Centrum
Rzeczoznawstwa
Budowlanego

Open Access Journal
Modern Engineering 4 (2021) 21-37
journal homepage: https://mengineering.eu/

Concept and cost-effectiveness analysis of a trigeneration system in a large healthcare facility

Michał ZARĘBSKI[1], Andrzej GRZEBIELEC[*1]

[1] Warsaw University of Technology, Faculty of Power and Aeronautical Engineering,
Institute of Heat Engineering, Warsaw, Poland

Abstract

This paper presents the possibility of using a high-efficiency trigeneration system to generate electricity, heat and cold for the needs of a large health care facility. The hospital building is an average of several buildings of the same class. It is a typical Polish object built in the second half of the twentieth century and subjected to thermal modernization consisting in insulation of external walls and roof and replacement of windows and external doors. Thermal modernization led the building to a condition that meets the technical requirements for year 2017. Therefore, the conclusions resulting from the work can be applied to the entire group of health care institutions. The demand for electricity was obtained as fifteen-minute periods, while the demand for heat and cold was calculated using the hourly method. The calculations were made on the basis of meteorological data for the Warszawa-Okęcie station. The choice of the most cost-effective option was determined by economic analysis. The considered variants were compared to the basic variant, which is the most typical solution, i.e. a compressor chiller. For the analyzed options, benefits compared to the baseline option were estimated. NPV indicators were calculated, which clearly stated the best scenario, for which electricity and gas prices was then performed.

Keywords: trigeneration, hospital, economic analysis, cogeneration, absorption refrigeration

1. Introduction

In large health care facilities, there is a growing interest in the construction of modern building systems, such as mechanical ventilation with air conditioning in rooms not referred to in the Regulation of the Minister of Health on detailed requirements to be met by the premises and equipment of an entity performing medical activity [1]. The rooms described in the regulation include operating theatres, isolation rooms or rooms for immunocompromised patients. The proportion of such rooms in the total area of an exemplary hospital is not significant, and the fact that these installations are required means that no attention is paid to the energy efficiency or environmental aspect of the refrigeration systems used. The extension of refrigeration systems to almost the entire usable area of the hospital is aimed at improving thermal and humidity comfort for staff and patients. Such a drastic increase in demand for cold forces to consider the efficient use of energy that translates directly into costs. Classic systems based on compressor units generate costs in the form of consumed electricity.

The hospital is therefore completely dependent on market electricity prices. Particularly worrying seems to be the growing uncertainty of the stability of electricity prices in Poland, the increase in which in recent years has been significantly influenced by the prices of CO_2 emission allowances. As can be seen in Figure 1, after several years of relative stability, we observe increasingly strong price fluctuations. The dashed line represents a trend line that clearly defines the trends in the market. Only price increases can be expected, which is caused by the decreasing pool of free emission allowances.

---

* **Corresponding author:** E-mail address: (andrzej.grzebielec@pw.edu.pl) Andrzej GRZEBIELEC

Received 2 November 2021
Available online 15 December 2021
ISSN 2450-5501
Published by Centrum Rzeczoznawstwa Budowlanego

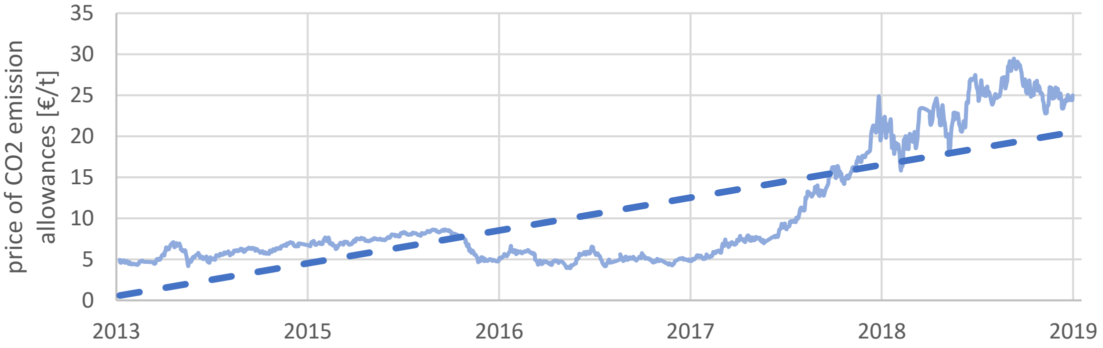

Figure 1. Prices of CO_2 emission allowances

In addition, the price of carbon dioxide emission allowances, commonly referred to as the "CO_2 price", is an increasing share in the retail price of electricity. Currently, it is estimated that this is about 20% of the price at the recipient, and this share will grow [2]. Considering the above, it becomes obvious that large electricity consumers are beginning to consider installing their own small generation sources. This solution will protect against unexpected fluctuations in electricity prices. It also allows to reduce the costs associated with supplying the facility with electricity.

Another aspect that large healthcare institutions must pay attention to is the high demand for heat used in central heating (CH), domestic hot water (DHW) and process heat (CT) installations. Hospital facilities are characterized by a high base heat collection throughout the year. This is related to the operation of the facility around the clock and the value of the correction factor due to interruptions in the use of domestic hot water equal to unity ($k_R = 1.00$) [3]. That means that the costs associated with the proper supply of heat to the facility are significant throughout the calendar year. Large healthcare facilities are mostly located in cities with district heating networks. These, on the other hand, are usually supplied by individual district heating companies, which results in the creation of a kind of monopolies and low competition [4]. This results in the introduction of a tough pricing policy, which, as in the case of electricity, burdens medium and large consumers with the risk of market fluctuations, and also increases the cost of the medium by the distribution part. Figure 2 shows how the heat sales prices in units not using cogeneration systems were shaped, the dotted line indicates the trend line along with the forecast for future years.

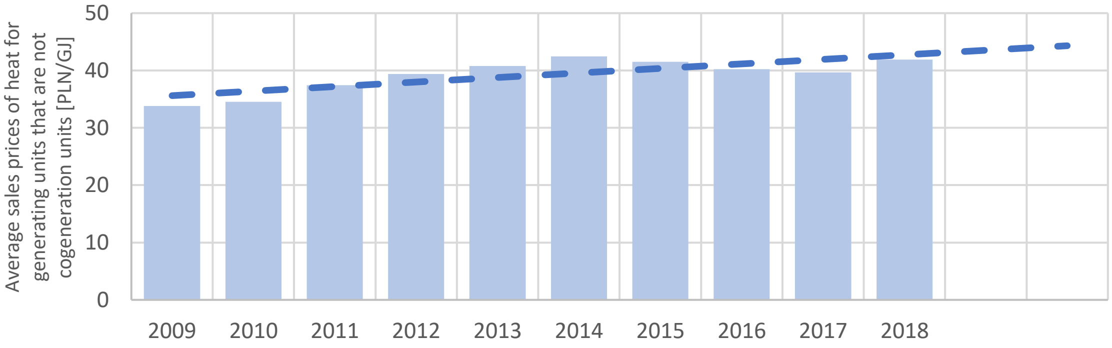

Figure 2. Average heat sales prices of non-CHP units [5]

As it can be seen, prices will grow steadily. The Energy Regulatory Office in its review of the heating market for 2018 [5] indicates two main reasons for such an increase, i.e. rising hard coal prices and, as in the case of electricity, the prices of CO_2 emission allowances.

1.1. Trigeneration as an opportunity to respond to negative trends

The above considerations clearly indicate the need to use own sources of electricity and heat generation. Taking into account also the fact that the analyzed hospital facilities on the wave of thermo-modernization projects are beginning to widely use air conditioning on a large usable area, the increased demand for cold should also be considered. This characteristic of media consumption in the company perfectly fits the concept of trigeneration, i.e. simultaneous production of electricity, heat and cold [6,7].

