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Innovative Modernization of Building Heating Systems: The Economy and Ecology of a Hybrid District-Heating Substation

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Abstract: Hybrid installations with respect to renewable energy sources are becoming more popular due to the stringent requirements for the energy efficiency of buildings. Therefore, the thermomodernization of a district-heating substation was proposed. Several scenarios, including different renewable energies (an air–water heat pump versus a heat pump with photovoltaics), different investment financing (equity or bank credit), and different purposes for heating demand (central heating or central heating with ventilation and domestic hot water), were analyzed. The economic aspects involved the calculations of the payback time and net present value, while the ecological and environmental characteristics were weighed using emission reduction. Each of the analyses resulted in different proposed modernization methods. However, taking both factors together, the computations proved that the most profitable was the scenario with energy demand for heating, domestic hot water, and ventilation purposes financed by means of bank credit with a thermomodernization bonus.

Keywords: hybrid installations; thermomodernization; renewable energy sources; economy; ecology

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1. Introduction

The word 'hybrid' is known in the English language since 1601 but was rarely used before c. 1850. It comes from the Latin language 'hybrida' and means offspring of a tame sow and wild boar, or a child of a freeman and slave. A hybrid vehicle is one that runs on two different fuels, gasoline or diesel, and electricity batteries or energy from the Sun. Nowadays, the word hybrid has exploded and is widely used, and generally, it means mixed, i.e., of two origins.

Hybrid installations are those that use at least two different forms of energy to produce heat for central heating, hot water, ventilation demand, or any other technological heat required by the process. It can be a combination of a variety of systems. When composed of one source, they are called monovalent, with two being bivalent and three being trivalent. The more complex the system, the higher the investment costs, but, on the other hand, the higher the efficiency of the system that is expected to be the outcome of the investment. Hybrid installations with district heating as an initial main heat source can be accompanied by large-scale renewable systems before it comes to the end user. There are many studies that describe the progress, perspective, transition, or evaluation of DH (district heating) from the first to fourth, and fifth generation, as in [1–3], or their benefits such as a decrease in the primary energy consumption of the entire energy system by 4.5% and a reduction in the costs of the system by 2.7%, as shown by Sorknaes et al. [4]. In their research, Ostergaard et al. [5] showed that the existing single-family houses located in Denmark could be supplied by ultra-low-temperature district-heating-serving radiators. Their research was carried out as part of strategic research for fourth-generation district heating.

EU (European Union) countries use different technologies for district-heating systems. Sayegh et al. [6] showed in their work that, despite these diverse solutions, in order to achieve the net-zero target by 2050, all EU countries are obliged to increase prosumers' participation and apply more flexible energy systems by integrating automation and renewable energy sources. However, district heating can also be supplemented by renewable energy (RE) as a deliberate decision by the investor when choosing a heating system.

Hybrid installations are gaining popularity and will expand in the coming years due to the increasingly stringent requirements for energy efficiency. The primary energy index for new buildings reduced from 12% to 34%, depending on the purpose of the building, from 2014 to 2021, respectively, according to Polish standards [7]. By 2050, district heating is expected to represent only 5% of the overall final energy use; additionally, 77% of that number will be renewable energy sources [8]. According to the Global Energy Review 2021 [9], the COVID-19 pandemic had a huge impact on global energy demand, and it was expected to increase by 4.6% in that year. Furthermore, coal demand was projected to increase by 60% more than all renewables and caused an increase in CO_2 emissions by 5% (1500 MT) [9]. To meet the net-zero policy by 2050, the integration of renewable energy sources is obviously necessary, but this objective is and will be encountered with many discussions along the way. An interesting overview was given by Jodeiri et al. [8]. The authors evaluated the research, achievements, technical aspects, and challenges in the integration of renewable energy sources into district-heating systems. Additionally, Sayegh et al. [10] showed several scenarios regarding the placement of a heat pump that could be implemented into district-heating networks. The authors took into account three locations, namely a central heat pump, a local heat pump, and an individual heat pump, but they also considered connection and operational modes as well as emissions. As stated in their work, 'the technical triangle', which consists of a heat source, the heat-pump technology, and heat requirements, allows one to design a high-efficiency and sustainable system with the heat-pump technology. Lygnerud et al. [11] established a business model for the combination of heat pumps and district heating for multi-family buildings in Sweden based on which various DH/HP combinations have already been installed. The optimization of HP and DH even reduces the annual heating costs by 33%. Their analysis also showed a reduction in CO_2 emissions of up to 75% when shifting to the proposed business model (the HP prio. mode to HP shift. mode). The integration of RES with the district-heating network also requires the introduction of energy storage systems into the distribution system. One of the options, among others, is to incorporate a latent heat storage system such as, for example, a cylindrical tank containing spherical phase-change material (PCM), as evaluated by Hlimi et al. [12]. The presented numerical tool can be used by designers of heating networks to size and also optimize storage systems under real exploitation conditions.

