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Combined heat pump and power plant. Part II: economic analysis

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1. Introduction

There exists numerous economic analysis of power plants breaking down the overall composition of electricity production costs, including the investment. The history of heat pump (HP) plants is more recent; therefore the number of publications related to their economic analysis is lower. Busato et al. [1] presents the economic analysis of HP plant which has been in operation for the last ten years. The compressor of the plant is turned by internal combustion engine fuelled by natural gas (NG). There also exist some surveys [2-3] of large HP plants presenting economic analysis and their competitive ability with regard to other heat production technologies. Further, the articles [4-7] outline economic analysis of HP systems; however, their investment costs are not evaluated. The authors of [8-9] propose numerical simulation and economic modelling of HP for residential heating systems. Economic and energy analysis is presented in [10] where investment costs are evaluated. Finally, the authors [11] propose interesting analysis of different heat and power technologies including the influence of wind power on investment of other heat and power technologies.

The economic analysis of the combined heat pump and power (CHPP) plant is partly presented in [12]. The authors draw a conclusion that the HP technology has an advantage both over the cogeneration and condensing boiler technology for district heating.

2. Cogeneration, condensing boiler or heat pump?

In response to this question, Lazzarin and Noro [4, 12] highlight the HP; it should be noted, though, that in their case, the HP works with the electromotor, not with a heat engine. The mechanical efficiency of a heat engine is always higher than electrical efficiency. Electrical losses of a plant arising due to generating, voltage transforming and other auxiliaries as well as because of distribution losses of a plant amount up to 10%.

On the other hand, the advantage of the heat pump depends on its efficiency, i.e. coefficient of performance (COP). When a low potential heat source has a relatively high temperature, the HP is advantageous, even though the required temperature for heating grid is very high. The power plants can offer their waste heat of high enough temperature so the HP could be very effective. However, general opinion prevails that cogeneration is the best manner of heat and power producing although its utilization efficiency does not exceed 80%. Meanwhile, the said efficiency of advanced condensing boilers, for example, exceeds 100%.

In order to find the answer to the question posed at the beginning of this section, let us analyse a case where all three heat production technologies use natural gas (NG) at a price of, let us say, 0.4 EUR/1m^3. Supposedly , the High Heat Value (HHV) and the Low Heat Value (LHV) of used gas is 36.6 and 33.8 MJ/m^3 respectively, or 10.2 and 9.4 kWh$_T$/m^3. In case when thermal energy is produced by an advanced condensing boiler, the amount of heat could exceed the LHV and, according to authors [12], the utilization efficienc is 1.03. Thus 1 m^3 of NG gives 9.7 kWh of thermal energy. The heat fuel cost depends on NG price, which in Lithuania, for example, is 0.4 EUR/m^3 (September 2012), so the cost is (0.4 / 9.7 =) 0.041 EUR/kWh$_T$. The final cost is higher by approximately 10% because of the operational and overhead (depreciation, profit, etc) costs of the heat plant. It means that the thermal energy would be realized to a heat distributor at a price of 0.045 EUR/kWh$_T$ with the 0.44 EUR income from each cube of gas.

The analysis of a typical cogeneration plant in Kaunas indicates that under the summer regime 1 m^3 of gas gives 3.3 kWh$_E$ of electricity and 5.8 kWh$_T$ of heat, which is exhausted into the surroundings. Cogeneration regime in winter gives only 1.7 kWh$_E$ of electricity and, in fact, the same amount of heat which is suitable for district heating. So, the realization of heat brings (5.8 × 0.045 =) 0.26 EUR/m^3.