Trigeneration is an extension of the concept of cogeneration, which defines the simultaneous production of two different energy carriers from a given fuel. In the case of trigeneration, also known as trigeneration, fuel is also used to produce a third energy carrier – cooling. The ability to produce three different media at the same time, at least two in combination, allows flexible control of the source to achieve its highest efficiency. Figure 3 shows the schematic diagram of the trigeneration system with access to external networks. Simplified energy flow is marked, taking into account the most significant losses.

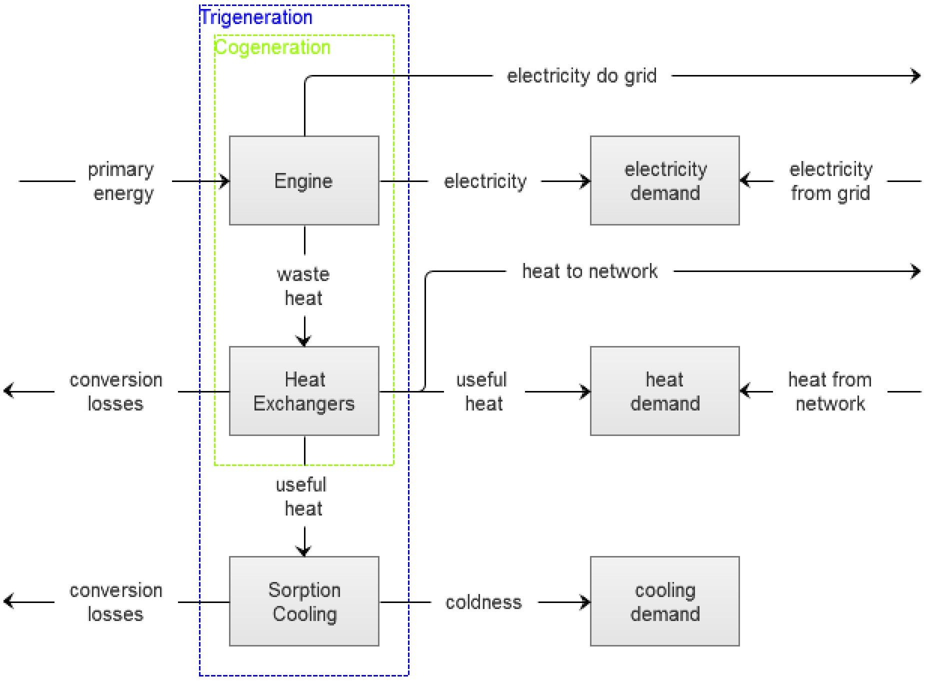

Figure 3. Schematic diagram of the trigeneration system

2. Analyzed object description

The facility analyzed in this paper is a large health care facility located in the Mazowieckie Voivodeship in Poland. As a result of the analysis, a building model was obtained that reflects the characteristic features of modernized hospitals in the Mazowieckie voivodships, but the characteristics of this style of construction mean that further analyses can be applied to similar buildings in Poland.

The building consists of three rectangular blocks, the highest of them with four above-ground floors, differing in construction technology. The main building was built in traditional brick technology from ceramic bricks typical of the 60s. In the 90s, two buildings in reinforced concrete skeleton technology with aerated concrete walls were added. In recent years, all walls have been insulated to meet the technical requirements of WT 2017 of U_{max} = 0.25 W / (m^2K). In the basement there are technical rooms, such as warehouses, ventilators or a heat substation room. On the ground floor and other above-ground floors there are patient rooms, treatment rooms and staff rooms, as well as bathrooms. Figure 4 shows the percentage share of all major room types in the analyzed facility. It is worth noting that one third of the area consists of corridors, locks and staircases, one third patient rooms and treatment rooms, and the remaining part are social rooms, toilets, bathrooms, cloakrooms, warehouses, technical rooms, kitchens and buffets.

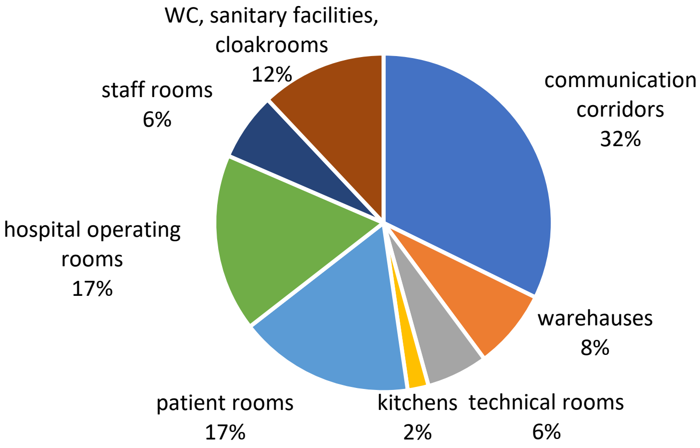

Figure 4. Usable area of analyzed object

The total heated area is 10300 m^2, and the volume is 42400 m^3. The building was designed for use by 350 people, but during further calculations a simultaneous occupancy factor of 0.9 was assumed to take into account the actual use of space.

Currently, the building has the following installations: electrical, water and sewage, central heating, domestic hot water, gas and mechanical ventilation with heat recovery. The electrical installation is powered by two cable connections. In the basement there are switchgears supplying individual electrical shafts and other two-storey switchgears. The central heating system in its current state consists of a heat node supplied from the municipal heating network (non-cogeneration, coal sources), horizontal steel ducts, exposed sectional radiators, cast iron. The hot water system is supplied from the same dual-purpose substation, and the circuits are insulated.

3. Energy Consumption Analysis

3.1. Electricity

The analysis of electricity consumption was made on the basis of fifteen-minute periods of electricity consumption received from the distribution system operator. These waveforms were created thanks to appropriate measurement and settlement systems. The facility has two medium-voltage electrical connections. Figure 5 shows the monthly electricity consumption.

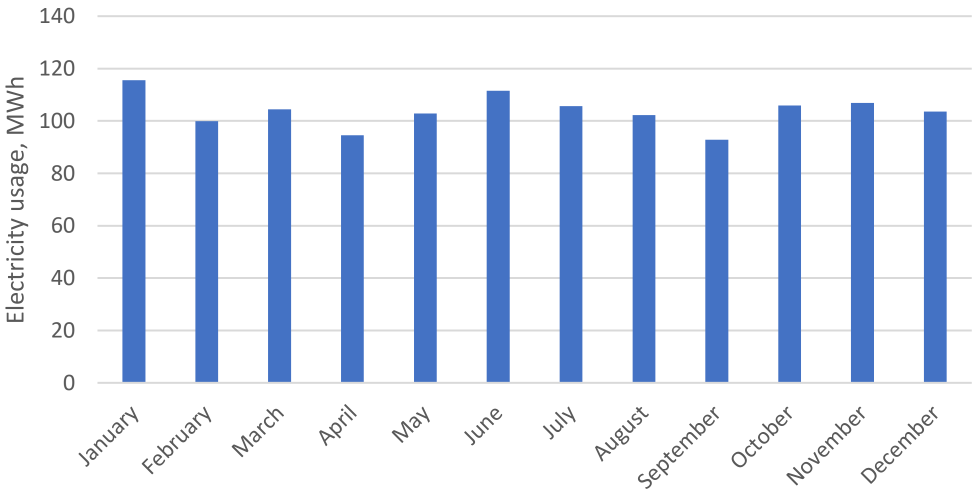

Figure 5. Monthly electricity consumption 2018

As it can be seen in the Fig. 5., the electricity consumption is actually constant throughout the year. Total annual electricity demand is 1 246 043 kWh. The cost of this kind of energy for the end user from the power grid was

770 000 PLN. The total cost, i.e. the cost of sale and distribution of electricity, was assumed at the level of 620 PLN/MWh gross.

Fig. 6. shows the exact daily electricity consumption profiles. Blue indicates the maximum intake for each fifteen-minute period, orange indicates the minimum, and gray represents the annual average for each fifteen-minute period.