An important date for the Polish fuel and energy sector was February 2021, when the Polish energy policy until 2040 was established [13]. The main goals of the Polish energy policy are, among others, the development of renewable energy sources with the implementation of offshore wind energy, the development of heating and cogeneration, and also improvement in energy efficiency, including the promotion of strategies leading to improvements in energy efficiency. The most important element of Poland's energy policy until 2040 is the reduction in greenhouse gas (GHG) emissions by approximately 30%, compared with 1990. Another factor is that, by 2040, the heating demand of all households must be covered by individual heating systems using zero- or low-emission sources. At the same time, and as a consequence of this energy policy, the National Research Institute in Poland published a road map in July 2021 to achieve the conditions of the community policy objectives for Poland until 2050 [14]. The authors stated in the report that it will not be enough to reduce fossil fuel consumption and develop renewable energy sources to achieve climate neutrality in the EU and Poland by 2050. In addition, in the entire economy, there will be a need to implement, among others, industry electrification, hydrogen use, expansion of electromobility, reduction in livestock production in the agricultural sector, and additional implementation of large-scale BECSS (bioenergy with carbon capture and storage), CCS (carbon capture and storage), and CCU (carbon capture) technologies.

In addition to the fact that each EU country has to meet the requirements of 2050, smaller-scale investors are also seeking not only the most energy-efficient approach but also systems with the longest life cycle and the solution that gives the best thermal comfort in the building. These solutions would be beneficial to them in terms of cost and payback time for their investments.

In their article, Famiglietti et al. [15] performed the life-cycle analysis of a district-heating system that serves the northern city of Milan and compared it with groundwater and vapor compression heat pumps as an alternative. The systems were to serve new constructions. The results showed that regardless of the current higher CO_2 emission of district heating, with the integration of heat recovery and the increased efficiency of existing appliances, it may have the potential to reduce CO_2 emissions at the time of implementation and in the future. An interesting approach was featured by Garcia et al. [16]. The authors showed tree-model configurations using, among others, a district-heating configuration together with a photovoltaic hybrid solar collector in a multi-family house located in central Europe. The research highlighted many benefits, including energy security, costs, and carbon dioxide emission, but the most important benefit is that exporting heat to a district-heating network and power to the electricity grid results in a profitable and energy-efficient option.

The use of more complex hybrid systems also has an impact on the choice of system control and forces one to seek alternative approaches and numerical solutions. Zanetti et al. [17] presented the cost and optimal control of a photovoltaic-assisted hybrid heat pump and a gas-fired boiler heating system, including a water tank used as thermal storage. Their results showed that this type of system, together with examined controls, can potentially save up to 20% of the energy consumption cost. Furthermore, the proposed control system increased photovoltaic self-consumption by more than 40%. Furthermore, Gustafsson et al. described a new alternative control approach for indirectly connected district-heating substations [18]. When the proposed optimized control-system-based heat meter was installed in every home in the city of Lunea, it gave a possible flow reduction of 7.4%. The impact on energy savings could also be achieved by using different structures for heat exchangers, as investigated by Chatys et al. [19], or by applying microstructures with the use of sintering technology to enhance the heat flux, as experimented by Dąbek et al. [20]. Not only heat losses [21] but also passive cooling systems have been investigated, including studies evaluating the improvement in cooling power [22].

However, the changeover to hybrid systems that are dedicated to residential heating systems and their application, in many cases, depends on the decision made by its users. A previous study [23] based on the heating alternative available in Finland included several heating options, which showed, among others, that changes in operating costs can have a greater impact on the decision made by households than changes in investment costs. Ruokamo suggested in the study's conclusion that the government shall introduce subsidies and taxes to support an already favorable assessment by households. Sajegh et al. [6] drew several conclusions in their article that can be implemented in all EU countries, even though existing DH systems have different schemes, technologies, or strategies for the implementation of renewable energy resources. The leaders in the market in central, northern, and eastern Europe are Germany, Scandinavian countries, and Poland, respectively. The degree of the implementation of renewable technologies differs in each county, but it is agreed that without this implementation, they will not meet the 2050 goal. DH can lower the cost of operation by up to 15%, comparable to any other technology, by improving heat generation, transmission, and percentages of RE usage and, consequently, having an impact on human comfort, health, and the environment.

There are many resources available on how to incorporate renewables into the DH network. As noted by Sayegh et al. [10], the possibilities of HP location are numerous. However, there are no papers analyzing the possibilities to retrofit district-heating substations including renewable energy sources. Therefore, the purpose of this paper is to estimate the environmental and economic parameters of the modernization of district-heating substations into hybrid ones with the application of renewable energy resources.

Evaluation methods are proposed in terms of costs, efficiency, and emission reduction for the analysis of several possible modernization techniques. The analysis also takes into account the consideration of different renewable energy sources, investment financing sources, or heating demands to be covered.