The cogeneration plant receives another part of income from the realization of power. The income depends on power market price as well as on the price assessed by local authority. The market price depends on the efficiency of power production in region. If average NG power production and plants utilization efficiency is 40% and 90% respectively, the constituent part of the fuel in the total price of power is 0.4/(9.4 × 0.9 × 0.4) = 0.12 EUR/kWh$_E$ and with the same operational and overhead costs is 0.13 EUR/kWh$_E$. Thus, the realization of power would give (1.7 × 0.13 =) 0.22 EUR/m^3 and a total (0.26 + 0.22 =) 0.48 EUR income from each cube of NG compared with 0.44 EUR/m^3 income generated by using a condensing boiler. At a glance, the difference is not big; however, if the fuel expense (0.4 EUR/m^3) is excluded, the income generated by the plants of both technologies differs twice in favour of the cogeneration plant.

However, as regards the advantage of the cogeneration plant, two factors should be taken into consideration. The first one is the market price of electricity. In Lithuania, for example, due to a relatively low Russian power price, the market price of the power does not exceed 0.058 EUR. In this case, the income of a cogeneration plant decreases up to 0.36 EUR/m^3, i.e. becomes significantly lower than the income generated by condensing boiler plant.

The second factor is related to the possibility of applying huge heat pumps in a cogeneration plant. This is feasible under two conditions: if there is a sufficient amount of low potential heat for evaporating the working fluid and a huge heat consumer nearby, e.g. a town with a developed district heating grid.

The advantage of a conventional heat pump against other technologies is based on several factors, the main of which is the COP. If a condensing boiler fuelled by wood (the price of which today is lower compared to the price of NG) determines the heat price, the COP of a heat pump must be higher in order to be competitive. The same is applicable if the regional power price is relatively high in respect to thermal energy price. Thus, it can not be asserted that the price of heat produced by heat pump will be lower compared to cogeneration and condensing boiler technology, especially if an electrical motor but not a heat engine is used.

Gas turbine combined-cycle (GTCC) is the most effective heat engine today to transform heat into mechanical energy (electricity). This new technology was developed in 1990s, and till now GTCC power plants have accounted to 88% of the total new generation capacity built, e.g., in the United States [13]. Why GTCC heat engine could not be employed in a CHPP plant that produces sufficient amount of electricity and heat? Moreover, the thermodynamic analysis (see Part I, [14]) clearly proves that the HP operated with GTCC heat engine gives a very high COP.

It should be noted that GTCC engines are very powerful which ensures their high efficiency and comparatively low price. Integration of such a big machine into an HP system is feasible only on two conditions: if a huge amount of waste heat is available in the power plant and if an even bigger heat consumer is situated nearby. This is exactly the case under consideration by this article, namely, a big town with a central district heating system and a cogeneration heat and power plant fuelled by natural gas. These are the exact conditions for getting exclusively low heat price for customers by HP technology. However, employing GTCC engine into the heat pump system would increase the heat price considerably due to high investments (capital costs). So, the analysis of the capital costs influence on the heat price is necessary that is presented in the next paragraph.

3. Capital costs

It can be assumed that, as a CHPP plant consists of two plants, its overall capital costs should be the sum of the investment costs of each plant separately. However, as some of the equipment would be shared, and as HP operates without an electro motor, in point of fact the overall costs would be smaller. Moreover, the lower heat pump plant cost, if compared to a conventional one, is determined by the fact that the low potential heat source is very effective and cost-efficient compared to usual sources, such as ground, sewage, air or territorial water. It is possible to find information and to calculate investments of the conventional HP plant of air-water or water-water system [15-18]. Although it is considered that heat pumps are expensive technology of heat production, the investment costs of large industrial HP plants are quite low. Martinus et al [19] present the specific costs of HP plants constructed in 1990's. As could be seen in Fig. 1, the specific investment cost is under 500 EUR/kW$_T$ for large HP plants. Moreover, the costs for conventional heat pump have a clear tendency to decrease. The data presented in Fig. 2 demonstrate that investment costs have decreased four times during the last twenty five years.

