in Chapter 4 of this article.

Nevertheless, the described technique can still be applied successfully without the above-mentioned adjustment. Unadjusted for equipment utilization pattern, the error margin of the resulting estimate will suffer. One should keep in mind however that this wider error margin is only an issue if the output power of a particular unit lies near the right-side boundary of the sample. In this case, the parameter Z will be skewed to the maximum when the output power of GT unit is higher than required. We carried out computations for choosing the optimum power plant equipment design in line with the proposed technique using a test sample of equipment. Our computations did not include an adjustment for GT utilization pattern. Table 3 summarizes findings from these computations.

Based on findings from computations and considering the proposed optimality criterion, the best choice of an equipment unit would be RR 501-KH5, a gas turbine produced by Allison Rolls-Royce, a power systems manufacturer from the UK. One should keep in mind that the electrical power of this GT unit is just 1,64% above the design power. Moreover, it should be understood that RR 501-KH5 is well ahead of its closest competitors in terms of Z. This means that, given the case at hand, the power-generating equipment manufactured by Allison Rolls-Royce is indeed the best choice from the standpoint of TCO minimization and considering that the final result would not be significantly altered if utilization patterns were accounted for. Nevertheless, the adjustment for utilization patterns of power plant equipment making up the sample may become crucial in less obvious cases.

Table 3: The results of application of the developed method of the main power equipment optimal choice

GTU	Capa-city, KW	Effici-ency, %	Costs, mln. $	Operatio-nal efficiency parameter	Cost parameter	Z
Taurus 65-8400	6000	33,1	3,5	3,02114	0,554851	0,17070
RR 501-KH5	6100	38,1	3,4	2,62467	0,5389981	0,14437
RR 501-KB7S	6180	32,4	3,5	3,08642	0,554851	0,17432
SGT-200-1S	6249	30,3	3,6	3,30033	0,5707039	0,19160
Taurus 65-8400	6290	32,7	3,6	3,05810	0,5707039	0,17778
Taurus 70	6295	31,6	3,6	3,16455	0,5707039	0,18386
Taurus 65-8401S	6300	32,9	3,6	3,03951	0,5707039	0,17672
GT6	6 630	32,7	3,7	3,05810	0,5865568	0,18281
SGT-200-1S	6726	31,9	3,8	3,13479	0,6024096	0,19247
GPB70D	6 744	30,6	3,7	3,26797	0,5865568	0,19512
SGT-200-1S	6745	31,3	3,7	3,19488	0,5865568	0,19083
Taurus 70	6844	32,9	3,7	3,03951	0,5865568	0,18172
GPB70	6 930	30,7	3,8	3,25732	0,6024096	0,19985
GPB70	6 930	30,8	3,8	3,24675	0,6024096	0,19921
Taurus 70	7250	32,8	4	3,04878	0,6341154	0,19734
Taurus 70-T10302S	7305	33,5	3,9	2,98507	0,6182625	0,18837
GPB80D	7 410	32,9	4	3,03951	0,6341154	0,19676
URAL 6000	6 000	27,3	3,75	3,66300	0,5944832	0,22129

IV. ACCOUNTING FOR EQUIPMENT UTILIZATION PATTERN IN THE TECHNIQUE FOR OPTIMUM SELECTION OF MAIN POWER PLANT EQUIPMENT

As a means of ensuring optimum equipment choice from the standpoint of TCO minimization, the technique described in this article assumes that the sample will be limited to GT units with output power greater than the rated power. This approach covers the entire range of GT unit models that can be fitted technically into a specific investment project. Nevertheless, as already pointed out earlier, efficiency will decline when an oversized GT stays underutilized. The shape of the efficiency-load dependency curve depends on the control mode in place at the GT unit.

Two GT unit control methods available generally are known as qualitative and quantitative. Power is defined as the flow rate of working medium multiplied by useful work:

$$N = GH, \qquad (6)$$

G - gas turbine gas flow rate (kg/sec);

H - disposable heat drop in a gas turbine (kJ/kg).

With qualitative control, power is decreased by reducing fuel supply to the combustion chamber (CC) so that useful work (H) also decreases. This control mechanism generally has the side-effect of increasing air flow rate by a certain amount. How much it increases depends on the flow-rate performance of the compressor. The qualitative method is least economical as it entails a significant decline in thermodynamic efficiency due to lower heat input temperature in the cycle.

