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A new Approach to Annual Costs in Industrial Combined Heat and Power Generating Plants as a Supporting Tool for Quick Estimation of their Modernization Necessary Costs

Nowe podejście do kosztów rocznych elektrociepłowni przemysłowych jako narzędzie wspomagające szybkie szacowanie niezbędnych kosztów ich modernizacji

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Keywords: *Cogeneration, Costs calculation, Industrial combined heat and power plants, Investment expenditures, Energy Conservation, Clean energy production*

Abstract

The results of research investment expenditures for the construction or modernization of industrial heat and power plants are presented. The modernization of these cogeneration power plants (usually low or medium power and fired with coal or other non-ecological fuels) is necessary due to the development of heat and electricity production in cogeneration. This will make it possible to meet the recommendations set out in the Green Deal, especially in the European Union's Medium Combustion Plants Directive. The goal of the paper is to present a new approach to the annual cost in industrial cogeneration plants as a tool supporting the quick estimation of the costs of their modernization. The novelty of this approach is that it proposes a multidimensional estimation of the cost of risk when making the initial modernization decision. The proposed model can be used to quickly assess the level of investment expenditures necessary to decide on the stage of planned cogeneration plants modernization. Additionally, on the example of typical heat and power plants in the chemical industry, a simplified analysis of the impact of the increase in steam parameters on investment expenditures was carried out. Using the techniques of econometric modelling and computer applications, formulas were derived to roughly define the dependence of investment expenditures in cogeneration plants on steam parameters and power of the plant. This can be useful for decision-makers in the industrial cogeneration plants rational modernization planning process.

Słowa kluczowe: *Kogeneracja, Kalkulacja kosztów, Elektrociepłownie przemysłowe, Nakłady inwestycyjne, Poszanowanie energii, Produkcja czystej energii*

Streszczenie

Przedstawiono wyniki badań nakładów inwestycyjnych na budowę lub modernizację elektrociepłowni przemysłowych. Modernizacja tych elektrowni kogeneracyjnych (najczęściej małej lub średniej mocy, opalanych węglem lub innymi paliwami nieekologicznymi) jest konieczna ze względu na rozwój wytwarzania ciepła i energii elektrycznej w kogeneracji. Dzięki temu możliwe będzie spełnienie zaleceń zawartych w Zielonym Ładzie, w szczególności w unijnej dyrektywie w sprawie średnich obiektów energetycznego spalania. Celem artykułu jest przedstawienie nowego podejścia do kosztów rocznych w elektrociepłowniach przemysłowych jako narzędzia wspomagającego szybkie szacowanie kosztów ich modernizacji. Nowością tego podejścia jest zaproponowanie wielowymiarowego oszacowania kosztu ryzyka przy podejmowaniu wstępnej decyzji modernizacyjnej. Zaproponowany model pozwala na szybką ocenę poziomu nakładów inwestycyjnych niezbędnych do podjęcia decyzji o etapie planowanej modernizacji elektrociepłowni. Dodatkowo na przykładzie typowych elektrociepłowni przemysłu chemicznego przeprowadzono uproszczoną analizę wpływu wzrostu parametrów pary na nakłady inwestycyjne. Wykorzystując techniki modelowania ekonometrycznego oraz zastosowania komputerowe wyprowadzono wzory umożliwiające zgrubne określenie zależności nakładów inwestycyjnych w elektrociepłowniach od parametrów pary i mocy elektrowni. Może to być przydatne dla decydentów w procesie racjonalnego planowania modernizacji przemysłowych elektrociepłowni.

1. Introduction

This currently, there are about 190 industrial combined heat and power plants (CHPs) in the polish industry with a total electrical capacity ca. of 3,000 MW. The industrial power industry is mostly based on low – and medium-sized sources producing electricity and heat in high-efficiency cogeneration, mainly for own and local needs. Electricity consumption at the site of its production reduces the flows in the National Power System (NPS) and transmission and distribution losses, reduces grid constraints, and increases the transmission capacity of cross-border connections. Industrial heat and power plants mainly operate in the steel, non-ferrous metals, chemical and paper industries. In addition, significant amounts of electricity are produced by Polish coking plants based on coke oven gas. The industry also has significant generation capabilities based on waste heat, methane

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and technological gases: coke oven, blast furnace or refinery. So far, these resources are partly wasted due to the lack of support for their energy use. A characteristic feature of the Polish industrial energy sector is the generation of electricity and heat in combined heat and power plants, usually fired with coal or other non-ecological fuels [11],[16]. The combined heat and power generating plants in the industry usually operate for their own production needs, only surplus energy is sold outside. Combined heat and power generating plants in industry are an important element of the national energy mix. The greatest potential for generation in cogeneration is located in combined heat and power plants in the chemical industry. It should be noted that apart from a few higher power CHPs, these are small sources in the (1-50) MW power range, equipped with backpressure and extraction-back pressure turbines operating in the combined heat and power production system. These sources are significantly worn out and require urgent modernization in the light of the Medium Combustion Plants Directive (MCP) and the requirements of Best Available Techniques (BAT). In general, BAT emission standards apply to high-size combustion plants, i.e. power plants and industrial plants, which emit into the atmosphere a large number of pollutants produced by the combustion of solid fuels. Many researchers have occupied with the problems of generating electricity and heat in combined heat and power plants. For example, their research concerned the use of gas in CHPs [1]; energy production in distributed energy sources [9],[10]; energy intensity in the industry [13]; analysis by mathematical modelling [14]; calculation of cost in CHPs[4]; the economics of energy production in general[12],[15]; comprehensive issues of power generation, operation, and control [17], or mathematical programming approach for the solution of combined heat and power economic dispatch [8]. The author of this paper notices a significant problem regarding the necessary modernization of old coal-fired CHP plants, which are forced by ecological standards. By 2021, the existing Polish coal-fired power plants and large industrial plants must undergo modernization and implement modern technologies that will minimize the emission of pollutants into the atmosphere: nitrogen oxide, sulfur dioxide, and PM particulates, as well as mercury emissions, the main industrial source of which are coal-fired power plants increasing the number of diseases and premature deaths caused by the effects of coal combustion. Complementary regulations i.e. Directive 2010/75 / EU of the European Parliament and of the Council of November 24, 2010, on industrial emissions (integrated pollution prevention and control), known as the "IED Directive", and in particular the MCP Directive, oblige to significantly of tightening on emissions to the environment from large industrial installations, especially coal-fired power plants and CHP plants. A significant part of the energy sector are medium-sized fuels combustion sources (subject to the MCP Directive) with a capacity in the range of (1-50) MW, which will face in near future significant challenges of modernization [2],[3]. The number of average fuel combustion sources in Poland is approx. 4,800 installations (according to the data of the Ministry of the Environment). It is then a great challenge that can be met by introducing cogeneration in place of heating boilers (potentially in about 220 localities), using modern systems with the use of ecological fuels in place of solid fuel boilers or the modernization of ECPs in sources fired with solid fuels. This paper is devoted to this last problem, describing a model for estimating the costs of modernization of old electricity and heat generation sources. This paper presents a proposal of multidimensional evaluation of risk costs model modification for investment effectiveness increasing in industrial power engineering.