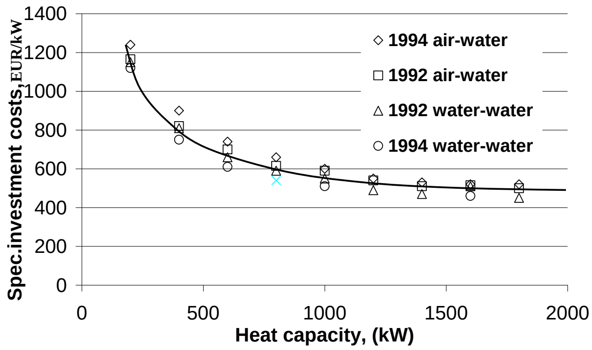

Fig. 1 Specific investment costs of different HPP subject to heat capacity [19]

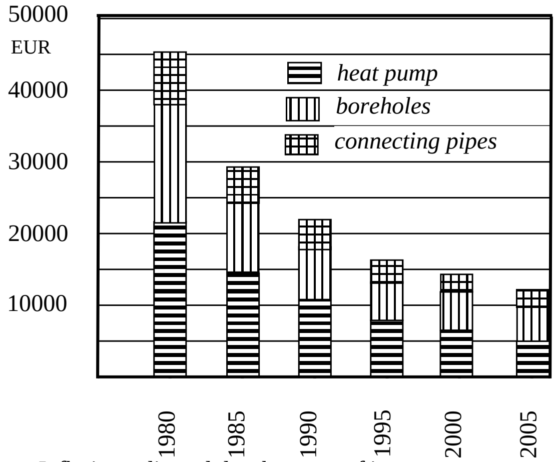

Fig. 2 Investment costs dynamic of conventional heat pump [19]

This phenomenon could be explained by an extremely dynamic development of conventional heat pumps and the further increasing market demand. According to the authors [19], the sales of heat pumps in Europe and Japan have increased by more than four times over the last fifteen years. As regards large heat pump plants, the analogous trend could be seen, in particular in China, the US and Scandinavian countries. Therefore, investment costs of large conventional HP plants should decrease as well.

The main cost component of conventional HP plants is related to heat extraction from low potential heat source. However, in our case, which is under consideration in this article, this component will be smaller due to the fact that there is no need either for specific and expensive boreholes or for big and specialised circulating pumps and fans in case heat is extracted from air and water respectively. In this case, the low potential heat is obtained in a very efficient way when one fluid condenses and another one evaporates.

Based on the considerations above, it can be assumed that the investment costs for the HP plant integrated into a CHPP plant should not be higher than 400 EUR/kW$_T$, that means that the overall investment cost for the power plant producing 250 MW heat would roughly constitute about EUR 100 million.

According to Stan Kaplan [13], investment costs of a modern GTCC power plant in 2010-2012 were about 1100 $/kW$_E$. Though it could be expected that construction in Eastern Europe should cost less, the costs for the modernization of Lithuanian Power Station, however, where a 455 MW GTCC bloc was built in place of the old steam turbine, was almost the same, namely, 1050 $/kW$_E$. Assuming that the costs for CHPP plant equal to the investment costs of both heat pump and GTCC plants built separately, the investment costs for a combined heat pump and power plant is 248 million EUR.

4. Payback

The payback of a CHPP plant depends on the payback of both HP and GTCC plants, the latter depending strongly on the sales price of electricity in a given region. This price has to be high enough to balance the production costs. However, it should be noted that in most Eastern European countries the electricity price is somewhat lower than in the Western European countries, because of several reasons. One of them is the import of cheaper electricity from Russia and Scandinavian countries. This is particularly applicable to the Baltic countries where the price of the imported electricity is lower compared to the one produced locally more than twice.