With the quantitative method, control is achieved by reducing working medium flow within the GT unit (G). This method is implemented technically by installing special devices at compressor inlet to alter the shape of its flow-through part – the guide vane assembly (GVA) and the turning vane assembly (TVA). The use of GVA alone brings down the flow rate by 30% to 40% relative to the design flow rate.

Fig. 1 shows the fundamental relationship between relative GT unit parameters and changes in output power. Within the range 1 (100% down to 80% of rated load) the GVA closes partially and quantitative control takes effect.

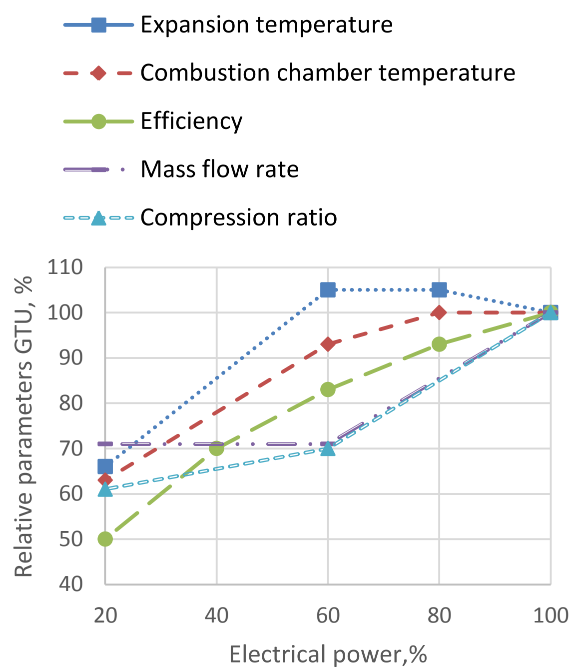

Fig. 1. Relative GT unit parameters as a function of load

Within the range 2 (80% down to 60% of rated load), fuel supply to the consumption chamber is reduced. Combined qualitative and quantitative control takes effect. Finally, within the range 3 (20% to 60% of rated load) the GVA is fully open, fuel supply reduction is used exclusively to achieve reduced output power.

As Fig. 1 illustrates, the decline in GT unit efficiency is least steep within the range 1 where quantitative control applies.

It should also be noted that qualitative control causes the thermal state of hot turbine parts to fluctuate, thereby shortening turbine life, requiring more frequent downtimes and ultimately increasing repair costs for the installation. These two circumstances define the range of GT unit output power which is used for generating the sample. If the output power range were expanded, increased repair expenses within the 20% to 80% control range would invalidate the comparability condition for evaluating individual power plant designs vis-à-vis each other. It is similarly impractical to base design on GT unit operating at efficiencies significantly below the rated value due to significant underutilization of plant capacity.

Let us examine the cause of declining efficiency with quantitative control in greater detail.

The drop in GT unit efficiency with quantitative decrease of output power is caused by a combination of thermodynamic cycle alterations and a drop in internal efficiency of compressor and gas turbine. Fig. 2 shows the thermodynamic cycle for rated and non-rated output modes.

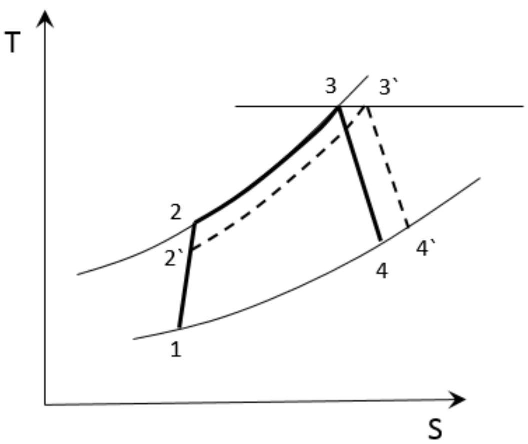

Fig 2. Quantitative representation of GT unit thermodynamic cycle in rated and non-rated output modes

In Fig. 2 the line 1-2 corresponds to the air compression process in the compressor at full rated output power while 1-2' corresponds to the same process in non-rated output mode. Heat input in the combustion chamber is shown as curve 2-3 and expansion of gases in the turbine corresponds to the line 3-4.

As the air flow rate decreases, the factor π of air compression in the compressor declines following the approximate Stodola-Flügel equation for GT unit:

$$\frac{G}{G_0} = \sqrt{\frac{T_{10}}{T_1}}\sqrt{\frac{\lambda_1^2\pi^2 \quad 1}{\lambda_{10}^2\pi_0^2 \quad 1}}, \qquad (7)$$

G, G_0 - flow rates of the working medium for the rated and derated output modes,

T_1, T_{10} - temperatures of working medium in the rated and non-rated output modes, respectively,

λ - hydraulic loss factor,

π - compression ratio.