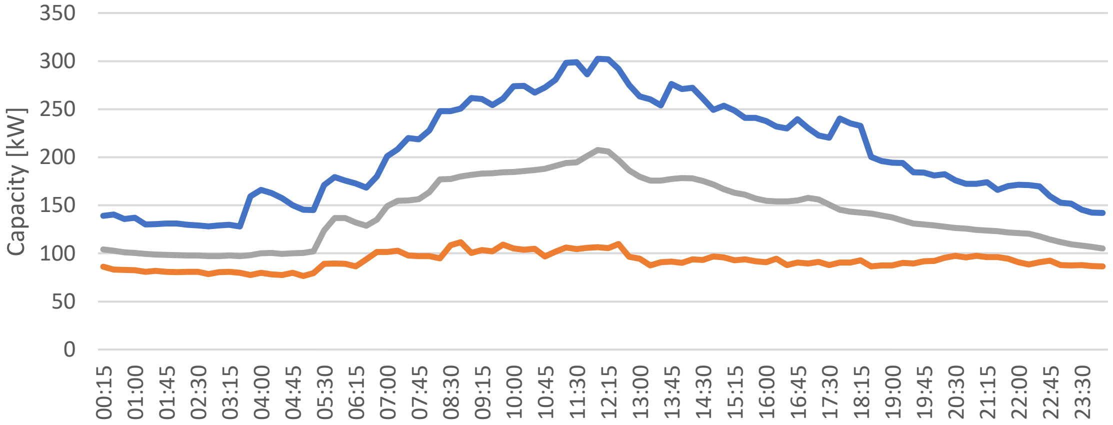

Figure 6. Daily average electricity demand profiles

Fig. 6. proves to be helpful in determining the nature of electricity consumption from the grid. As it can be seen, the maximum consumption during the year never exceeds the level of 302 kW, and this level is achieved only in the summer peak. The average annual daily electricity demand does not exceed 205 kW, and apart from breaks independent of the consumer, it never falls below 80 kW. This is mainly due to the occurrence of lighting installations with an installed capacity of 85 kW.

3.2. Heat and cold

Heat demand was made using a simple hourly method. According to the result of this method the annual useful energy demand is of the same order of magnitude as the expected value determined by means of the indicator and amounted to 1 263.88 GJ. The monthly distribution of heat demand is shown in Fig. 7.

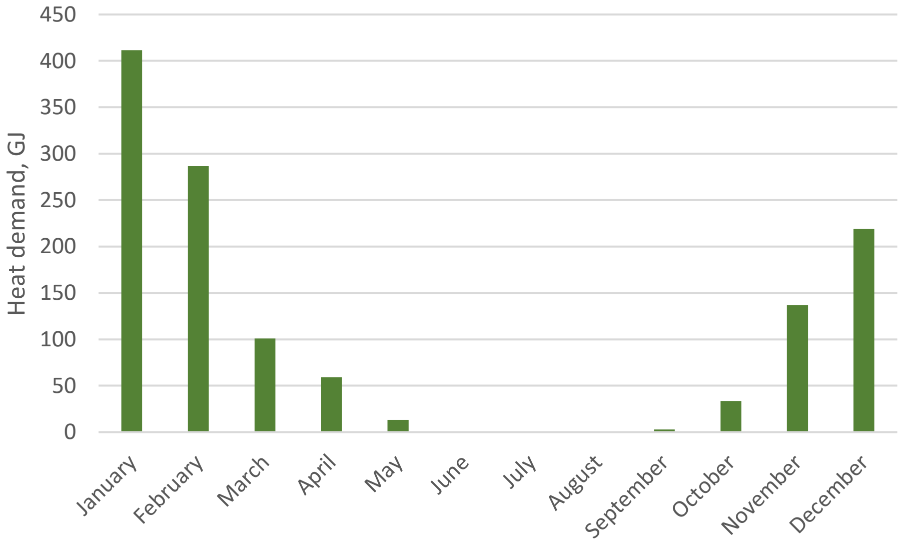

Figure 7. Monthly distribution of heat demand for space heating

As it was expected, the greatest demand occurs in the winter months. It was noticed quite a significant difference in demand between December and January. This is due to the outside temperatures occurring during these months. The average monthly temperature in January was -3.63 °C, while in December it was 2.53°C. Calculation was made on measured data.

Similar, hourly calculation was made for cold demand. Results are shown in Fig. 8.

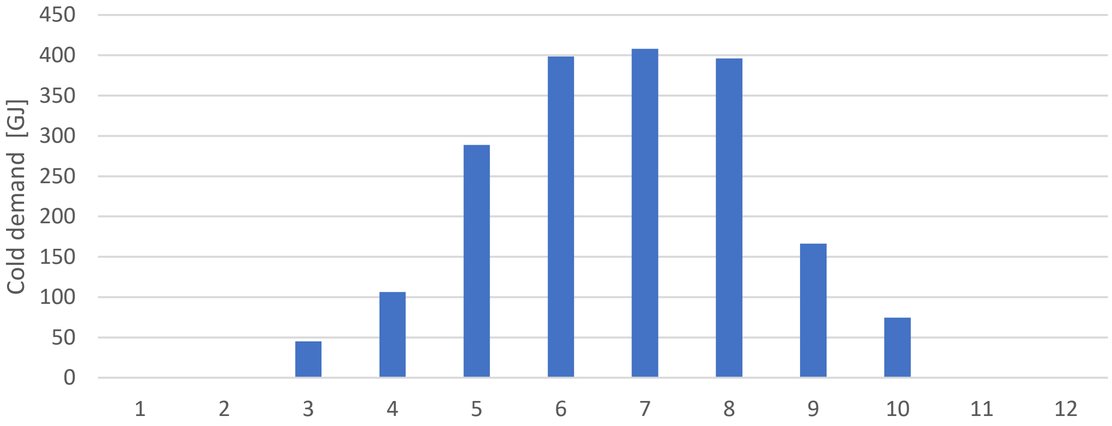

Figure 8. Monthly distribution of cold demand

As expected, the highest demand occurs in the summer months, i.e. June, July and August and remains around 400 GJ / month. This is due to the high outside air temperatures during these months. The highest cooling capacity is 483.1 kW. In summer, there are days when the demand for cooling capacity does not fall to zero. For example, Figure 9 shows three days from the first week of August.

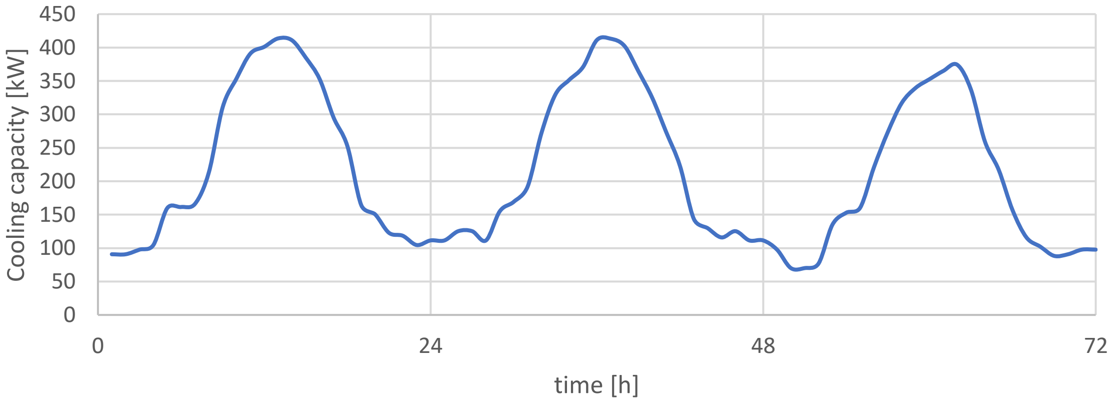

Figure 9. Example of cooling capacity requirement for three days in August

As it can be seen in the figure 9, during the indicated days the demand for cooling capacity reaches a maximum of 413 kW and a minimum of 70 kW. Only during 15% of the June-August period, the demand for cooling capacity falls below 30 kW.