2. Capital investments in cogeneration

In industrial cogeneration, small and medium-power cogeneration plants (in the order of 1.2-12.0) MW are mainly used. The investment expenditures in existed facilities are known based on actually incurred costs, and in planned facilities, they are determined in the conceptual phase based on unit expenditures for main energy devices. Specification of the main devices is a contractual matter and can be done with any level of detail. Usually, the inputs relate to the installed electricity capacity of the generating source. Determining the profitability of heat and electricity generation in cogeneration usually depends on the method of economic calculations used and assumptions regarding the adoption of specific numerical values, mainly concerning inputs, costs, energy fuel prices, etc. In cogeneration, capital costs for power generation may be reduced through cost-sharing in the energy generation process. The capital costs over what would otherwise be needed for steam production in the separate facility need to be charged to power generation in many instances. Also, a system with relatively low capital costs, e.g., gas turbines, may be efficiently employed in cogeneration. The fuel – and capital – savings advantages of cogeneration mean the in a wide range of circumstances cogeneration would provide electricity to industrial customers at less cost than the cost of electricity from a central – station power plant (the replacement cost for central – station electricity). Industrial cogeneration provides a classic example of the energy-pricing problem when new power plants are added to the utility grid. In this case, customers are insulated from the full impact of their higher costs because these higher costs are “rolled in” with the costs of the much cheaper old industrial CHPs to obtain an average price. Society would reap significant economic benefits if, instead, decisions relating to energy sources were made based on a comparison of replacement costs. Planners and decision-makers must deal with a set of complex problems when assessing investment decision in the power sector, regarding with the following characteristics:

- a broad range of options, including demand-side possibilities as well as traditional generation;
- a high degree of uncertainty associated with many of the main planning parameters, such as demand growth, capital costs, fuel prices;
- a multiple and often conflicting objectives.

The traditional power planning approach emphasized a single economic goal, i.e. to minimize cost. However, there is increasing awareness and understanding among policymakers and planners of other effects associated with power investment decisions, such as environmental quality. Power planning, as well as planning of many other sectors, is a multi-option, multi-objective decision process carried out within an uncertain environment. The decision process involves assessing conflicting objectives, such as economic development, financial viability, and environmental protection, to find an acceptable compromise solution.

Referring to mentioned issues, in the next part of this paper, the annual costs model modification and proposal of multidimensional investment risk measure are presented.

3. Annual cost model modification

The most universal method that has been known and applied in investment planning and designing, rating as well as in exploitation planning for many years is the annual cost method. In general, the annual cost method consists of replacing the cost flow $Ø(K)$ which is the sum of not identical costs K_n in different years with an equivalent flow of identical costs K_r, converted by means of a discount rate:

$$\Phi\,(K) = \sum_n K_n (1+p)^{-n} = \sum_n K_r\,(1+p)^{-n} = \\ = K_r \sum_n (1+p)^{-n} = K_r\,\frac{(1+p)^N - 1}{p\,(1+p)^N} \qquad (1)$$

Using the above formula, K_r is determined:

$$K_r = \frac{p(1+p)^N}{(1+p)^N - 1}\Phi(K) = r\Phi(K), \quad (2)$$

where:

$$r = \frac{p(1+p)^N}{(1+p)^N - 1} \quad (3)$$

is the coefficient of capital costs which depends on discount rate p and the length of the averaging period N.

The total cost of investment consists of fixed costs, independent of the present production, and variable costs, proportional to the production. In general, an analysis of economic effectiveness utilizing the annual costs method consists in the replacement of the sum of all costs incurred in particular years (not identical) with an equivalent flow of identical costs K_r, averaged by applying a discount rate.

The modification flow of incurred costs allows determining the required revenue, which meets the expenditure caused by an investment decision. The total cost of investment consists of fixed costs, independent of the present production, and variable costs, proportional to the production. A simplifying assumption is made for capital-intensive power engineering installations that fixed costs depend on expenditure costs through the coefficient r and also on extensive renovations. Other fixed costs (mostly on equipment maintenance) usually constitute 2 – 4% of average fixed costs. For example in heat and power stations, fuel costs constitute the greatest part of variable costs. Fixed costs represent an averaged flow of investment expenditures. Money to cover investment expenditures may come from the investor's resources and from loans, additionally from sold bonds or from the issue of shares to raise finance. Moreover, it must assure the coverage of the amortization of assets, an income tax, a property tax as well as property insurance and insurance related to the circulation of capital. Fixed costs are discounted to assess their share in the annual costs decision. The simplified annual costs model modification allows taking into account the risk impact on annual costs K_r, according to the formula:

$$K_r = K_s + K_z + K_{ryz} \quad (4)$$

where:

K_r – annual costs,
K_s – annual fixed costs,
K_z – annual variable costs,
K_{ryz} – risk costs.

In this paper, the author gives a modification of formula (4) by adding risk costs (K_{ryz}), which should be evaluated before and during power plant construction.

The following formula can calculate the annual risk costs:

$$K_{ryz} = e_p \cdot K_{nd} \quad (5)$$

where:

K_{nd} – levelized capital investment,
e_p – investment risk factor.

The factor was created on the application of some elements of the taxonomic method with a high level of estimation probability [7]. Several methods are allowing taking into account the risk in calculating the efficiency of planned investments or modernization, such as a method to revise the effectiveness of the investment project, the account of sensitivity, probabilistic-statistical simulation methods, operating methods, or taxonomic methods.