Assuming a fixed temperature at GT inlet, the start of expansion then shifts toward the higher entropy area, leading to increased exhaust temperatures. Heat transfer to the cold source grows per formula (8) while the thermal efficiency of the cycle deteriorates.

$$\eta_t = 1 - \frac{Q_{cs}}{Q_{hs}}, \qquad (8)$$

η_t - thermal efficiency of the cycle,

Q_{cs} - the amount of heat transferred to a cold source,

Q_{hs} - the amount of heat transferred to the hot source.

Compressor and gas turbine designs have a significant impact on the severity of efficiency drop experienced by these units. Within the assumed non-rating range (100% down to 80% of rated load), the reduction in GT unit efficiency is explained mainly by thermodynamic factors. Any decline in internal GT and compressor efficiencies would be insignificant in this area, and its contribution to overall decline of GT unit efficiency is marginal [12, 13]. Therefore any further adjustments of the operational savings parameter for GT unit utilization will be based solely on thermodynamic assumptions.

The nature of relationship between GT unit load and its efficiency must be determined prior to augmenting the proposed adjustment technique with an operational savings factor accounting for GT power plant utilization pattern. It would be convenient to use the following relative quantities for clarity reasons: relative efficiency (η_{rel}) and relative load N_{rel}. These values can be determined using the formulas (9) and (10):

$$\eta_{rel} = \frac{\eta}{\eta_{rated}}, \qquad (9)$$

$$N_{rel} = \frac{N}{N_{rated}}, \qquad (10)$$

N_{rated}, η_{rated} - output power and efficiency, respectively, in the rated output mode.

Computations with GE Gate Cycle software have been performed to determine the nature of relationship $\eta_{rel} = f(N_{rel})$. Gas turbine plant with rated output power within the design range of 6 to 7.5 MW have been selected for computations. The following units have been investigated: Taurus 60 SC, Siemens SGT-200, Taurus 70 SC, Siemens SGT-100 MD. For each of these units, relative efficiency values have been obtained with relative output power non-rated from 1 to 0.8. The resulting data was then used to construct single-factor regression models for every unit under study to describe the drop in relative efficiency caused by a corresponding reduction of relative output power. Fig. 3 shows the results.

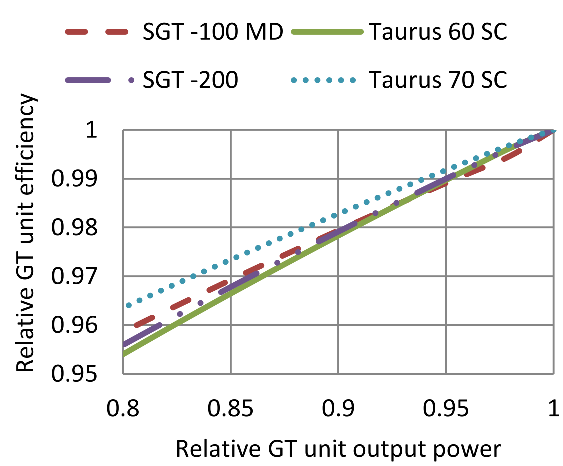

Fig. 3. Plot of relative GT unit efficiency as a function of changing relative output power

Fig. 3 shows that the efficiency of these units drops at different rates. This scatter of relative GT unit efficiency values at relative output power of 0.8 can be explained by differences among GT units at hand in technical parameters such as air compression rate in the compressor π_c and gas temperature upstream of the gas turbine T_{comb}. Table 4 details some technical parameters of GT units considered above.

Table 4: Selected technical parameters of GT units under study

GT unit model	Compression rate π_c	Temperature T_{comb}, °C	GT unit efficiency, %
Siemens SGT-100 MD	14.4	1110	30.3
Siemens SGT-200	12.1	1024	31.3
Taurus 60 SC	12.3	1093	31.5
Taurus 70 SC	15	1121	32.8

Considering that the function for adjusting GT unit efficiency to its load is expected to be applied at an early stage of pre-investment surveys when the feasibility study is ridden with multiple uncertainties, such a function can be obtained by averaging across four functions for the GT units selected above. The obvious drawback of this approach is that the resulting adjustment will be less accurate, however this inaccuracy is minor relative to the general uncertainty of estimates in the feasibility study. Therefore this simplification may be considered well-justified.