As can be seen from the above analysis, it is possible to use a trigeneration installation. In periods of the year when there is no demand for heat for heating purposes, it can be seen a high demand for cooling. In addition, the nature of the operation of the analyzed facility means that continuous collection of domestic hot water at a constant level should be expected. Thanks to the stable minimum demand for heat for most of the year by combining the satisfaction of SH, DHW and cold demand, it will be possible to increase the annual heat production by the considered cogeneration (trigeneration) unit, thanks to which it will be profitable to select a device with a larger installed electrical capacity. In the further part of the work, an analysis of graphs of ordered cooling capacity will be performed in order to select a refrigeration unit and heat output with the added demand for an absorption unit in order to select a cogeneration unit.

4. Selection of trigeneration system devices

This chapter uses the data from the previous chapter to select the appropriate devices that make up the trigeneration system. At the beginning, the required operating parameters of the absorption unit were determined on the basis of cooling power consumption waveforms. On the basis of the refrigeration unit selected in this way, the total heat output intake routes were determined, i.e. taking into account the demand of the refrigerator in question. Finally, two variants of the selection of cogeneration units were determined and the functioning of the system was described.

4.1. Absorption unit

4.1.1 Base cooling capacity requirement

The most important parameter of the analyzed chiller is the cooling capacity to be provided. In order to select the cooling capacity at the appropriate level, an order graph of the cooling capacity over time was made, which is presented in Figure 10.

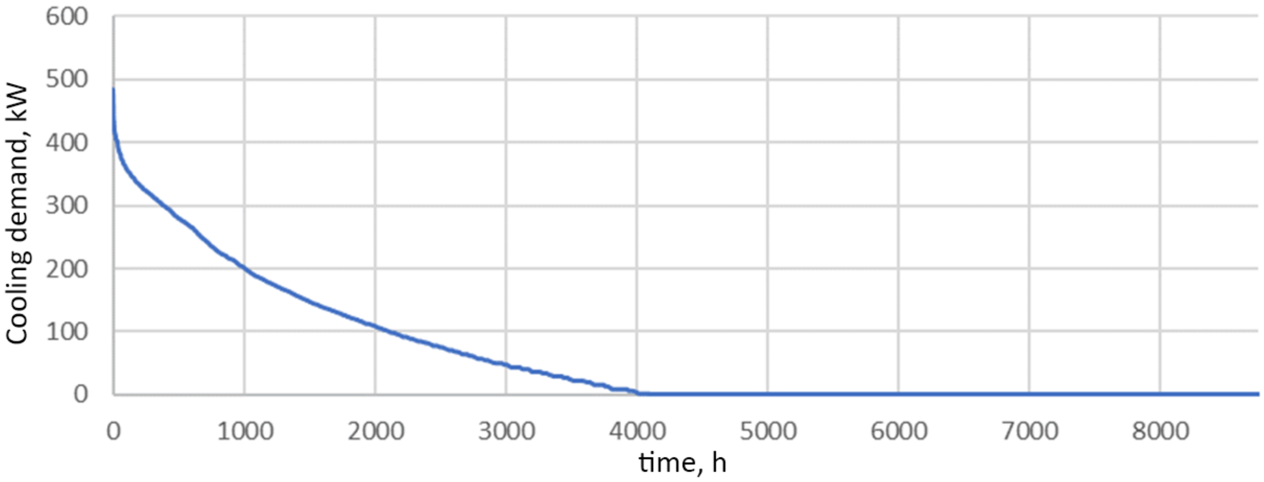

Figure 10. Ordered diagram of cooling demand in whole year

As it can be seen in the Fig. 10, the maximum demand for cooling capacity is as much as 483 kW. The average seasonal value of the demand for cooling capacity is about 130 kW. Taking into account the typical percentages of the minimum load of absorption units at the level of 25% to 30%, the average demand value is additionally considered, excluding hours when the demand was less than 50 kW. In this case, the average value is already close to 173 kW. The cooling demand is less than 200 kW for nearly 3,000 hours of the 4,101 hours of operation of the chiller. Therefore, it was decided that the best solution would be to use a system of two refrigerators with lower power working in parallel. With these assumptions and comments, two absorption units Shinsung Engineering Zephyrus SAB- HW 005G1 with a cooling capacity of 176 kW each were selected.

4.1.2 Absorption unit parameters

Table 1 presents the technical parameters of selected absorption unit.

Table 1. Basic parameters of selected absorption unit [8]

No	Parameter	Value	Unit
1.	Cooling capacity	176	kW
2.	Minimum cooling capacity	44	kW
3.	Hot water temperature	95/80	°C
4.	Cooling water temperature	31/36	°C
5.	Chilled water temperature	13/8	°C
6.	Hot water flow	14,4	m^3/h

No	Parameter	Value	Unit
7.	Cooling water flow	65	m^3/h
8.	Electrical power consumption	3,1	kWw
9.	Seasonal cooling efficiency coefficient	0,72	-

The unit meets the required parameters. The minimum cooling capacity that can be achieved without a significant decrease in efficiency is 44 kW, which is 25% of the nominal load. In the case of a system of two such chillers, the minimum power is still 44 kW, which means that one of the coolers is operating, while the maximum cooling capacity is 352 kW in parallel operation. In addition, it should be noted that for the operation of refrigerators it is required to dissipate the heat stream of cooling water and dissipate it in cooling towers. This flux is about 370 kW for each unit.

Assuming nominal operation, the system will consume a maximum of 25,426.2 kWh of electricity during one year of operation, which will not significantly affect the current electricity consumption, as this amount is just over 2% of the current electricity demand. For the calculation of the system's operation, a linear dependence of electricity consumption for own needs on the demand for heat was assumed.

Taking into account that chillers cannot operate with a load in the range of 0-100%, but only 25 - 100%, peak compressor coolers should be taken into account in the calculation of heat demand for refrigeration units. It is assumed that compressor coolers will cover the demand for cooling below 44 kW and above 352 kW.

4.2. CHP unit

4.2.1. Total heat power demand

To determine the required power of the cogeneration system, an ordered diagram of thermal power has been prepared, which is shown in Figure 11.

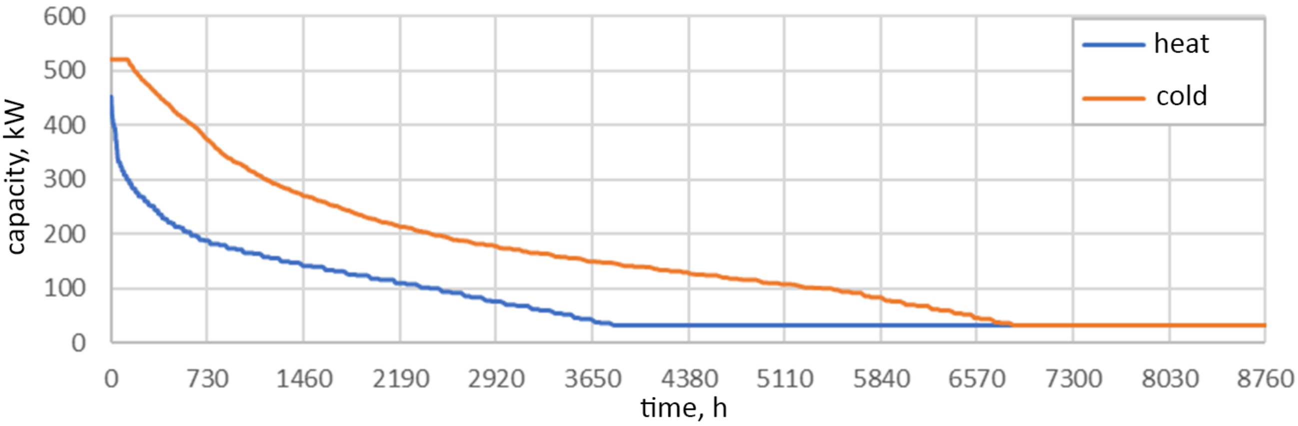

Figure 11. Ordered diagram of heat power demand

The blue color indicates a graph ordered by heat power for domestic hot water and central heating. Orange is marked with a graph ordered for thermal outputs also taking into account the required heat output to supply air conditioning units. The maximum capacity determined in this solution is 521.5 kW. As it can be ssen in the figure, the maximum power of the refrigeration units is taken into account, which manifests itself as a plateau. The average annual power is nearly 157.5 kW.