This paper presents two methods of risk assessment used so far. One of the most frequently used methods in risk assessment is correcting the parameters of the project. The method of correcting the parameters of the project concerns primarily the adjustment rate and rates of return, as these parameters are particularly vulnerable to major changes in the long run. With regard to power engineering, the above method is used to assess the risks of investing in distribution companies. In the simplest analysis, the cost of risk is taken into account by increasing discount rate.

Risk analysis requires a correction of cash flow due to the estimated overall investment risk. A simple weighted average cost method by Bayes is the most commonly used, involving an estimate of possible losses as a product of the probability of loss and flow value it relates to.

Keeping financial accounts of the project is to develop different scenarios of investment/modernization for a period of N years, with different percentage rates.

Values adopted for calculation result from the expected impact exerted by the state on the level of interest rates. These values should take into account both the rate of inflation as well as the risk premium paid. Using the revised interest rate, the rate of security investments r_s is fixed. The following formula is aimed to assess the profitability of investment:

$$NPV = \sum_{t=1}^{N} \frac{S_t}{(1+r+r_k)^t} = \sum_{t=1}^{N} \frac{S_t}{(1+r_s)^t} \quad (6)$$

where:

NPV – net present value,
S_t – balance of cash flow in year t,
r – coefficient of annual capital costs,
r_k – corrective value,
r_s – rate of security value, taking into account changing money value over time, and the risk connected with project analysis.

Another frequently used risk assessment method is the sensitivity method. A sensitivity account is a method of searching for critical values at which investments have economic benefits. This method is usually used in the effectiveness assessment of investment projects in power engineering and heat power.

The purpose of the sensitivity account is to determine how the selected input variables of the effectiveness of investment account affect the net discounted value of the NPV or internal rate of return *IRR*.

The method of risk assessment using the account of sensitivity requires the following steps (see Fig.1):

- determining the material scope of investment,
- choice of uncertainty values being the account parameters whose influence on project effectiveness will be subject for analysis,
- defining the variability range of uncertain values,
- constructing an evaluation process model,
- defining fluctuation range at an assumed variability of uncertain values (based on the existing model).

In terms of market conditions, the risk associated with energy investments is one of the most important issues of planning investments.

The size of the risk affects both the market and technical factors, as well as the policy related to state power economy. This paper is limited only to the most critical problems. The essential question is the selection of the risk investment variables. The proposed model can be used with a series of variables x_j that are variables of the following types: economic, financial, technical, social, political, legal, etc. Selecting the diagnostic variables is an important step in the suggested risk assessment method. Described using a set of diagnostic variables, the analyzed energy market investment/modernization strategies can be treated as real, multi-feature objects. Such objects can be analyzed for the risk involved under appropriate methods of comparative cluster analysis.

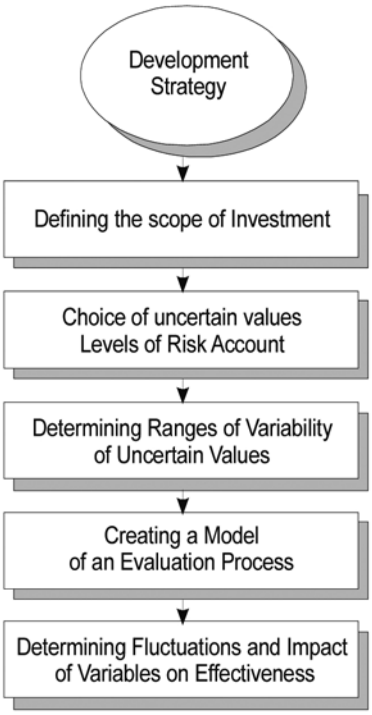

Fig.1.Using sensitivity account for investment risk assessment (adopted from W. Kamrat [5]).

Rys.1.Wykorzystanie rachunku wrażliwości do oceny ryzyka inwestycyjnego(zaczerpnięty z W. Kamrata [5])

The methods put numerical representations of the input variables in the center of studies, i.e. treat them as the objects of study. This makes it possible to obtain information on the uniformity within the set of the objects considered, i.e. uniformity within the considered set of numerical data. When numerical representations of the input variables are used to study different strategies, the set of the data analyzed is found non–homogenous, as it groups entities that differ in size, technology, and/or technical equipment.

Therefore, to study regularities occurring in investment strategies the non–homogeneous data set should be split into relatively uniform subsets which can then be studied using methodologies and techniques of the comparative cluster analysis. All things considered, using a cluster and spatial measure to assess risk has the advantage of enabling the positioning of relatively uniform features along individual axes of the spatial model. Besides, this kind of measure can be easily interpreted in its simple graphic representation. Its disadvantage, compared to the synthetic (unilateral assessment measure), is the unavailability of a simple way to rank objects against a single, synthetic ratio. Furthermore, it is easy to end up with a set including non–diagnostic features which will hinder the identification of characteristic types and increase the amount of work needed to complete the calculations. The latter argument is used to justify the use of the so-called reduction of the description of the studied space. The purpose here is to eliminate doubled information (e.g. closely correlated space constituents), data of low informative value (low information capacity), and little differentiation between the features of the objects grouped in the studied set. A synthetic scale of the investment risk is constructed by employing the comparative cluster analysis method. Comparative cluster analysis serves as a tool for comparing variables (reflecting the features and specificity of processes) that can be expressed in identical or different measurement units. In this paper, the author proposed a new approach to risk assessment, using elements of taxonomic analysis.

This paper is limited to the selected problems regarding the elements of taxonomic methods application for costs model modification.

For the present purposes and investment process is understood to denote construction, development, or modernization of the sources of energy produced. Further on this is called an investment strategy. Observations are positioned along a synthetic scale of the investment risk under the previously mentioned model method. Here, the Euclid distance (in multidimensional space, the borders of which are determined by the number of variables) is calculated for all values of the factor objects from the factor values of the hypothetical "model" object defined based on "the most desirable" values of the variables found in the entire set of the investment strategies. The objects "closest" to the model have the most preferable parameters in terms of the adopted criterion, i.e. represent the lowest investment risk. For formal reasons, it is more convenient to use a standardized scale (between **0** and **1**) to depict the positioning of the objects. The "best" object is represented by the highest value, the „worst" by the lowest.

Thus, in the present paper strategies involving the lowest risk are found at the beginning of the synthetic investment risk scale, while those burdened with the highest risk coming at the end (see Fig.2[16].