2. Materials and Methods

Thermomodernization involves processes that aim to reduce the heating demand in the building. The changes consist of modifications in heating and ventilation systems, as well as building structures or systems that supply hot water to the recipient. According to the legal act [24], the retrofit may include several operations, which result in the following features:

- Lowering the energy required to heat water for central heating and domestic hot water (10–25%);
- Reduction in heat loss (25%);
- Alteration or modernization of energy sources using renewable or cogeneration energy sources.

2.1. Economical Aspects

In order to properly assess the efficiency of an investment project, it is necessary to perform economic calculations leading to the evaluation of the cost-effectiveness of the analyzed project. The accounts are based on a comparison of the outlays on the investment, on the one hand, with the financial benefits of the project, on the other.

There are many instruments that allow the assessment of investment projects in terms of their profitability as well as economics. Interpreting the results of these assessments is essential to properly verify the financial features of the project and, moreover, to arrive at a decision on whether to engage in the project or abandon its realization.

Efficiency evaluation methods involve two groups: simple and complex. The first group does not include the money–time–value adjustment, while the other presents the discounting processes.

Initial assessments are related to simple methods. They are found to feature a wide range of disadvantages, such as fixed values in each period of time. The most commonly used rate is simple payback time (SPBT), which is expressed in years or months and determines the amount of time necessary to repay the investment outlay from monetary income that results from the project. Generally speaking, the shorter the SPBT value is, the more profitable the investment is.

In complex efficiency evaluation methods, a discounting process is used, which is a computational procedure for the calculation of the present value of the amount of money based on its value at a specified moment in the future. The methodology considers the discount rate, where the percentage includes the bank rate, as well as the inflation processes in the analyzed period of time.

The most popular complex method is the net present value (*NPV*) calculation rate. It is the difference between the financial outlay and the current values of the monetary income.

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

I_0—the investment costs, PLN;
CF_t—cash flow in the t-period, PLN;
r—return rate, %;
n—number of time periods *NPV* can be easily interpreted as follows:

- If $NPV < 0$—the investment is not cost-ineffective (the project should be rejected);
- If $NPV = 0$—the investment is indifferent (the financial outlays and the current values of the monetary incomes are equal);
- If $NPV > 0$—the investment is economic (the project can be realized).

A novel approach to economic analyses is life-cycle cost (LCC) analysis [25]. In order to calculate the LCC rate, it is required to consider all the costs that will be incurred during the lifetime of a product, work, or service, which consist of three types related to the stage of their life cycle. Initial costs include the purchase price and all the associated costs such as delivery, installation, or insurance. The operating costs comprise the costs of energy, fuel, water use, spares, and maintenance. The costs associated with the last phase of the life cycle, such as end-of-life costs (decommissioning or disposal) or residual values (revenue from the sale of products), are also calculated.

2.2. Ecological Aspects

A measurable effect of each thermal upgrade is the reduction in the emission of harmful substances into the Earth's atmosphere. Table 1 shows the unit emission factors for various pollutants related to selected types of fuel [26].

Table 1. Specific emission factors (*EF*) for different pollutants.

Fuel Type	Unit	SO_2	NO_X	CO	CO_2	Particulates	Soot	Benzo(a)Pyrene (BaP)
Coal heating plant	kg/Mg	0	0	0	93.49	0	0	0
Electric energy	kg/kWh	0.0091	0.0023	0.00069	1	0.0015	27×10^{-7}	54×10^{-9}
Electric energy—PV System	kg/kWh	0	0	0	0	0	0	0

The total emission of a specific pollutant for central heating or ventilation systems and domestic hot water was calculated separately on the basis of Equation (2), where n is the total number of the systems.

During the heating season, the emission of pollutants by a boiler room is as follows:

$$E_E = \sum_{1}^{n=3} (B_x \cdot EF_x)_{H,V,DHW}, \ \frac{kg}{annum} \tag{2}$$

n—total number of parts of the system;
B_x—the amount of fuel used to cover the demand for central heating (H), ventilation (V); and the preparation of domestic hot water (DHW), respectively;
EF_x—unit emission factor for a specific fuel type and a pollutant.

As an example, the total annual emission of CO_2 from the boiler room is given by the following equation:

$$E_{E_{tot}}^{CO_2} = (B_H \cdot EF_{CO2}) + (B_V \cdot EF_{CO2}) + (B_{DHV} \cdot EF_{CO2}) \tag{3}$$

The fuel consumed by the system, B_x, is derived from the usable energy ($Q_{H+V,nd}$ or $Q_{W,nd}$, kWh/annum), the total efficiency of the system n_{tot}, and the calorific value H_u.

In the next step, it is necessary to calculate the equivalent emissions for individual substances (apart from CO and CO_2) before and after thermal upgrading, E_r, which is the ratio of the so-called toxicity index K and the previously computed emissivity. The environmental effect for equivalent emissions was determined from Equations (4) and (5).

$$E_{red} = E_{r0} - E_{r1}, \ \frac{kg}{annum} \tag{4}$$

$$E_{red} = \left(1 - \frac{E_{r0}}{E_{r1}}\right) \cdot 100\% \tag{5}$$

E_{r0}, E_{r1}—the equivalent emissions for individual substances before and after thermal upgrading, respectively.