4.2.2. Selected CHP aggregate parameters

Several cases of configuration of CHP units are being considered. Taking into account such a large discrepancy between the maximum and minimum value, it was decided to select aggregates with thermal outputs of 142 kW, 260kW and 491 kW. It should be taken into account that the demand for energy lower than 400 kW occurs for 8139 hours a year, which is nearly 93% of the year or over 11 months. Therefore, larger aggregates would operate with less efficiency than efficiency at nominal power. Below are the parameters of the aggregates selected for analysis.

Table 2. Selected parameters of the analyzed CHP units

No	Parameter	Cogenerator			Unit
		A	B	C	
1.	Electric power	104	201	357	kW
2.	Heat output	142	260	491	kW
3.	Gas demand	282	560	952	kWh/h
4.	Nominal efficiency	0,874	0,846	0,891	-
5.	Minimum electric power	52	101	179	kW
6.	Minimum heat output	95	158	309	kW

A – TEDOM Cento 100, B – MTU Onsite Energy GC201N5, C – MTU Onsite Energy MTU 12V400 GS

It is assumed that the above devices are selected in such a way as to meet the heat demand for the largest possible part of the year. In this case, the production of electricity is of secondary importance, as it is not assumed that heat can be sold to the district heating network.

4.2.3. Proposed options

Five main options have been selected, which are presented in detail in Table 3. Variants A, B and C are called 104, 201 and 357 respectively from their nominal electrical power for simplicity of reading. In addition, simplified combination schemes of variants are shown in Figure 12.

Table 3. Comparison of cogeneration options

Variant	Option 1	Option 2	Option 3	Option 4	Option 5
	3 x 104	104 + 201	2 x 104 + 201	104 + 357	2 x 104 + 357
Total electrical power [kW]	312	305	409	461	565
Total heat output [kW]	423	402	544	633	775
Minimum heat output [kW]	95	95	95	95	95
Heat production [MWh]	1 097	1 155	1 149	1 069	1 145
Electricity production [MWh]	782,97	839,73	803,51	765,64	820,47
Gas consumption [MWh]	2 154	2 369	2 296	2 084	2 227
Total efficiency	0,8730	0,8419	0,8507	0,8800	0,8827

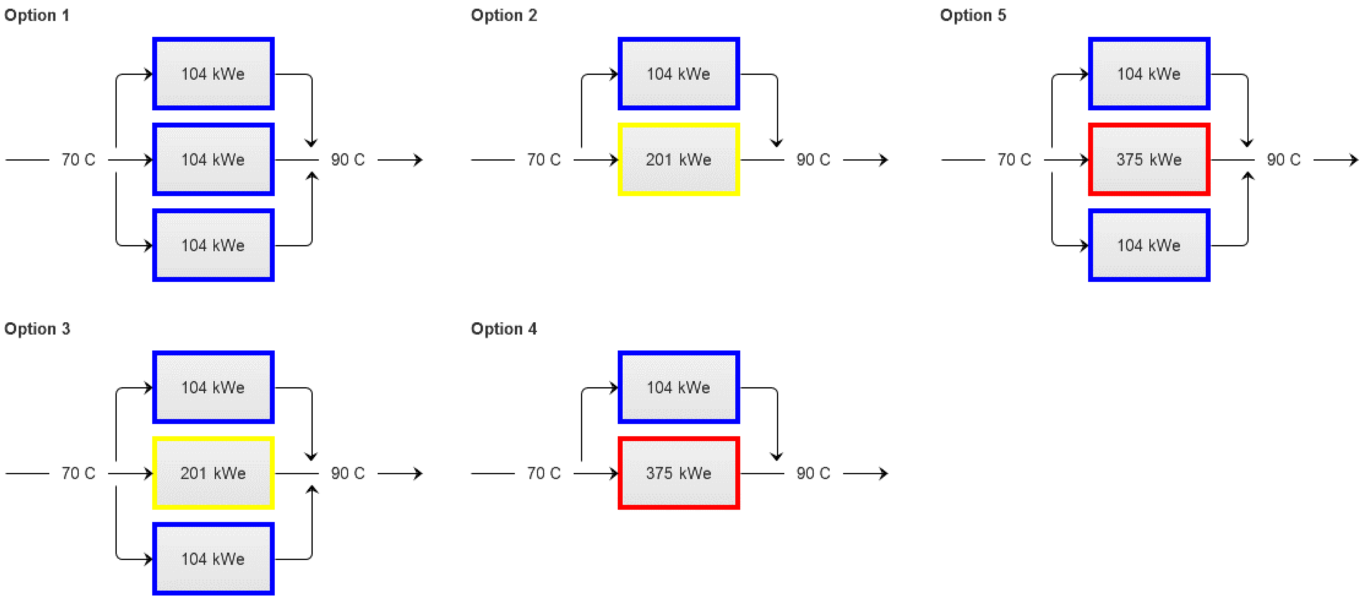

Figure 12. Basic parameters of proposed cogeneration options

As it can be see, the variants were selected to cover the largest possible area of demand during the year. Units with higher capacity are to serve as a basic source, while smaller 104 kW aggregates are to complement them. In the case of option 1, the aggregates are equivalent.

Electricity, heat and gas consumption have been calculated for each hour based on heat and cold demand, taking into account transmission, regulation and utilization efficiency and seasonal cooling efficiency coefficient.

4.3. System operation

It is assumed that the system will supply the internal heating network and the internal electric grid. The operation of the engines is subordinated to the current heat demand. The minimum operating capacity of each engine separately is taken into account. That is, the case with the highest efficiency is always considered. The work of a large engine that has reached the minimum operating point is taken over by a smaller engine. During the analysis, cases were encountered in which the large engine did not run for several hours, while the smaller engine worked at full load. This meant that the demand was less than the minimum operating point of the large engine and more than the maximum point of the small engine. In such cases, variants 1, 3 and 5 worked, because the second smaller engine took over. However, it is worth noting the differences in the total heat production in these cases. Despite the two smaller engines, the total heat production is lower than in variant 2. The same is true for the 4, where the 357 kW engine did not work optimally due to the high minimum operating point. In terms of heat production, the most optimal variant is variant 2. The operating time of the aggregates in the analyzed variants is presented in Fig. 13.

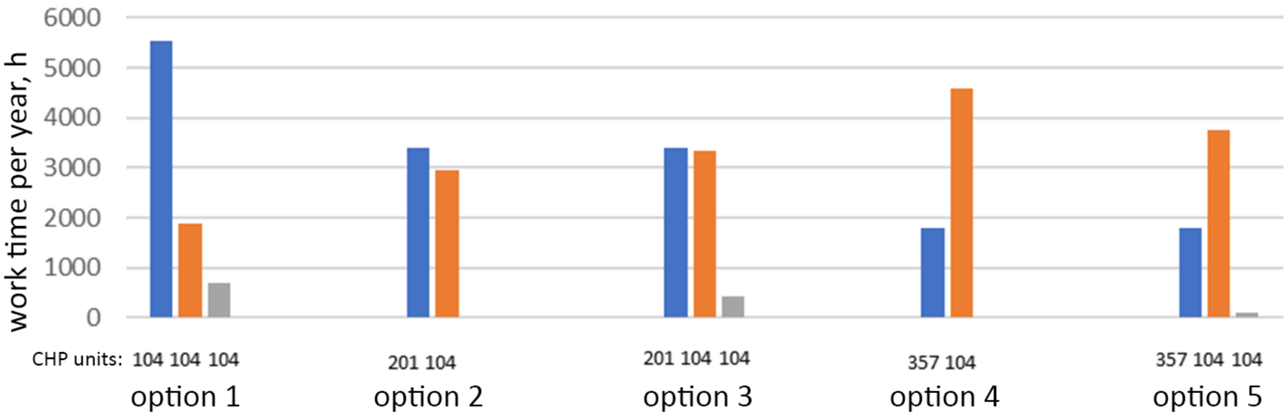

Figure 13. Comparison of the operating time of individual CHP units in all options

As it can be seen in the Fig. 13., the most balanced running time is in variant 2, where both units run about 3,000 hours per year. Variants 3 and 5 are the worst. In these cases, the No. 3 units run for 441 and 89 hours respectively. In terms of operation, the best is the No. 1 unit in variant 1, which works over 5,500 hours a year.