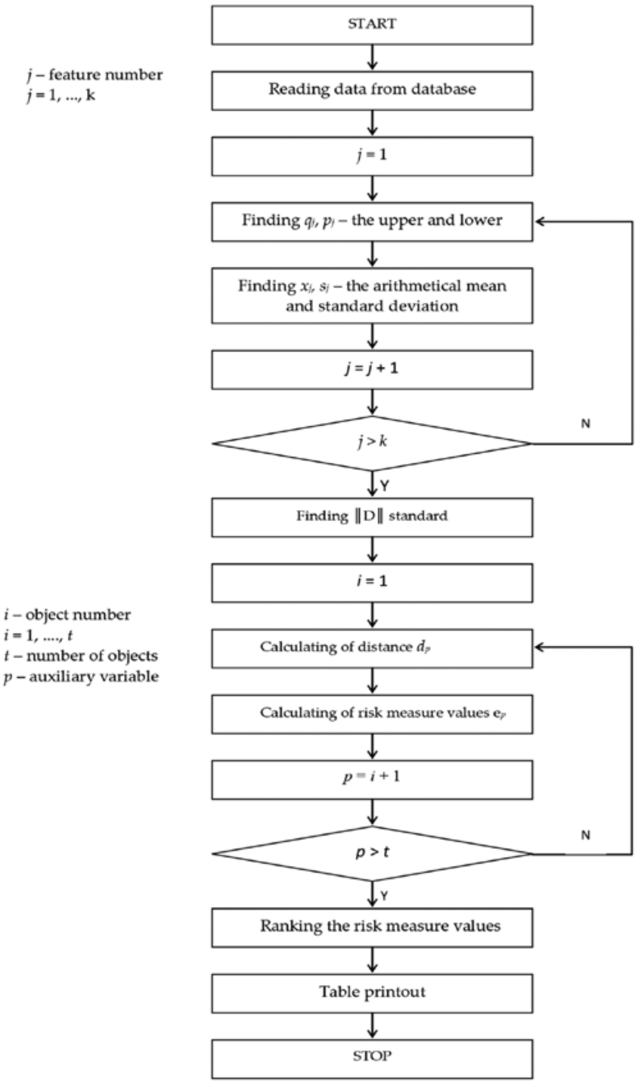

Fig.2. Diagram of the algorithm of identifying the investment risk (adopted from W. Kamrat [5]).

Rys.2. Schemat algorytmu identyfikacji ryzyka inwestycyjnego (zaczerpnięty z W. Kamrata [5])

This concept involves measuring an investment risk using rate risk measurement techniques. Rate risk should be assessed by taking into account the specific taxonomic variables. In order to build a synthetic scale of investment risk, multivariate analysis of comparison was used, which hierarchically arranges units on a synthetic scale by applying the so-called standard method. In the end, the investment risk is measured using the following e_p synthetic rate risk formula:

$$e_p = 1 - \frac{d_p}{\|D\|} \tag{7}$$

where:

$$d_p = \left[\sum_{j=1}^{k} (x_{pj} - q_j)^2\right]^{\frac{1}{2}} \tag{8}$$

x_{pj} – normalized value of j^{th} variable in p^{th} investment strategy; $\| D \| = d(P, Q)$ – distance between ”poles” (max., min.) characteristic of investment strategy.

An important fact is that the risk can be subdivided into several categories along the synthetic scale. Such subdivision is not only possible but also recommendable. It seems purposeful to identify the following five investment risk categories:

- low risk– for strategies with a ratio above <0, 0.1);
- medium risk– for strategies with a ratio between <0.1, 0.2);
- increased risk– for strategies with a ratio between <0.2, 0.3);
- high risk– for strategies with a ratio between <0.3, 0.4);
- extreme risk– for strategies with a ratio below <0.4, 1.0>.

To summarize, it must be noted that the use of methods taking into account risks depend on situational determinants and the specificity of decision-making processes. An additional benefit gained here is the possibility to compare the cost of risk to the installed power. In this way, we arrive at the unit risk cost for a specific investment strategy. The values of the risk rates range between <0, 1>. The closer the e_p value is to **1**, the higher risk is involved in each investment strategy. The presented approach to estimating the cost of risk allows for identifying such costs in changing market conditions, with technical, economic, and location parameters characteristic for a given investment in the power industry recognized. This is particularly crucial in planning the processes of investing in the regional power industry and local energy markets.

4. The expenditure calculation of CHPs in industry

The effectiveness of producing heat and power in cogeneration systems, which – among others – depends on live steam parameters, is an object of studies, related to the industrial heat and power generating plants. The effect of making fuel economies in the cogeneration system, in comparison with power, is the result of raising steam pressure and temperature at the turbine inlet in a back-pressure and a back-pressure-extraction system. On the other hand, however, the raising of live steam pressure increases capital investments in heat and power generating plants, affecting disadvantageously the profitability of combined heat and power production. In this paper, it is attempted to give the methodology of such a research approach that has subsequently been applied to the analysis of some selected plants (CHPs) in the chemical industry which are the typical part of the industrial heat sources in Poland. Referring to mentioned issues the structure of this section is arranged, as the following: attempt of costs analysis and approximation of specific capital investment in CHPs are presented.

For selected industrial heat and power generating plants, the specific capital investments, referred to the electrical and thermal power according to the live steam pressure, are determined (see Table1). The total capital investments in industrial heat and power plants can be determined by the model method according to the indices of specific investments in the following parts of a heat and power plant [6]:

- turbine house,
- high-pressure boiler house,
- water boiler house.

If a heat and power plant consists of groups of units having the same power output, then the total capital investments (I) can be calculated by the formula:

$$I = I_m + I_{kp} + I_{kw} \tag{9}$$

where:

- capital investment in a turbine house,
- capital investment in a high-pressure steam boiler house,
- capital investment in a water boiler house.

The following simplified relations are applied to the analysis of the effect of raising live steam parameters on capital investments:

$$I = K_{n1} \cdot P \tag{10}$$

where:

– $K_{n1} = f(P_j, p_0, t_0)$,
– K_{n1} – specific capital investment in CHP$_s$, M€/MW,
– P_j –installed electrical power in j^{th} plant,
– p_0 – live steam pressure at the turbine inlet, MPa,
– t_0 – live steam temperature at the turbine inlet, .