2.3. Analyses

The structure analyzed in this article is a service building with an area of 1300 m^2, where the heat demands for three purposes are equal: 39 kW (central heating), 31.5 kW (domestic hot water), and 24.5 kW (supply of a water heater in the ventilation unit). To date, all the heat demand has been supplied via district heating from a coal boiler at a local heating plant and transferred to the building system by means of a plate heat exchanger.

Thermomodernization involves the adaptation of district-heating substations to hybrid district-heating substations. Such systems include renewable energy sources. Since the air–water heat pump is considered the least expensive heat pump due to the lack of excavations or drills necessary, it was selected as a solution in this analysis. It can be employed alone, as the only renewable energy source in the building, or incorporated with a photovoltaic system that transfers the energy for the compressor power demand, both constituting the hybrid system. However, in each case, it is necessary to provide the peak heat source, which will be district heating. All the suggested modernization strategies are presented in Figure 1.

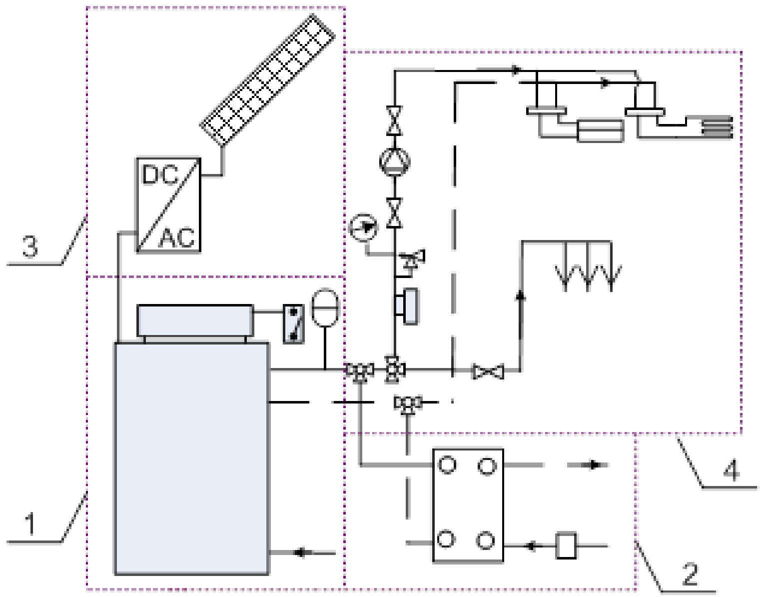

Figure 1. Schematic diagram of the system: 1—heat pump; 2—district heating; 3—photovoltaics; 4—building technology.

In this study, several possible processes were proposed. Four of them involved the analysis of only the central heating system, while the other four also included domestic hot water and ventilation heating demand. The modifications, depending on the presumed problem, used different renewable resources: an air–water heat pump or the combination of a heat pump and a photovoltaic system. The assumptions were related to covering the investment costs from various sources, either with equity or with bank credit. Although incurred bank loans involve the loan rates to be paid, it may be a beneficial solution since it allowed us to apply for a thermomodernization bonus.

In this research, several possible instruments were analyzed, which are listed in Table 2. An air–water heat pump was chosen that has 20 kW of heating power and a coefficient of performance of 3.4. The data for the heat pump were selected on the basis of the producer's specification sheet, based on which the performance characteristics included in this analysis were identified for an external air temperature of 2 °C.

Table 2. Researched solutions for a hybrid district-heating substation.

Options	Modernization
I heating	Air–water heat pumps (two units) cover the heat demand for central heating during the heating season.
II heating + bank credit + bonus	Air–water heat pumps (two units) cover the heat demand for central heating during the heating season. Costs are covered with bank credit. Part of the costs is covered with a thermomodernization bonus.
III heating + photovoltaics	Air–water heat pumps (two units) cover the heat demand for central heating during the heating season. The photovoltaic system powers the heat-pump compressors.
IV heating + photovoltaics + bank credit + bonus	Air–water heat pumps (two units) cover the heat demand for central heating during the heating season. Photovoltaic system powers the heat-pump compressors. Costs are covered with bank credit. Part of the costs is covered with a thermomodernization bonus.
V heating + domestic hot water + ventilation	Air–water heat pumps (five units) cover the heat demand for central heating during the heating season as well as the heat demand for domestic hot water and ventilation during the whole year.
VI heating + domestic hot water + ventilation + bank credit + bonus	Air–water heat pumps (five units) cover the heat demand for central heating during the heating season as well as the heat demand for domestic hot water and ventilation throughout the year. Costs are covered with bank credit. Part of the costs is covered with a thermomodernization bonus.
VII heating + domestic hot water + ventilation + photovoltaics	Air–water heat pumps (five units) cover the heat demand for central heating during the heating season as well as the heat demand for domestic hot water and ventilation throughout the year. The photovoltaic system powers the heat-pump compressors.
VIII heating + domestic hot water + ventilation + photovoltaics + bank credit + bonus	Air–water heat pumps (five units) cover the heat demand for central heating during the heating season as well as the heat demand for domestic hot water and ventilation throughout the year. The photovoltaic system powers the heat-pump compressors. Costs are covered with bank credit. Part of the costs is covered with a thermomodernization bonus.