Due to this reason, it is risky and unprofitable to invest into a construction of new power generating capacities or into modernization of the existing ones without the ensuring the State guarantees to buy the electrical power at a price higher than that of the market. The Government of Lithuania, for example, increased the final price of electricity for the consumers by adding the so-called Public Service Obligation (PSO), this way creating the possibility to carry out the modernization of the existing generation capacities. Today the modernized Lithuanian Power Station has the possibility to sell electricity at a price which is twice higher the market price. The selling price of electricity of cogeneration plants which, too, require modernization, is also higher than the market price nearly twice.

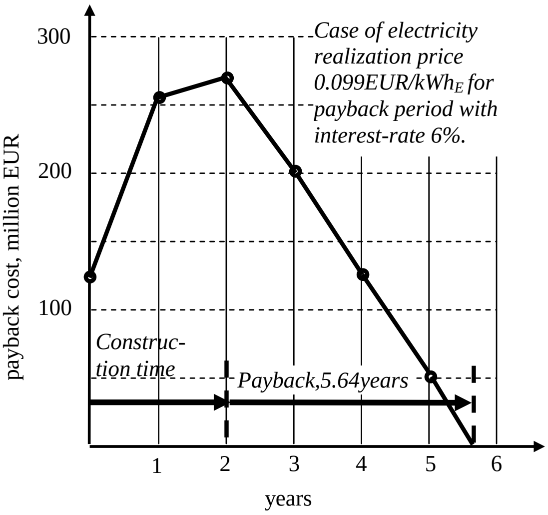

Fig. 3 Dynamic of payback costs during CHPP plant construction and paybak

The investment into novel CHPP plants, as proposed by the author, could be economically sound and thus interesting due to very low heat production costs. Indeed, the payback of the capital costs would be shortened namely at the expense of the heat consumers. As seen from Fig. 5, the price difference is 0.0606 EUR/kWh$_T$, which allows, as is in case of Kaunas City, to accumulate 80.5 million EURO as the return capital (66.5 mln in winter and 14.0 mln in summer with the annual heat demand 1.32×10^9 kWh$_T$). The return of investment would be no longer as 3.7 years under the interest-rate of max 6%, and on condition that the electricity will be sold without incurring losses (Fig. 3). It is, however, difficult to achieve, in spite of the fact that the electricity is generated by the most effective GTCC power plant. If the natural gas price is 0.4 EUR/m^3, the fuel cost of kWh$_E$ is 0.091 EUR, which, together with additional expenses (see part I, [14]) makes 0.099 EUR/kWh$_E$. This electricity price is much higher than the today's (September 2012) market price, which is 0.046 EUR/kWh$_E$.

Therefore the payback of a novel CHPP plant depends mostly on the selling price of electricity. In case of our example, the CHPP plant produces 0.71×10^9 kWh$_E$ in winter season and 0.77×10^9 kWh$_E$ in summer (with capacity factor 90%). If electricity is realized with the profit of 10%, (i.e. electricity realization price is 0.109 EUR/kWh$_E$), the CHPP plant can assign additionally 14.7 million EUR from the electricity selling. The payback period is 3.0 years in this case (Fig. 4). The period may be longer or shorter depending on the electricity realization price. For example, the second case of realization price (0.109 EUR/kWh$_E$) is preferential price which Government adjusted for Lithuanian Power Station in 2012. After its modernization (in 2013) this price was increased to 0.145 EUR/kWh$_E$. The third case is the price (0.0008 cEUR/kWh$_E$) adjusted for cogeneration power plants which had not been subjected to modernization whereas the fourth and the fifth are the market prices which differ by PSO (about 0.02 EUR/kWh$_E$ in 2012).

The heat price paid by Kaunas customers in the current season is 0.098 EUR/kWh$_T$. Its main component is the so-called variable part related to NG price. To be more precise, this is the price which the heat distributor pays to the heat producer. This price also includes some part of other costs of the heat producer. The official part of the heat distributor is 0.0138 EUR/kWh$_T$ and the taxes make 9% of the sum (see the first column of Fig. 5).