Table1.Set of analyzed CHPs [6]

Tabela 1. Zestaw analizowanych elektrociepłowni [6]

No.	Power plant	Power output, MW	Live steam pressure at the turbine inlet/ temperature, MPa/^{0} C	Specific capital investment, mln €uro/MW
1	CHP 1	1,6	3,9/450	1,684
2	CHP 2	2,0	3,9/450	1,902
3	CHP 3	2,3	2,5/400	1,876
4	CHP 4	2,5	3,9/450	1,210
5	CHP 5	2,5	3,9/450	1,404
6	CHP 6	2,5	9,8/525	1,191
7	CHP 7	2,5	3,9/450	1,154
8	CHP 8	2,6	2,5/400	1,840
9	CHP 9	2,7	3,9/435	1,104
10	CHP10	3,0	3,9/420	1,806
11	CHP 11	3,9	3,9/450	1,153
12	CHP 12	4,0	3,9/450	1,713

Using the data presented in Table1, the specific capital investment depending on the power output ($K_{n1(1)}$) and the specific capital investment depending on the live steam pressure ($K_{n1(2)}$) were searched.

It turned out that the best representation of real capital investment is natural logarithmic functions (Euler’s number base e = 2,72), namely:

- for capital investment depending on the power output:
  $y = -0.316 \ln x + 1.8043$ (11)
  where: y – capital investment,
  x – power output;
- for capital investment depending on the live steam pressure:
  $y = -0.146 \ln x + 1.7455$ (12)
  where: y – capital investment,
  x – live steam pressure.

The approximated costs are presented in Table 2, Table 3.

The approximated specific capital investment depending on power output $K_{n1(1)}$ estimated with the use of the selected function range from 1.656 mln €uro/MW to 1.691mln €uro/MW, while the average deviation of cost approximation shows a spread in the range: – 17% to +50%. The obtained results confirm the fact of the diversity and poor repeatability of CHPs systems solutions, which were built in different time periods. Therefore, the proposed dependence of costs on output power for determining the costs planned for industrial CHPs modernization can only be used for a rough estimation of costs for modernization.

Table 2. Specific capital investment $K_{n1(1)}$ [6]
Tabela 2. Jednostkowe nakłady inwestycyjne Kn1(1) w zależności od mocy zainstalowanej

No.	Plant	Real specific capital investment, mln €uro/MW	Approx. specific capital investment, mln €uro/MW	Deviation of cost approx.,%
1	CHP 1	1,684	1,656	-1,67
2	CHP 2	1,902	1,586	-16,61
3	CHP 3	1,876	1,691	-9,87
4	CHP 4	1,210	1,679	39,08
5	CHP 5	1,404	1,679	19,58
6	CHP 6	1,191	1,679	40,90
7	CHP 7	1,154	1,697	47,05
8	CHP 8	1,840	1,673	-0,09
9	CHP 9	1,104	1,669	51,17
10	CHP 10	1,806	1,654	-8,41
11	CHP 11	1,153	1,619	40,41
12	CHP 12	1,713	1,615	-3,34

Table 3. Specific capital investment $K_{n1(2)}$, [6]
Tabela 3. Jednostkowe nakłady inwestycyjne $K_{n1(2)}$ w zależności od ciśnienia pary świeżej

No.	Plant	Real specific capital investment, mln €uro/MW	Approx. specific capital investment, mln €uro/MW	Deviation of cost approx.,%
1	CHP 1	1,684	1,547	-8,13
2	CHP 2	1,902	1,547	-18,66
3	CHP 3	1,876	1,611	-14,13
4	CHP 4	1,210	1,547	27,85
5	CHP 5	1,404	1,547	10,18
6	CHP 6	1,191	1,412	18,55
7	CHP 7	1,154	1,547	18,55
8	CHP 8	1,840	1,547	-15,93
9	CHP 9	1,104	1,546	40,04
10	CHP 10	1,806	1,547	-14,39
11	CHP 11	1,153	1,546	34,08
12	CHP 12	1,713	1,547	-9,69

The approximated specific capital investment depending on the live steam pressure $K_{n1(2)}$ estimated with the use of the selected function range from 1.412mln €uro/MW to 1.611mln €uro/MW, while the average deviation of cost approximation shows a spread in the range: – 19% to +40%. The obtained results confirm the fact of the diversity and poor repeatability of CHPs systems solutions, which were built in different time periods.

Therefore, the proposed dependence of costs on the live steam pressure for determining the costs planned for industrial CHPs modernization also can only be used for a rough estimation of costs for modernization.

Generally speaking, for better cost estimation, detailed analyzes should be made, using the proposed dependencies to initially determine the costs of modernized CHPs.

The graphic illustrations of the proposed functions found are shown in Fig.3, Fig.4.[6].

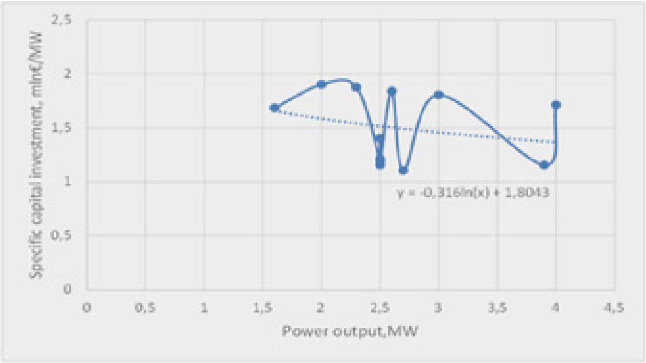

Fig.3. Specific capital investment $K_{n1(1)}$
Rys.3. Jednostkowe nakłady inwestycyjne $K_{n1(1)}$ w zależności od mocy zainstalowanej

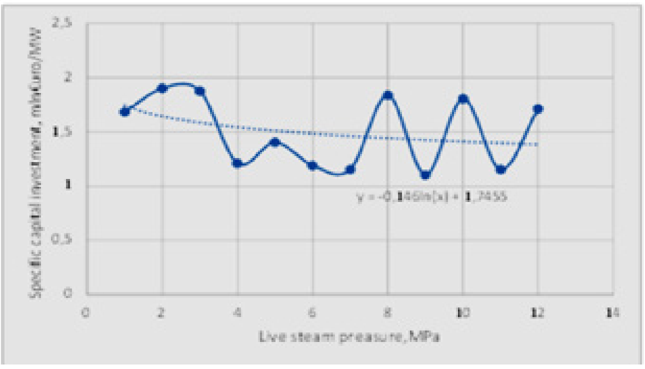

Fig.4. Specific capital investment $K_{n1(2)}$
Rys.4. Jednostkowe nakłady inwestycyjne $K_{n1(2)}$ w zależności od ciśnienia pary świeżej