The annual heat demand in the building for central heating and ventilation is 503,115 kWh and for hot domestic water is 11,498 kWh.

When analyzing the building heating system, only two heat pumps were required, whereas, when including domestic hot water and supplying the energy to the ventilation heater, five heat-pump units were calculated. Heat pumps worked as the only heat source in the building until the external temperature reached 2 °C. Then, an additional energy source was required, and therefore, a heat exchanger was used to transform the heat from the district-heating system as well.

The temperatures in the region were analyzed using the data collected throughout the year available on internet websites [27] for several years. The data revealed that, during the heating season, temperatures below 2 °C accounted for 50% of the time, which is shown in Figure 2.

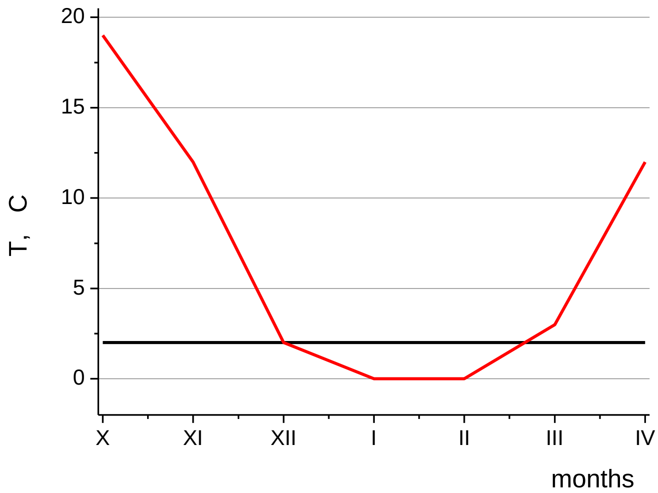

Figure 2. A sample external temperature distribution in Kielce, Poland, during the heating season.

In several investigated options, a photovoltaic system was also included as another additional renewable energy source. Photovoltaic cells supplied the heat-pump compressor with electrical energy. The electricity required to power one compressor was 5.9 kW. The cells were selected with a power of 510 W each. Furthermore, as an electricity accumulator, valve-regulated lead-acid batteries were chosen with a capacity of 120 Ah each. It was also necessary to equip the system with an inverter to transform the direct current into an alternating current.

The selected system was analyzed on the basis of characteristic meteorological years and statistical climate data for buildings' energy calculations in Poland [28]. The data were collected from the Institute of Meteorology and Water Management in Poland database and present, amongst others, the total radiation values for 30 years.

3. Results and Discussion

3.1. Economy

The results in terms of economic aspects involve the calculation of the investment costs as well as the financial savings resulting from thermomodernization. The calculated values allowed economic analyses on the basis of economic rates. The investment costs were considered using the analysis of the data available from the producers' websites and are summarized in Table 3.

Table 3. Thermomodernization costs.

Device	Characteristics	Cost	
Air–water heat pump	20 kW power output	62,500.00 PLN	13,324EUR
Photovoltaic panel	510 W power output	1500.00 PLN	320 EUR
Photovoltaic battery	120 Ah capacity	980.00 PLN	209 EUR
Photovoltaic inverter	10 kW power output	3800.00 PLN	810 EUR

The costs of district heating, including fixed and variable fees, were 3400.00 PLN/MW (725 EUR/MW) monthly and 16 PLN/GJ (3.40 EUR/GJ), respectively.

Preferential credit was taken for a 10-year (methods II and IV) or 20-year (methods VI and VIII) return payment period, with an 8.2% lending rate yearly in a bank that specializes in environmental protection. The thermomodernization bonus was 21% of the loan value. In the case of thermomodernization using only a central heating system, the credit amounted to 100,000.00 PLN (21,329 EUR) with a 10-year return payment period of time, but when analyzing domestic hot water and ventilation as well, it amounted to 200,000.00 PLN (42,637 EUR) for 20-year return payment.

The simple payback time (SPBT) was calculated according to the assumptions given for each problem (methods I to VIII; see Table 1) and is presented in years in Figure 3. The analyzed costs were only investment costs.