In cases where the heat demand was not covered by the installed cogeneration units, it was assumed that they would be covered by heat from the district heating network from the existing connection. A similar assumption was made in the case of electricity. In addition, it is assumed that the electricity generated, which will not be subject to self-consumption , will be sold to the distribution network. Table 4 compares cogeneration systems in terms of their installed capacity utilization.

Table 4. Comparison of installed capacity utilization rates

unit	Option 1	Option 2	Option 3	Option 4	Option 5
1	0.66	0.37	0.32	0.12	0.16
2	0.22	0.33	0.38	0.53	0.44
3	0.08	-	0.05	-	0.01

Installed capacity utilization rates were calculated as the product of the installed thermal capacity and operating time, which was assumed to be 8,000 h, as 760 h per year needed for inspections and oil changes (about a month) was assumed. Again, option 2 is considered to be the most balanced and therefore optimal.

The last important indicator is the coverage of demand by each variant and by external sources. Covering the demand for heat and electricity was taken into account. The above analysis is presented in Figure 14, where the shares of local and external sources in the total demand for heat and electricity are compared.

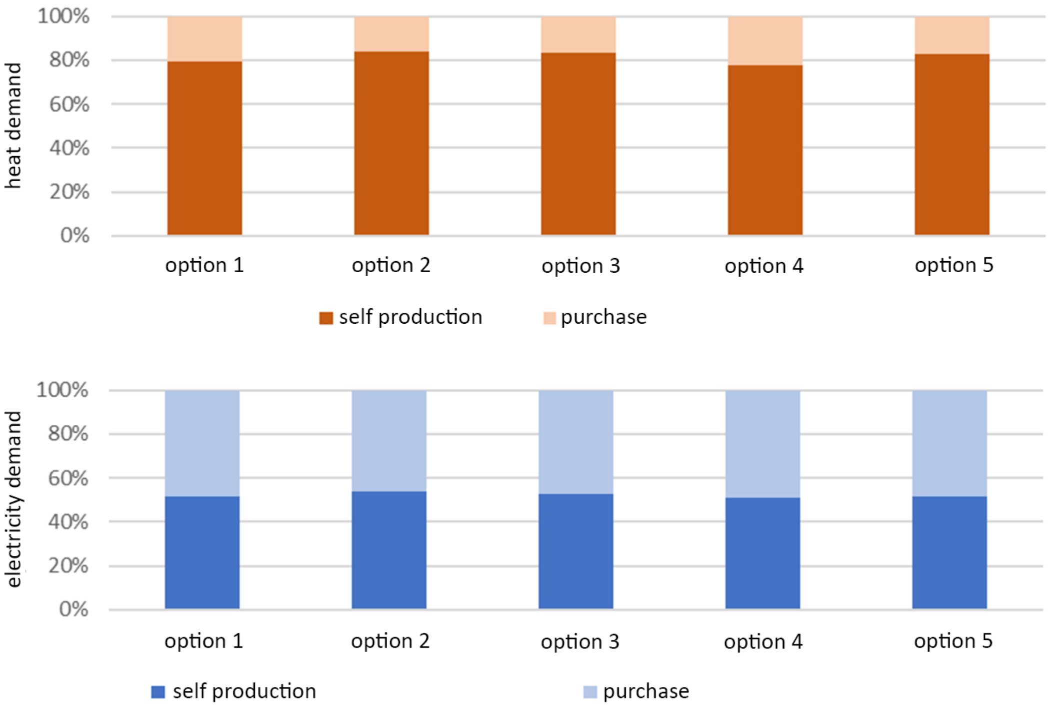

Figure 14. Comparison of the contribution of options to energy demand

According to the analysis, option 2 guarantees the largest share of local sources in the total demand for both analyzed energy media. In the case of heat demand it is 83.71%, in the case of electricity demand it is 53.87% of the total demand. For technical analysis, the optimal variant is variant 2, i.e. a 201 kW engine in combination with a 104 kW motor. The economic analysis presented in the next chapter will ultimately determine the choice of the best option, but at this stage it is concluded that options 3 and 5 should be rejected for technical reasons in the rest part of the analyze.

5. Economic analysis

In order to obtain a clear verdict on which option is the most cost-effective, an economic analysis should be carried out for each variant from the previous chapter.

5.1. Basic assumptions

For the economic analysis, basic assumptions were made to perform calculations of operating costs. The assumptions are as follows:

Table 5. Assumptions for the economic analysis

Ingredient name	Net cost	Unit
Gas variable fee	160.00	PLN/MWh
Variable fee en. El.	620.00	PLN/MWh
Heat variable fee	190.00	PLN/MWh

Ingredient name	Net cost	Unit
The selling price en. El.	204.15	PLN/MWh
Cogeneration support	141.19	PLN/MWh

The costs in the table above are based on the market review and invoices for 2019. The electricity sales price was assumed on the basis of volume-weighted average prices on the Day-Ahead Market of the Polish Power Exchange for the period 2018-2019. This value amounted to PLN 226.83 / MWh, however, a margin of 10% is assumed for the trading company servicing the source (or entering the source into a virtual power plant). Support for cogeneration was adopted on the basis of the regulation on the parameters of the new support mechanism for high-efficiency cogeneration [9], which sets the amounts of guaranteed premiums for 2019 and 2020. The support scheme was not taken into account for the most cost-effective option, due to the lack of certainty of receiving a bonus. After selecting the best option, the calculations were performed again assuming a cogeneration premium.

The reference for the calculations was the basic option, i.e. the installation of compressor chilleres and the purchase of electricity and heat from external networks. It should be noted that the capacity of compressor chillers is assumed to be the same as that of absorption chillers, therefore the investment costs associated with peak demand compressor coolers are not taken into account, as they would occur in all cases and do not count towards the savings analysis. Options 1, 2 and 4 from the previous chapter have been compared to the basic option.

5.2. Cost comparison

5.2.1. Capital costs

Market offers of CHP units as well as unit prices (PLN/MW) of compressor and absorption chillers were used to determine the investment costs. A comparison of the three options in previous chapter with the basic option is shown in Table 6. The prices shown are net prices.

Table 6. Comparison of investment costs

Device	Investment cost [PLN]			
	Basic variant	Option 1	Option 2	Option 4
Compressor chiller	300 000.00	-	-	-
Absorption chiller	-	550 000.00	550 000.00	550 000.00
CHP unit	-	1 500 000.00	1 189 935.00	1 534 902.00
Amount	**300 000,00**	**2 050 000.00**	**1 739 935,.00**	**2,084,902.00**
Difference	**-**	**1 750 000.00**	**1 439 935.00**	**1 784 902.00**

The prices shown in Tab. 6. include the costs of all components, assembly and connection and commissioning of devices. As you can see, the basic option is characterized by almost six times lower investment cost than the other options. Option 2 is characterized by the lowest investment cost of the other two options considered and is PLN 1,439,935 more expensive than the basic option. For further calculations, the differences between the actual costs of the analysed options and the cost of the baseline option will be treated as investment costs. This is because it is the value that the investor must add to the underlying investment.