The following conclusions can be used in practical applications:

- the raising of live steam pressure at the back-pressure turbine inlet from 2.5 MPa up to 3.9 MPa gives the decrease of specific capital investments in industrial heat and power plants of only about 3,7%;
- on another hand, the raising of live steam pressure at the back-pressure turbine inlet from 3.9 MPa up to 9.8 MPa gives the decrease of specific capital investments in industrial heat and power plants of about 9%;
- -the proposed method allows for a quick estimation of expenses in the case of planning the modernization of the CHP plant by changing the technology and installed electric capacity.

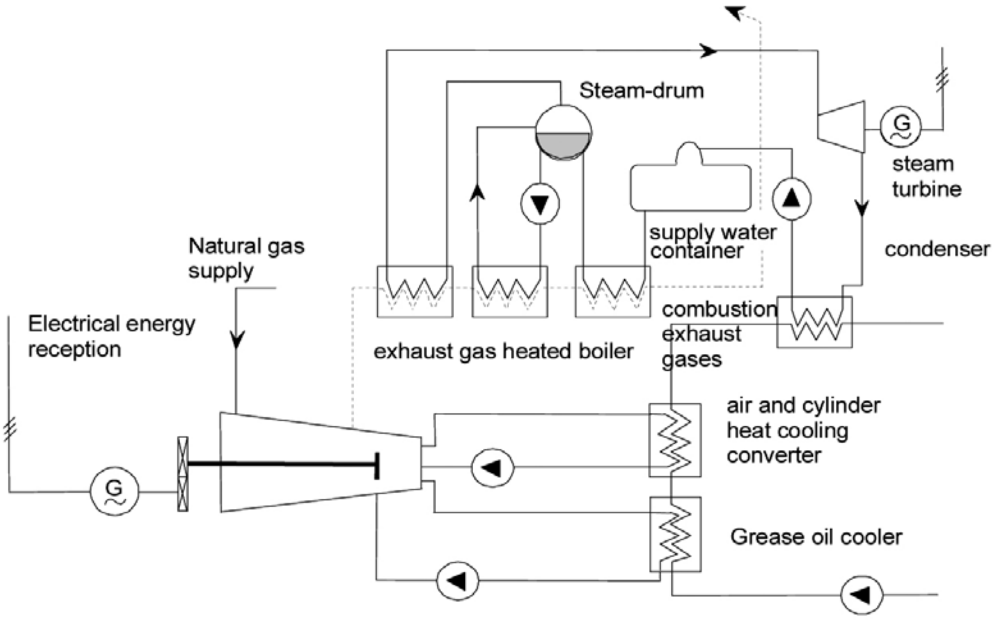

Fig.5.Power energy unit with a gas engine in a PECC system

Rys.5. Blok energetyczny z silnikiem gazowym w układzie PECC

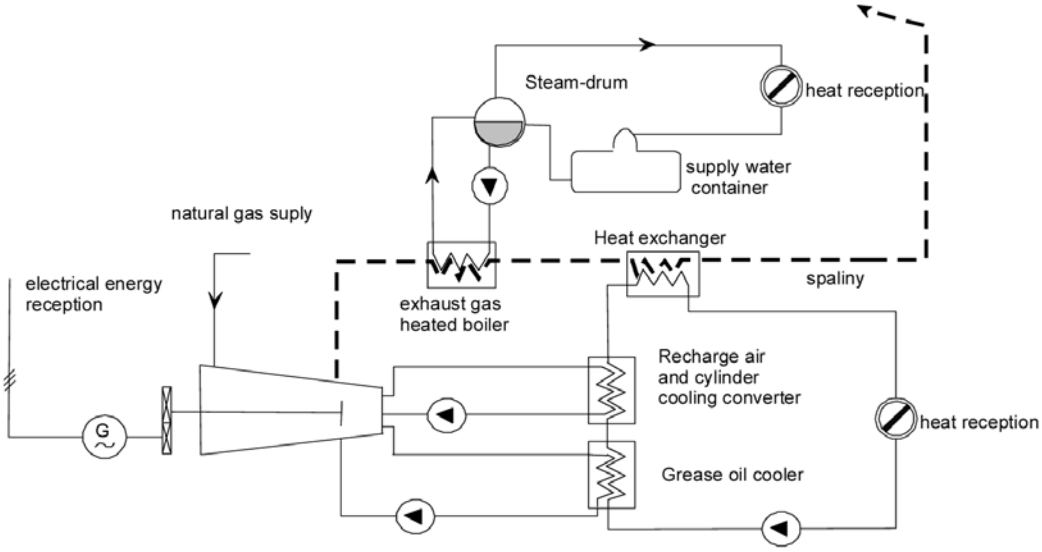

Fig.6.Transmission energy unit of steam and water utilizing waste heat

Rys.6. Blok energetyczny pary i wody gorącej z wykorzystaniem ciepła odpadowego

5.Combined systems of engine blocks, turbines and fuel cell systems for industrial power engineering modernization

Power systems using gas engines and small turbines (typical of distributed generation, and disseminated) have the potential of cost-effective solutions at low cost, high energy efficiency and environmental benefits wherever gas is available. PEPs (Pure Energy Plants) provide a simultaneous supply of heat and electricity in the most efficient way at the present time.

For industry use, systems heated by exhaust gases producing steam and hot water can be applied. The overall scheme of such a system is shown in Fig.5, and the main technical data are summarized in Table 4.

What is more, blocks with small power gas turbines prove useful especially for industrial power engineering modernization.

Dispersed sources in the form of blocks associated with gas turbines and boilers recovering water heat from a gas turbine exhaust is an attractive option not only for carbon technologies, but also for Diesel blocks.