Fig. 4 shows the final plot of the function linking relative GT unit efficiency to relative output power for units within the output power range of 5.5 to 7.5 MW.

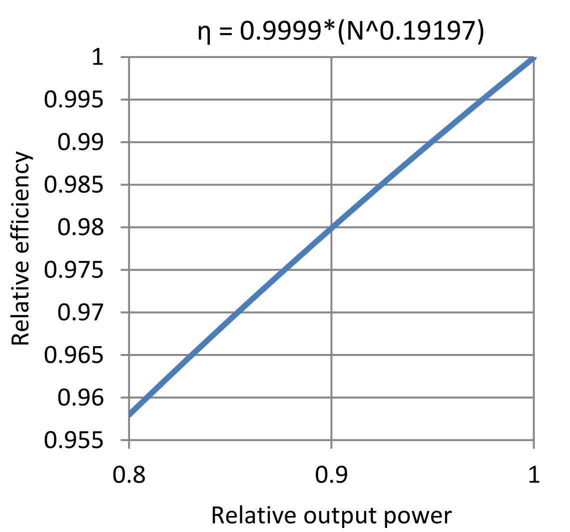

Fig. 4. A plot of relative efficiency as a function of relative output power

The resulting equation makes it possible to integrate utilization pattern considerations in the proposed primary power plant selection technique and to adjust the function for determining the operational savings factor (11):

$$C'_{gtu} = \frac{1}{\eta_{gtu} \quad 0.9999 \quad N_{rel}^{0.19197}} \qquad (11)$$

V. CONCLUSIONS

Our study was concerned with the problem of justifying the choice of primary power plant equipment for investment projects suffering from uncertainty and incompleteness of input data. It has been shown that there is no significant correlation of CAPEX structure with either the output power of GT power plant or the make and model of its primary equipment. We have provided proof that economically sound choice of primary power plant equipment is indeed possible without a full-scale feasibility study, calling just a few economical and technical parameters of equipment into comparison.

Based on our statistical analysis of technical and cost aspects of GT power plant, a technique was proposed for ensuring optimum selection of equipment at functional design study stage of gas-turbine power plant projects. Our technique is grounded in the criterion for assessing the optimality of power plant equipment choice with the goal of arriving at the best GT design solution from the standpoint of CAPEX and OPEX minimization. The technique accounts for uneven utilization patterns of primary power plant equipment.

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LIST OF ABBREVIATIONS AND SYMBOLS

APCS – automated process control system,
CAPEX – capital expenditures,
CC – combustion chamber,
FS – feasibility study of pre-investment stage,
IEP – investment project in the energy sector,
IPP – industrial production personnel,
GT – gas turbine,
GTPP – gas turbine power plant,
GTPP-CHP – gas turbine power plant combined heat and power,
GTU – gas turbine unit,
GVA – guide vane assembly,
GWHE – gas-water heat exchanger,
OPEX – operating expenditures,
TVA – turning vane assembly,
C^{FC}, $ – the value of fuel costs,
C'_{GTU} – GTU efficiency parameter,

CC_{GTU}, mln \$ – GTU cost of the selected interval capacity,

CC'_{GTU} – capital costs parameter,

G, kg/sec – gas turbine gas flow rate,

G_{ic}, KW – installed generation capacity,

G_{nom}, KW– required nominal generation capacity of the plant,

H, kJ/kg – disposable heat drop in a gas turbine,
and non-rated output modes,

K_n – conversion factor of units of electrical energy (KWh) into units of heat of combustion (kJ),

N_{rated}, KW – output power, respectively, in the rated output mode,

N_T, hour – the number of working hours in a year,

P^{FC}, \$ – the price per cubic meter of natural gas,

Q^{FC}, kJ/m^3 – heat of combustion of natural gas,

Q_{cs}, kJ/kg – the amount of heat transferred to a cold source,

Q_{hs}, kJ/kg – the amount of heat transferred to the hot source,

T_1, T_{10}, K – temperatures of working medium in the rated and

η_{GTU}, % – gas turbine efficiency,

η_{rated}, % – output efficiency, respectively, in the rated output mode,

η_t, % – thermal efficiency of the cycle,

λ – hydraulic loss factor,

μ – the share of depreciation,

π – compression ratio,

σ, mln \$ – standard deviation,

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