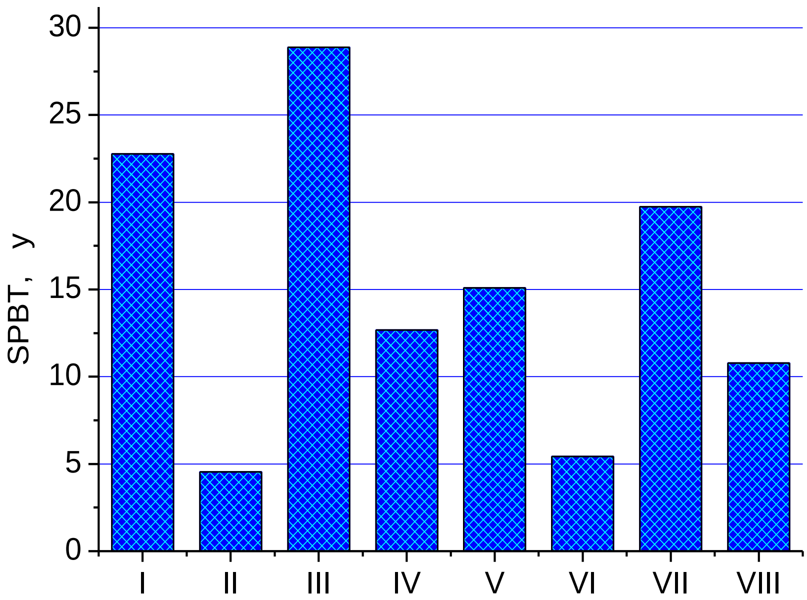

Figure 3. Simple repayment time (SPBT) in years for each option analyzed (methods I to VIII according to Table 1).

The most economically viable were the options with bank credit and a thermomodernization bonus, both for only heating purposes (method II) and for the method with all systems included, i.e., heating, domestic hot water, and ventilation demand (method VI). The trend resulted from the lowest investment costs due to the staggering bank credit costs over time.

The longest simple payback period was found only in the heating system with renewable energy sources, regardless of whether it involved only the heat pump (method I) or the combination of the heat pump and photovoltaic system (method III).

This was not the case when all the costs required to incur to complete the investment were taken into account. The results of the return time, which include not only the investment costs (incurred before the project launch) but also the costs necessary throughout the life cycle of the project, are presented in Figure 4.

The calculations are summarized and shown in years. The only economically viable option was found to be the energy supply to meet the heating demand, hot water demand, and ventilation demand, with all the costs covered by the investor's own assets.

In each case (Figures 3 and 4), the analysis excluded the options with a payback time greater than 20 years due to the lifetime of the devices.

Another commonly used economic rate is the net present value (NPV), which takes into account the change in monetary value over time. Calculations were carried out for the discount factor that included the current inflation rate and the interest rate on bank credit in Poland. The results presented in Figure 5 were calculated for 25 years as the life-cycle time of the investments.

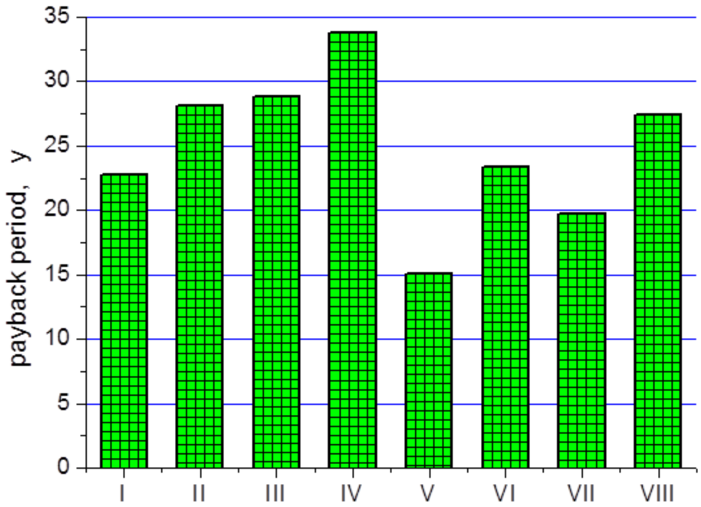

Figure 4. Payback time for each option analyzed (methods I to VIII according to Table 1).

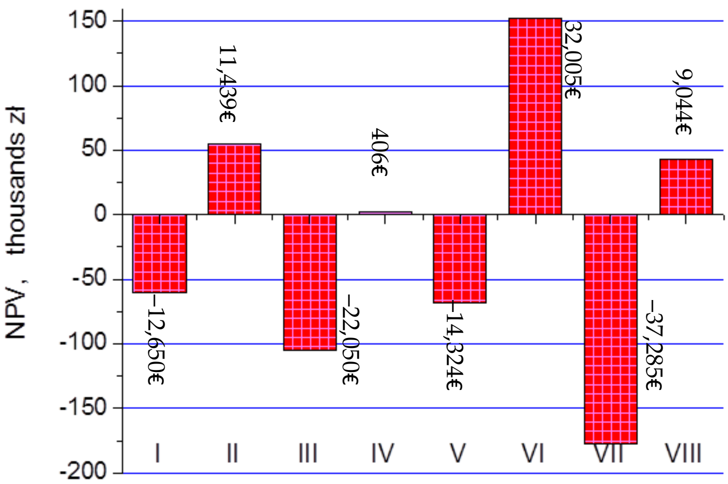

Figure 5. Net present value in thousands PLN (and in thousands EUR) for each option analyzed (methods I to VIII according to Table 1).