Table 4. Technical data of a PECC system

Tabela 4. Dane techniczne systemu PECC

Unit configuration	**4 x W16V25 SG (four gas units with common single gas turbine)**
Electric power [MW]	4 x 2,8 + 1,2 = 12,4
Heat power [MJ/s]	12,4
Steam pressure [MPa]	1,0
Live steam [°C]	380
Calorific value of gas [MJ/Nm^3]	33-40
Fuel stream [Nm^3/h]	~ 2800
Heat demand [kg/s]	2,1
Full load emission [g/kW×h] NO_x CO	0,9 1,8
electric energy production efficiency [%]	43
Unit efficiency [%]	86

Currently available blocks with gas turbines reach powers of several hundred kW. In the case of industrial plants which supply water vapour for technological use, dominant blocks are combined with gas turbines, since such systems provide better operating parameters.

Table 5. Main technical data for energy transmission unit
Tabela 5. Główne dane techniczne bloku energetycznego pary i wody gorącej z wykorzystaniem ciepła odpadowego

Unit configuration	1 x W12V25 SG	2 x W16V25 SG
Power [MW]	2,1	5,6
Unit efficiency [t/h]	1,8	4,8
Heat power in steam [MJ/s]	1,2	3,1
Heat Power in hot water [MJ/s]	1,5	3,9
Production efficiency: [%]: – electric energy – steam – hot water	 40 22 27	 40 22 27
Losses [%]	11	11

In the technological system of gas turbine plants, shown in Fig.7, exhaust gases from the combustion chamber – KS (outflow from a gas turbine – TG) flow through the heat exchanger – W.

Fig.8 shows a simplified diagram of an industrial plant with a recovery boiler. In this system exhaust gases from the combustion chamber – KS, flowing through the gas turbine – TG are directed to the recovery boiler – KO, where industry steam and heat water are generated in a technological process.

The coupling of such processes diametrically shortens a chain of thermodynamic reactions, reduces energy losses due to the elimination of unnecessary reactions, reduces investment, reduces investment expenditure on a superfluous apparatus and reduces exploitation costs.

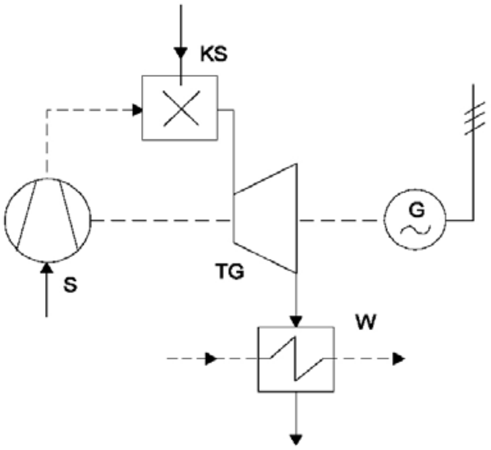

Fig. 7. Simplified scheme of a thermal power plant with a small power gas turbine
Rys. 7. Uproszczony schemat elektrowni cieplnej z turbiną gazową małej mocy

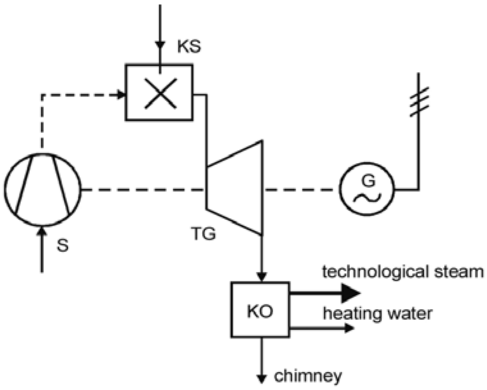

Fig.8. Simplified scheme of an industrial small power thermal power
Rys.8. Uproszczony schemat elektrociepłowni przemysłowej małej mocy

Another interesting energy technology for the modernization of CHP plants may be systems using fuel cells. Fuel cells may definitely be the technology of the future. Fuel cells are a common source of clean electricity generation at the recipients. It is estimated that they will be used primarily in industrial buildings, hotels, hospitals and public buildings. In addition, fuel cells are simultaneously a heat source, which can be used similarly to coupled systems.

A fuel cell is a clean and non-noise-emitting power generator of efficiency, suitable for power generation at the recipients. The characteristics of this equipment grants energy companies the opportunity for a new type of action. Energy from fuel cells fulfill the requirements of clean energy without the extension of electricity transmission and/or distribution lines.

The feed fuel for cell fuels is natural gas, which when air enriched creates a gas mixture rich in hydrogen. Chemical processes occurring in fuel cells result in the generation of electricity, heat, water and small amounts of carbon dioxide.

The most common fuel cell is a unit combined with phosphoric acid. It contains all the components necessary to convert natural gas into electricity and heat. The parameters of heat produced are sufficient for municipal use in the form of hot water or heat for heating buildings, for example.

Currently the following three types of popular cells are worth attention:

- acid (PAFC – Phosphoric Acid Fuel Cells),
- carbon (MCFC – Molten Carbonate Fuel Cells),
- solid (SOFC – Solid Oxide Fuel Cells).

The cells differ in efficiency and electrochemical reaction temperature. The highest efficiency yield reaching up to 60% can be achieved in the case of MCFC, SOFCs yield the highest temperature (around 950 ÷ 1000°C). They can be used in combined cycles with a steam turbine or in coupled systems demanding high parameters of received heat.

The fuel cell system with melted carbonate (MCFC) powered by natural gas for a power plant of 3 MW is presented in Fig.9.

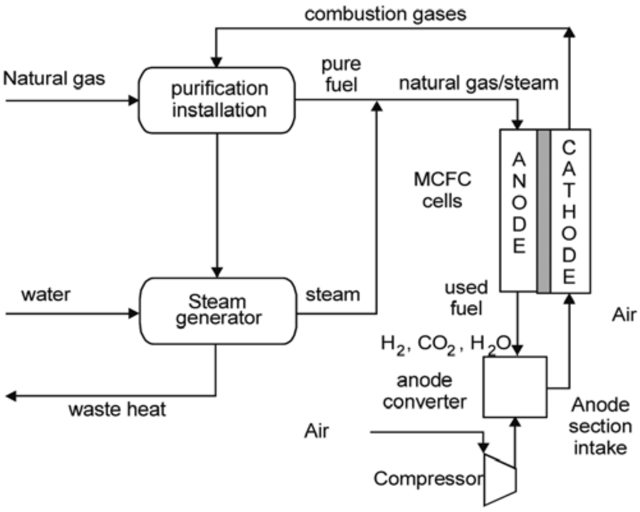

Fig.9. The fuel cell system with melted carbonate (MCFC) powered by natural gas for a power plant of 3 MW
Rys.9. System ogniw paliwowych ze stopionym węglanem (MCFC) zasilanych gazem ziemnym dla elektrowni o mocy 3 MW

Natural gas is purified of sulphur compounds in the fuel treatment plant. Steam is added to the non-reformed fuel stream before it is supplied to the fuel cell, where internal reforming occurs. The fuel reacts electrochemically with an oxidizer in the fuel cells generating a power of 3 MW DC . The parameters of the MCFC system are shown in Table 6.