Let us suppose that the heat customers will pay the present price during the payback period. The second column of the Fig. 5 demonstrates the heat price composition in this period. It is clear that the main part of the price is the payback cost, which brings 0.0606EUR from each kWh$_T$ Costs of the distributor as well as taxation stay the same.

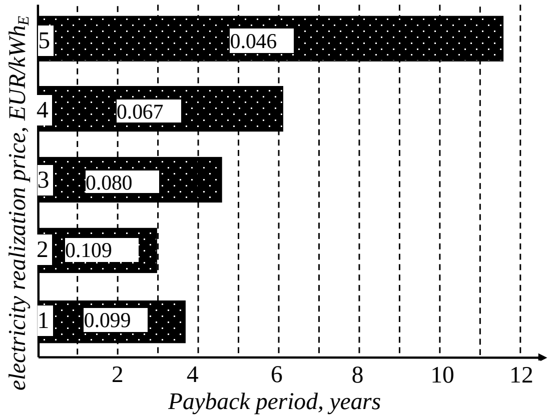

Fig. 4 Payback period subject to power realization price

5. After payback

The composition of the heat price after the payback is presented in the third column of the Fig. 5 The final price for Kaunas consumers is 0.0315 EUR/kWh. The operation cost of the novel CHPP plant is calculated assuming that the number of the employees will be double compared to the present figure, and their average salary will be 780 EUR/month. The expenditure for social insurance, electricity, maintenance and repair are taken into consideration, too.

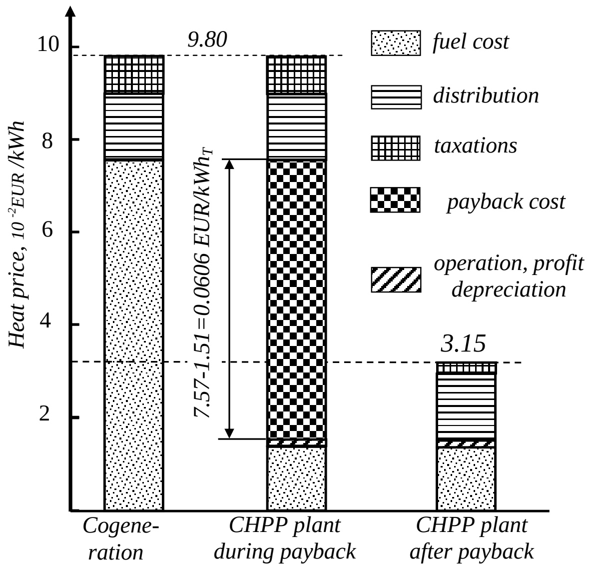

Fig. 5 Comparison of heat price before, during and after payback

The heat price of 0.0315 EUR is very low compared to the price presently paid by the consumers (0.098 EUR/kWh$_T$). This heat price may be considered by the decision makers as incorrect with respect to the electricity price. Therefore, it is highly probable that after the payback the CHPP plant may be pressed to sell its electricity at a price lower than its production cost, i.e., to sell it at a market price, adding said PSO. As can be seen in Fig. 6, in this case the heat price would increase up to 0.058 EUR/kWh$_T$. This price could be even be higher (0.0785 EUR/kWh$_T$), if the CHPP plant would be obligated to sell its electricity at a real market price. However, this is not likely to occur as it would be discriminatory with regard to other power plants operating in the country. Moreover, the CHPP plant produces both electricity and heat, namely, the products which are politically and socially sensitive. This is particularly valid as regards the heat, for which the consumers bear much higher expenditure than that for electricity. Therefore the three columns in the middle of the Fig. 6 are the most probable after the payback period.

The situation with NG price in the USA and Europe seems challenging due to significant price differences there. The low NG in the USA influences its decrease in Europe. The price of NG has a big influence on the heat and electricity price of the CHPP plant. The lower the NG price, the lower the electricity production costs. Consequently, the heat consumers bear smaller burden of subsidizing the sales of electricity, which, in its turn mean that they pay less for the heat. Therefore, the NG price has a double effect on heat price (Fig. 6).