5.2.2. Operating costs

To determine the profitability of the investments presented in the previous section, all the most important operating costs should be presented. First, an analysis of variable costs of purchasing electricity, heat and gas was carried out. The balance sheet also includes profit on resale of generated excess electricity. The results are shown in Table 7.

Table 7. Comparison of energy costs

Cost	Annual utility costs [PLN]			
	Basic variant	Option 1	Option 2	Option 4
Electricity purchase costs	924 666.19	379 542.81	359 423.94	381 725.29
Heat purchase costs	128 350.82	53 680.69	42 695.22	59 119.44
Gas purchase costs	-	344 598.54	379 105.41	333 490.94
Sale of electricity	-	28 268.99	33 232.34	25 450.07
Balance sheet	1 053 017,01	749 553.06	747 992.23	748 885.59
Difference	**-**	**303 463.95**	**305 024.78**	**304 131.42**

The difference from the balance of profits and costs compared to the basic option is treated as savings. The investor must create a refrigeration system in the facility. It should be recalled that the savings thus obtained do not take into account the cogeneration premium that can be obtained. As you can see, option 2 generates the highest savings of the three options considered.

Other operating costs that must be taken into account are the costs incurred in connection with ensuring the continuity of the system's operation, i.e. inspections and ongoing repairs, as well as maintenance. The calculation shall be made on a fifteen-year basis, in connection with subsequent calculations taking into account the cogeneration premium valid until year 2034. Two-year warranties on all devices are also included. The costs, which are determined according to the item as a percentage of the investment value, are shown in Table 8. Operating costs for the entire service life are shown in Table 8.

Table 8. Determination of operating costs over the total life of installation

Device	Year of operation	Operating cost in relation to the cost of the device
Compressor chiller	1 - 2	0%
	3 - 5	3%
	6 - 10	5%
	11 - 15	10%
Absorption chiller	1 - 2	0%
	3 - 10	1,5%
	11 - 15	2%
CHP unit	1 - 2	0%
	3 - 7	2%
	8 - 12	3,5%
	13 - 15	5%

These costs do not yet constitute a sufficient comparison. In order to summarize the expenses related to the operation of the analyzed systems, an analogous table is presented below, which includes the previously reported costs of energy utilities and profit from their sale. It should be noted that changes in energy prices are not yet taken into account. The results are presented in Tab. 9.

Table 9. Total operating costs

Year of operation	Total cost of ownership [PLN]			
	Basic variant	Option 1	Option 2	Option 4
1	1 053 017	749 553	747 992	748 885
2	1 053 017	749 553	747 992	748 885
3	1 062 017	787 803	780 040	787 833
4	1 062 017	787 803	780 040	787 833
5	1 062 017	787 803	780 040	787 833
6	1 068 017	787 803	780 040	787 833
7	1 068 017	787 803	780 040	787 833
8	1 068 017	810 303	797 889	810 857
9	1 068 017	810 303	797 889	810 857
10	1 068 017	810 303	797 889	810 857
11	1 083 017	813 053	800 639	813 607
12	1 083 017	813 053	800 639	813 607
13	1 083 017	835 553	818 488	836 630
14	1 083 017	835 553	818 488	836 630
15	1 083 017	835 553	818 488	836 630
Amount	**16 047 255**	**12 001 796**	**11 846 606**	**12 006 617**
Difference	-	4 045 459.29	4 200 649.31	4 040 637.95

As it can be seen from the above calculations, in a fifteen-year perspective, all variants are more profitable to maintain than the basic option. Despite higher maintenance costs, i.e. inspections and repairs, cogeneration units with absorption refrigerators guarantee lower costs of energy media, which in total gives lower total costs. The economy compared to the basic variant is similar in each case, but variant 2 again guarantees the best result. The calculated savings for options 1, 2 and 4 are after fifteen years higher than investment costs by PLN 2,295,459.29, PLN 2,760,714.31 and PLN 2,255,735.95, respectively. For option 1 and 4, these values are very similar, while option 2 generates a profit higher by about 21% than the average of the other two variants. Nevertheless, the next step is to perform a detailed indicator economic assessment.

5.3. Economic assessment

First, the NPV indicator was calculated, i.e. Net Present Value, calculated according to the formula:

$$NPV = \sum_{t=0}^{n} \frac{CF_t}{(1+r)^t} - I_0 \tag{1}$$

where:

CF_t - Cash Flow,
r - discount rate,
I_0 - initial expenditure,
T - subsequent years.

The discount rate was adopted on the basis of the reading of the reference value of the discount rate announced by the Office of Competition and Consumer Protection for the period from 01.01.2020 [10]. This value is r = 2.84%. Cash flow here means the savings of the options under consideration explained earlier in relation to the basic option, i.e. the difference between the columns in Table 13. Year 0 is considered to be the moment of investment. The calculated cumulative cash flow values are shown in the graph in Figure 20.

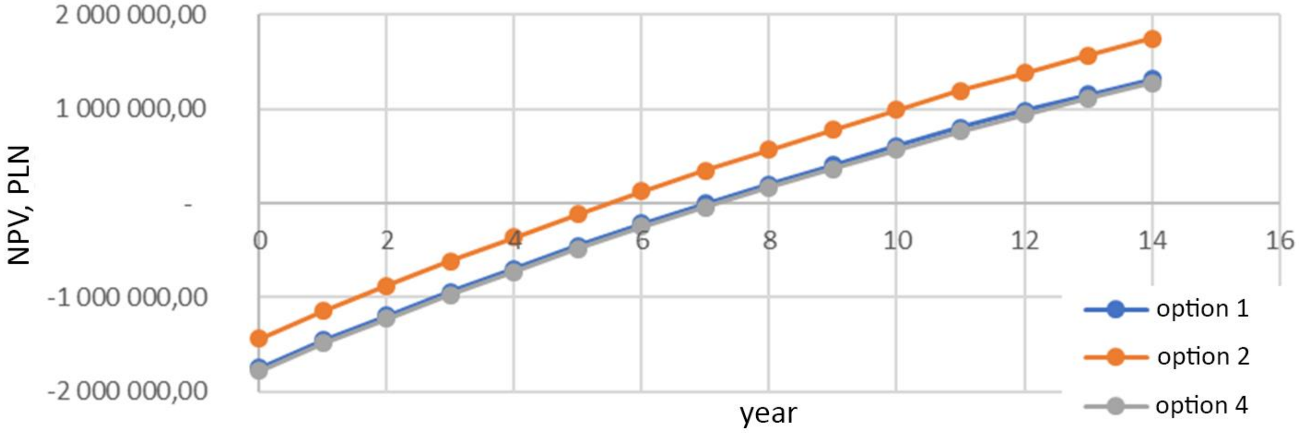

Figure 15. Cumulative cash flows for the analyzed options

The present value after fifteen years of investment for option 1 is PLN 1,328,661.70, for option 2 PLN 1,734,295.86, for option 4 PLN 1,292,365.29. The change to a positive value is called the discounted DP (Discounted Payback) period and amounts to 7.03 years, 5.47 years and 7.19 years respectively for the analyzed cases. Option 2 guarantees the shortest payback period, with very similar payback periods for variants 1 and 4.

Another important indicator of investment assessment is the Internal Rate of Return (IRR). It is calculated by transforming the following formula:

$$\sum_{t=0}^{n} \frac{CF_t}{(1+r)^t} - I_0 = 0 \tag{2}$$

The above formula should be transformed to determine the value of r. IRR determines whether the investment provides a rate of return higher than the cost of capital, and therefore speaks about the profitability of the investment. IRR ratios after fifteen years are 13.04%, 18.01% and 12.63%, respectively. Option 2 again guarantees the best indicator.