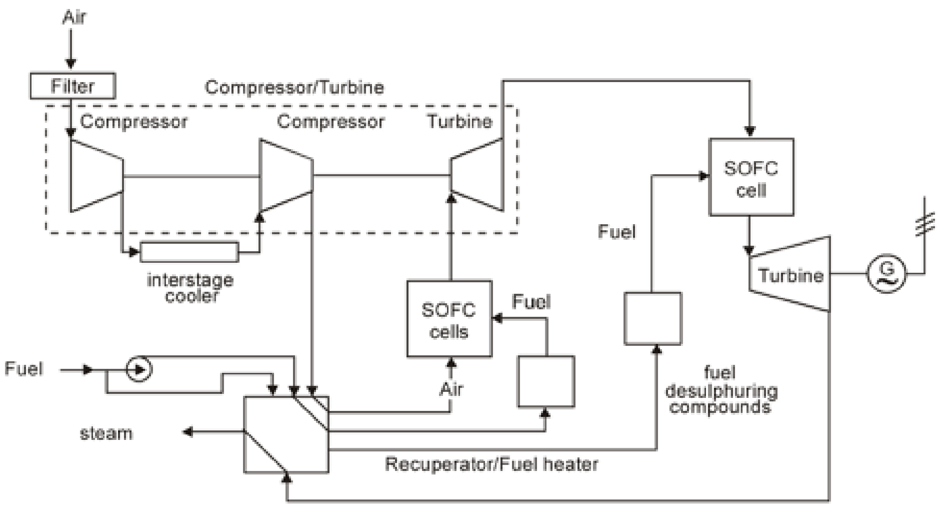

Fig. 10. Scheme of a unit equipped with SOFC of 4.5 MW

Rys. 10. Schemat bloku energetycznego o mocy 4,5 MW z ogniwem SOFC

Table 6. Parameters of the MCFC unit fuelled by natural gas with internal reforming

Tabela 6. Parametry bloku MCFC zasilanego gazem ziemnym z reformingiem wewnętrznym

Operation parameters	Unit	Value
Voltage to cell	V	0,64
Current density	mA/cm^2	No data
Working cell temperature	°C	650
Outlet pressure	MPa	0,1
General marker of fuel usage	%	78,0
Heat power to the system	MJ/s	4,8
Gross fuel cell power: Gross DC power Losses Gross AC power	 MW MW MW	 3,0 0,15 2,85
Own demand	MW	0,05
Net Power	MW	2,80
Electric efficiency	%	58
Unit heat usage	kJ/kW·h	6207

The system of pressure solid oxide fuel cells (SOFC) of 4.5 MW fueled by natural gas is presented in Fig.10 and the system operation parameters are outlined in Table 7.

Table 7. Parameters of the SOFC unit fueled by natural gas

Tabela 7. Parametry bloku energetycznego o mocy 4,5 MW z ogniwem SOFC zasilanego gazem ziemnym

Operation parameters	Unit	High pressure fuel cells	Low pressure fuel cells
Voltage to cell	V	0,63	0,62
Current density	mA/cm^2	Not available	Not available
Working cell temperature	°C	1000	1000
Outlet pressure	MPa	0,85	0,29
General marker of fuel usage	%	78	78
Heat power to the system	MJ/s	6,68	
Fuel cell Gross power DC power Losses AC power	MW	 3,22 0,13 3,09	
AC unit gross electric power AC cell fuel power Turbine power AC unit power	MW	 3,09 1,40 4,49	
Own demand	MW	0,04	
Net Power	MW	4,45	
Electric efficiency	%	63	
Unit heat usage	kJ/kW·h	5714	

The generator working on the common shaft with the turbine generates 1.4 MW of power fed to the AC network, and the exhaust at a temperature of 649C is utilized to warm the fuel streams and the oxidizer. The fuel stream obtained at the system outlet leaves the power section (fuel cell stock) at a temperature of 258°C. Power generation systems based on fuel cells are a dynamic and interesting branch of power energy. However, the development of fuel cells, like any new technology, is associated with relative high capital and the need to finance scientific research. Fuel cells in present time will be able to effectively compete in the market with much lower cost technologies in electricity generation, based mainly on coal combustion. Industrial power plants using fuel cells seem to be very promising, especially in cogeneration systems.

6. Conclusions

The concept of taking into account the investment risk with the use of elements of a multidimensional comparative analysis was proposed, which allows to assess the risk and hence its cost in the structure of the annual cost. This method has been used by the author in the development study of local heat and electricity markets. The method can be useful for evaluation of investing or modernizing risk in power engineering. For the example of some selected plants in the chemical industry works an analysis of the effect of rising of live steam parameters on capital expenditure has been carried out. The determined model dependences of elementary capital expenditure in industrial heat and power generating plants on steam parameters, and turbine set power can be used in the optimization of parameters and programming rational modernization of old coal fueled CHPs.

The article proposes a simplified model for quick cost estimation of the CHP plant modernization. In the initial phase of the decision-making process on the modernization of the CHP plant, the decision-maker would like to know what level of expenditure on modernization will have to be planned. make a decision to modernize the CHP plant. In many European countries, and especially in the countries of Eastern and Central Europe, there is an urgent need to modernize the energy economy, combined with increasing the efficiency of energy use in production processes. This is an important issue for the reindustrialisation of old inefficient industry, which should be implemented for the rational use of energy and the environment. The new approach to annual costs in industrial combined heat and power generating plants proposed in the paper may be useful for decision-makers, analysts and planners who make decisions in risk conditions. It is especially important in industry due to the European Union Medium Combustion Plants Directive towards to clean energy production.

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