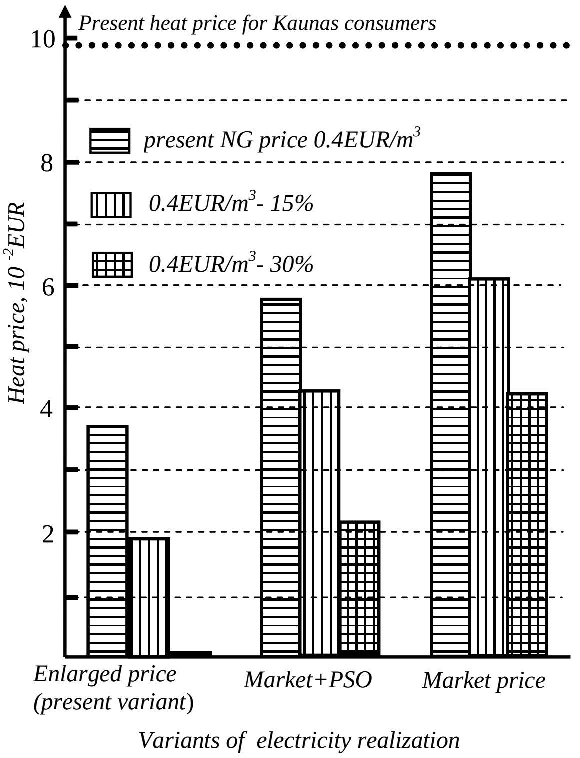

Fig. 6 Heat price compare with electricity and NG gas price

The market price of electricity has influence on the heat price as well. The electricity price forecasts are difficult to make. One of the forecasts predicts even 0.084 EUR/kWh$_E$ in 2020, which would allow the CHPP plant to profit from the sales of electricity in addition to heat. The diagrams presented in Fig. 7 demonstrate the dependence of the heat price on predicted power market price under different NG prices and the models of electricity sales.

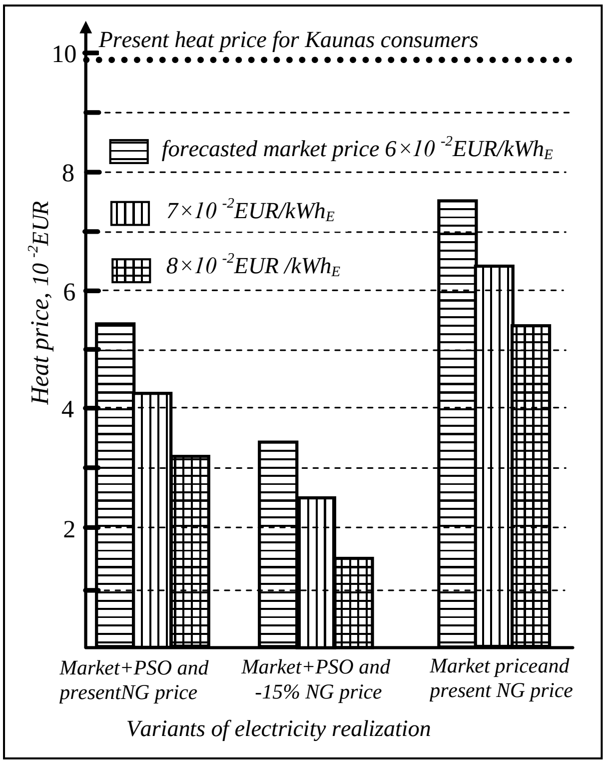

Fig. 7 Heat price compare with predicted market price of electricity

Market prices of electricity and NG are related because part of power stations is fuelled by NG. Therefore the case with the highest predicted market price of electricity and with a 30% lower NG price is not presented in the Fig. 7 as hardly probable. The case with a 15% lower NG price is quite probable in future, all the more that the present 0.4 EUR/m^3 price in Lithuania is the highest one among the neighbouring countries. So, it can be stated that the heat pump technology in the novel CHPP plant can ensure much lower heat cost and also profitable production of electricity.