The last considered indicator used to evaluate investments and the final choice of the option is the so-called profitability ratio, or PI (Profitability Index), calculated from the formula:

$$PI = \frac{\sum_{t=0}^{n} \frac{CIF_t}{(1+r)^t}}{\sum_{t=0}^{n} \frac{COF_t}{(1+r)^t}} \tag{3}$$

where:

CIF (Cash Inflow) – positive cash flows in year t,
COF (Cash Outflow) – negative cash flows in year t,
r - discount rate,
n - number of years.

All variants have obtained a positive NPV, so we can calculate PI. In the case of the analyzed investment, savings were considered positive flows, while investment and operating costs above the basic option were considered negative. It is clear from the calculations that option 2 is the most cost-effective at PI = 2.07. Investments in option 1 or 4 provide a return ratio of 1.66 and 1.63 respectively. This means that all three options are cost-effective because their PI values are positive, but the higher the value, the more profitable the project. Therefore, it is concluded that option 2 is the best in economic terms. For this case, an analysis of the sensitivity of the investment to fluctuations in the electricity and gas markets is then carried out.

6. Conclusions

The above work was created in connection with the noticeable development of local sources of electricity and heat. Due to the trend of increasing the thermal comfort of patients and hospital employees, large healthcare facilities decide to install air conditioning systems. These systems consume a lot of electricity. For this reason, it was decided to analyze the possibility of implementing a trigeneration system. The analyzed facility underwent thermal modernization consisting in adapting external partitions to the technical conditions in force in 2017. Current electricity consumption was analyzed on the basis of power consumption waveforms obtained from the distribution network operator as hourly data for 2018. In addition, heat demand was calculated using a simple hourly method in accordance with PN-EN ISO 13790:2009. In this way, the processes of demand for heat and cooling power were determined. These data were used in the next step to select absorption chillers with a total cooling capacity of 352 kW together with cooling towers with a total capacity of 740 kW. An alternative is compressor systems, which were later analyzed as a basic variant. It was assumed that the investor's assumption is the need to make an air conditioning system in the building. The next stage was the selection of cogeneration units that would be able to supply the building with heat for the longest possible period of the year. As a result of the analysis of heat demand, taking into account the heat needed to power the absorption units, three basic CHP units with a capacity of 104 kW, 201 kW and 357 kW of electrical power were selected. On the basis of graphs of ordered demand for thermal power, five systems were selected, which are variants marked with numbers from 1 to 5. The next stage consisted in determining the operating conditions and results of the work of five systems. The most energy during the year was provided by the system from variant No. 2, i.e. the 201 kW and 104 kW engine system. Parallel operation of these engines allowed to generate 676.95 MWh of electricity for self-consumption and sell 162.78 MWh to the power grid. The operation of the system provides 1,155.02 MWh of heat per year, which is almost 84% of the total demand. This production saves over PLN 320.50 thousand per year compared to the basic variant, and including the cogeneration bonus, i.e. the new subsidy system for the next 15 years, this saving amounts to almost PLN 439,200.00 per year. Using the tools of the indicator economic analysis, the most cost-effective option was selected. The investment cost, variable costs and operating costs were determined. This allowed for an analysis of discounted cash flows, on the basis of which the net present value (NPV) and internal rate of return (IRR) after fifteen years of operation were calculated. Their values are PLN 1,926,992.82 and 19.31%, respectively, and including the cogeneration bonus PLN 3,224,176.85 and 28.63%. Discounted payback periods are respectively without co-financing and with it 5.17 years and 3.42 years. The investment was also subject to a sensitivity analysis, which showed that the worst possible cases do not mean that the project will cease to be profitable. Current trends in the electricity market indicate that the situation will be favorable in the coming years, as electricity prices are expected to increase.

References

1. Rozporządzenie Ministra Zdrowia z dnia 26 marca 2019 r. w sprawie szczegółowych wymagań, jakim powinny odpowiadać pomieszczenia i urządzenia podmiotu wykonującego działalność leczniczą.
2. Ciepiela, D., CO2 coraz mocniej wpływa na ceny energii, https://www.wnp.pl/energetyka/co2-coraz-mocniej-wplywa-na-ceny-energii,349650.html [access: December 15th 2019]
3. Rozporządzenie Ministra Infrastruktury i Rozwoju z dnia 27 lutego 2015 r. w sprawie metodologii wyznaczania charakterystyki energetycznej budynku lub części budynku oraz świadectw charakterystyki energetycznej
4. Łuba, P., Wardak-Bielenis, J., Van den Bossche, I. „Rynek ciepła w Polsce", pwc 2012
5. Urząd Regulacji Energetyki, „Średnie ceny sprzedaży ciepła wytworzonego w należących do przedsiębiorstw posiadających koncesje jednostkach wytwórczych niebędących jednostkami kogeneracji" https://www.ure.gov.pl/pl/cieplo/ceny-wskazniki/7904,Srednie-ceny-sprzedazy-ciepla-wytworzonego-w-nalezacych-do-przedsiebiorstw-posia.html [access: December 15th 2019]
6. Grzebielec A., Rusowicz A.: Analysis of the use of adsorption processes in trigeneration systems. *Archives of Thermodynamics* 34 (2013) 35-49.
7. Jarosiński M., Grzebielec A.: Analiza opłacalności systemu trójgeneracji w budynku sanatoryjnym. *Rynek Instalacyjny* 10 (2018) 20-26
8. Termster absorpcja, *Agregaty absorpcyjne zasilane gorącą wodą AB-HW G1/SAB-MW G0/SAB-LW G0.*

9. Rozporządzenie Ministra Energii z dnia 21 sierpnia 2019 r. w sprawie maksymalnej ilości i wartości energii elektrycznej z wysokosprawnej kogeneracji objętej wsparciem oraz jednostkowych wysokości premii gwarantowanej w roku 2019 oraz 2020
10. Urząd Ochrony Konkurencji i Konsumentów, „Stopa referencyjna i archiwum” https://www.uokik.gov.pl/stopa_referencyjna_i_archiwum.php [access: Jamuary, 11th 2020]
11. Eurostat, *Combined Heat and Power (CHP) data*, 2015.
12. Feidt, M., Dupont, J.L., Oger, A., *33rd Informatory Note on Refrigeration Technologies*, International Institute of Refrigeration, styczeń 2017.
13. Hendriger, J., Ziętek, P., Chludzińska, M., *Wentylacja i klimatyzacja materiały pomocnicze do projektowania*, Venture Industries Sp. z. o.o., Warszawa 2013.
14. Krajowy Ośrodek Bilansowania i Zarządzania Emisjami Zespół Zarządzania Krajową Bazą, *Wartości opałowe (WO) i wskaźniki emisji CO2 (WE) w roku 2016 do raportowania w ramach Systemu Handlu Uprawnieniami do Emisji za rok 201*, Warszawa 2018.
15. Krajowy Ośrodek Bilansowania i Zarządzania Emisjami Zespół Zarządzania Krajową Bazą, *Wskaźniki emisyjności CO2, SO2, NOX, CO i pyłu całkowitego dla energii elektrycznej na podstawie informacji zawartych w Krajowej bazie o emisjach gazów cieplarnianych i innych substancji za 2018 rok*, Warszawa 2018.
16. Lipiński, P., *Synteza i pomiary właściwości fizykochemicznych i termodynamicznych układów dwuskładnikowych cieczy jonowych do zastosowań w chłodnictwie absorpcyjnym*, Warszawa 2015.
17. Mihaela, C., Liceul Tehnologic Turburea, Gorj, *Methods Of Increasing The Efficiency Of Gas Turbines*, Annals of the „Constantin Brancusi” University of Targu Jiu, Engineering Series , No. 1/2018.
18. National Oceanic and Atmospheric Administration, *NNCD Climate Data Online*, [w:] ncdc.noaa.gov, [online:]https://www7.ncdc.noaa.gov/CDO/cdopoemain.cmd?datasetabbv=DS3505 [dostęp 15 grudnia 2019].
19. The European Association for the Promotion of Cogeneration, *COGEN Europe Response Inception Roadmap on Strategy for long-term EU greenhouse gas emissions reductions*, Bruksela 2018.