The investment is unprofitable if NPV amounts to negative values. The results showed that the discounted costs exceeded the discounted financial benefits. On that basis, all the options in which the costs were covered with the investor's own funds were uneconomical. The highest profits were observed in method VI: supplying heating + domestic hot water + ventilation by means of bank credit. The credit would be reduced with the thermomodernization bonus.

Last but not least, the economical indexes of life-cycle costs were calculated. The incurred costs were analyzed for the whole lifetime of the system, which was assumed to be 25 years. The investment costs were calculated according to Table 3. The operating costs included annual inspections and maintenance expenses. For the scenarios with only the heat pump as the thermomodernization method (methods I, II, V, and VI; see Table 2), the costs of electricity used for the compressors' drive were also calculated. Furthermore, the costs of the incurred bank credit were provided for the LCC study (methods II, IV, VI, and VIII; see Table 2). The reprocessing cost, that is, the end-of-life cost, provided the last component of the conducted calculations. In the case of the thermomodernization bonus, financial asset values caused a decline in the LCC level (methods II, IV, VI, and VIII; see Table 2). The results of the conducted calculations are presented in Figure 6.

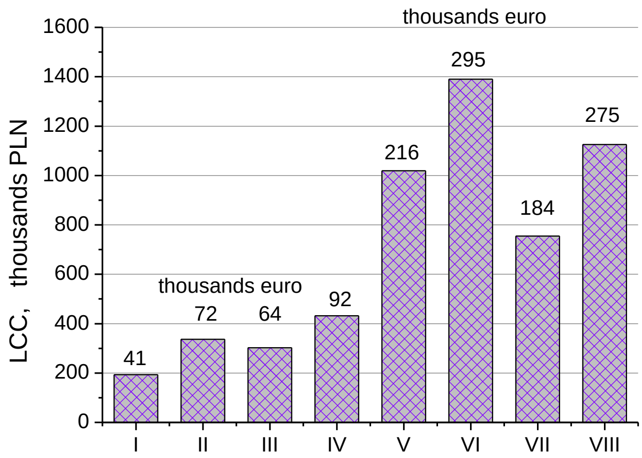

Figure 6. Life-cycle costing in thousands PLN (and in thousands EUR) for each option analyzed (methods I to VIII according to Table 1).

The first and foremost logical conclusion that emerged from these LCC calculations led us to the deduction that investments in the thermomodernization of only central heating (methods I–IV) were less expensive. On the other hand, when comparing the thermomodernization of all the systems in the building (central heating + domestic hot water + ventilation), method VII required the least expenses during the lifetime of the installations. Method VII concerns central heating + domestic hot water + ventilation + photovoltaics with no bank credit.

3.2. Ecology

The computations of the annual amounts of harmful substances emitted into the atmosphere, including the most important ones, i.e., carbon emissions, together with the environmental effect for all the scenarios listed in Table 2 are shown in Figures 7 and 8.

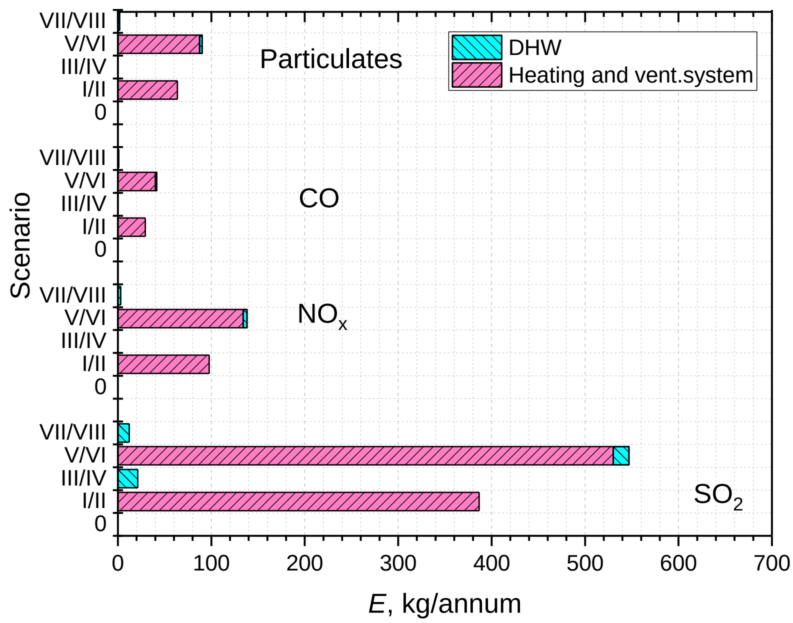

Figure 7. Environmental effect of thermal upgrading for the building and the scenarios: '0'—before; 'I–VIII'—after thermomodernization (four pollutants).