6. Ecological aspect

Ecological aspect of this project is also important both from the environmental and economic point of view. In compliance with the EU legal acts**,** every ton of CO_2 which is non-exhausted due to more effective technology is worth 20 EUR. Therefore, a company with the modernised capacity higher than 20 MW is entitled to an annual receipt of this “green” money until at least 2020.

It is known that every 1000 m^3 of burned natural gas is responsible for 1.96 ton of CO_2 exhausted to surroundings [12]. Actually, in order to produce 1.32×10^9 kWh of heat by cogeneration technology, 318 mln m^3 of NG is needed (193 mln m^3 in winter season and 126 mln m^3 in summer season). The cogeneration plant also produces 0.36×10^9 kWh of electricity in winter and the same amount in summer.

Both electricity and heat would be produced much more effectively in a CHPP plant. The same amount of electricity (0.72×10^9 kWh_E) would be produced by fuelling 164 million m^3 of NG (1 m^3 of NG gives 4.4 kWh_E by GTCC technology [19]) and the 1.32×10^9 kWh_T will require additional 45 million m^3 (1 m^3 of NG gives 29 kWh_T by HP technology [19]). Consequently, the total amount of burned NG would be decreased from 318 million m^3 to 209 million m^3 i.e. by 109 million m^3. This would reduce the CO_2 exhaustion by 214 thousand ton. The owners of a CHPP plant could get annual income of 4.3 million EUR.

7. Conclusions

The economic analysis of the novel CHPP plant proves cost-effectiveness of presented heat pump and power technology. It determines short payback period and an advantageous heat and power price. CHPP plant can produce heat for a big town with district heating system by heat pump technology, which is more effective than cogeneration technology. Short payback period is determined by low heat production cost, which enables subsidising the sales of electricity in case its cost is higher than the power market price. In view of the forecasted power market and natural gas prices, the CHPP plant technology is able to ensure competitive production of electricity and to offer heat to consumers at a much lower price.

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V. Dagilis

KOMBINUOTA ŠILUMOS SIURBLIO IR ELEKTROS JĖGAINĖ. ANTRA DALIS: EKONOMINĖ ANALIZĖ

R e z i u m ė

Straipsnyje pateikta naujos šilumos siurblio ir elekros jėgainės ekonominė analizė. Analizė rodo, kad kombinuota šilumos siurblio ir elektros gamybos technologija yra efektyvi, kas sąlygoja trumpą atsipirkimo laiką ir žemą šilumos kainą. Jėgainė gali gaminti šilumą šilumos siurblio pagalba dideliems miestams. Žema šilumos savikaina suteikia galimybę subsidijuoti elektros pardavimą, jei rinkos kaina yra žemesnė už savikainą. Jėgainė gali užtikrinti konkurencingą elektros gamybos kainą žvelgiant į perspektyvines elektros bei dujų kainas bei užtikrinti ženkliai žemesnę šilumos kainą palyginti su šiandieninėmis.

V. Dagilis

COMBINED HEAT PUMP AND POWER PLANT. PART I: THERMODYNAMIC ANALYSIS

S u m m a r y

The paper presents economic analysis of combined heat pump and power plant. The analysis proves the cost-effectiveness of the combined heat pump and power technology which determines short payback period and low heat price. The plant can produce heat for large town by heat pump technology. Low heat price provides possibility to subsidize electricity realization in case it is higher the market price. According prospective electricity market and natural gas prices the presented plant technology ensures competitive electricity cost and able to provide heat at much lower price compare with present.

Keywords: heat pump, power plant, cogeneration.

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