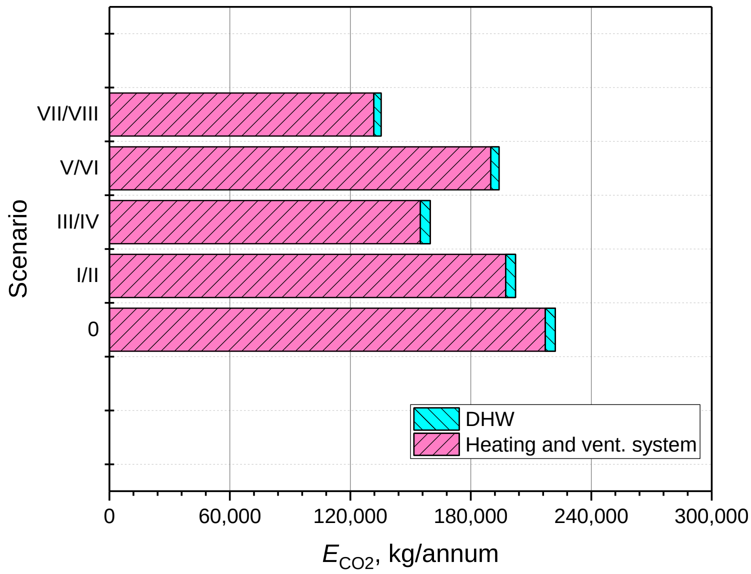

Figure 8. Environmental effect of thermal upgrading for the building and the scenarios: '0'—before; 'I–VIII'—after thermomodernization (carbon dioxide).

The results of the environmental effect for the equivalent emissions are presented in Table 4.

Table 4. Equivalent emissions for the optimal thermal-upgrading option in the building.

Pollutants Emitted	Toxicity Index K	0	I/II	III/IV	V/VI	VII/VIII
		Emissions for Options, E_E Upgrading, kg/year				
SO_2	1.00	0.00	386.56	0.00	546.90	12.06
NO_X	0.75	0.00	97.70	0.00	138.23	3.05
Particulates	0.75	0.00	63.72	0.00	90.15	1.99
Soot	3.75	0.00	0.11	0.00	0.16	0.004
BaP	30,000.0	0.00	0.002	0.00	0.003	0.000072
Pollutants emitted	**Toxicity index K**	**0**	**I/II**	**III/IV**	**V/VI**	**VII/VIII**
		Equivalent emissions for options, Er upgrading, kg/year				
SO_2	1.00	0.00	386.56	0.00	546.90	12.06
NO_X	0.75	0.00	48.85	0.00	69.11	1.52
Particulates	0.75	0.00	31.86	0.00	45.07	0.99
Soot	3.75	0.00	0.29	0.00	0.41	0.009
BaP	30,000.0	0.00	45.88	0.00	64.91	1.43
Total equivalent emissions		0.00	513.44	0.00	726.41	16.01
Environmental effect for equivalent emissions, E_{red}, kg/year			−513.44	0.00	−726.41	−16.01
Environmental effect for equivalent emissions, E_{red}, %			-	-	-	-

4. Conclusions

The thermomodernization of a district-heating system was proposed to be a hybrid system with the application of a heat pump and photovoltaics. Analyses included efficiency assessment and emission reduction calculations. The modernization scenarios are presented in Table 2.

It can be stated that both the options with bank credit and the absence of a photovoltaic system (methods II and VI) were the most economically viable solutions. This was proved by means of the lowest SPBT values (less than 5 years) as well as the highest NPV values (more than 50 thousand PLN, which equals 106,593 EUR) at the same time. The thermomodernization bonus decreased the cost values, even with the bank interest rates. However, photovoltaic systems increased expenses regardless of the growth in savings.

In terms of protecting the natural environment against the emission of harmful substances, the most reasonable option to modernize a building was method VII/VIII, for which the ecological effect for the equivalent emission was the highest. The reduction in carbon dioxide emissions was also the most significant here and amounted to approximately 40%, compared with the state before the thermal modernization. It should be also highlighted that the heat from coal heating plants is environmentally friendly, and due to highly effective installations for flue-gas desulfurization and denitrification, nearly all of the most significant pollutants (apart from CO_2 emissions) are negligibly small.

The analysis of two factors, namely the economic and ecological aspects of the proposed solutions, proved that method VI was the most profitable, which involved the financing of the energy demand for heating, hot water usage, and ventilation purposes with bank credit along with a thermomodernization bonus. Although the analysis of its environmental aspects revealed a lower reduction in pollutant emissions than in the case of method VII/VIII, the financial characteristic of this modernization method is not to be overestimated.

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