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Section: Energy for Buildings

Modernisation of the Existing Energy Supply System to CO_2 Neutral System: Lithuanian Town Case Study

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Abstract

The main principle of the sustainable planning is to achieve the maximum effect with the lowest cost. Generally, district heating is the main heat supply system in the countries of northern climate. In some cases, it is an old and worn out system, which should be modernized. Currently, this system has a great potential for energy savings. It is clear that in order to achieve ambitious environmental energy efficiency goals, local renewable energy resources should be integrated. However, one of the main problems is the evaluation which heat supply alternative (centralised or decentralised) is better. This work aims to evaluate the integration of renewable energy resources in existing small district heating system by using known environmental methods.
The results showed that district heating in combination with renewables (biomass and solar energy) is the most environmentally friendly solution for heat supply. The implementation of those measures enables to reach nearly zero CO_2 emission. The analysis in terms of 3E multi-criteria allows to involve other indicators (energy and economic) in overall decision-making process. This evaluation proved the effectiveness of district heating system with solar collectors and economiser, implementing the modernisation of buildings.

Keywords: district heating; renewable energy sources; modernisation; energyPRO, 3E factor.

Nomenclature

CHP	combined heat and power
DHC	district heating company
DHS	district heating system
DHW	domestic hot water
HRE-EE	Heat Roadmap Europe
JSC	joint-stock company
x	non-dimensional (comparative) criteria of primary energy, CO_2 emission or expenses
Subscripts	
CO2	CO_2 emissions
ex	expenses
max	alternative with maximal value
n	pending alternative
pe	primary energy

1. Introduction and review

The balance of the world energy production sector shows that only 11% of the consumed primary energy is related to the renewables. Moreover, the power plant losses reach 55% and the supply chain – 8% [1]. 45% of the European Union's (EU) final energy consumption is used for heating. In Europe, there are more than 6,000 district heating systems, which together meet 12% of Europe's total demand. Sustainability of delivered heat can be increased by expanding the existing district heating systems. About 74% of district heat used in the 27 EU member states was recycled heat from electricity production (CHP), waste-to-energy plants and industrial processes. Only about 20% of district heat was produced directly from fossil fuels and 6.4% – from renewable energy. In 2011, the share of citizens served by district heating exceeded 50% in six

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European countries: Iceland (92%), Lithuania (67%), Latvia (64%), Denmark (61%), Estonia (54%) and Finland (50%) [2]. The large spread of district heating in the particular regions does not mean the efficiency of those heat supply technologies. For example, the main fuel used for district heating in Lithuania is still natural gas (about 73%) [2]. The district heating sector has a basic role to play in the EU low-emissions energy system of the future. However, the energy efficiency potential of the district heating sector is not being properly evaluated by the EU. It is also reflected in the all-important Energy Roadmap 2050 [3]. The recent analysis of the proposed Heat Roadmap Europe (HRE-EE) scenario [4] shows that district heating should be considered as an essential technology for the cost-effective decarbonisation of the EU energy system [5].

Sustainable urban design has become more relevant in recent years and topics like liveability and clean energy attract considerable attention. Mostly people are interested in energy savings in individual buildings, but only integrated measures can lead to a liveable and durable low carbon city or, in time, even to an energy neutral city. Plenty of evaluation criteria (energy, environmental, economic, social, etc.) in sustainable planning often require special approach [6–9] which can answer multiple questions. In combination with saving energy, supply and the generation of energy within the city, the vision of energy-neutral city comes closer. It should be emphasized, that special attention is given to the energy supply with district heating using renewables [10].

The target to increase the amount of renewable energy in national balances and reduce greenhouse gas emissions is accelerating the utilisation of resources such as wind, wave, tidal, solar, waste, and biomass. The studies of renewable energy use in decentralised heating systems proved their efficiency [11–14], but the district heating has much bigger potential for its utilisation [15]. All renewable sources have their own advantages and disadvantages. Some of them have a limited potential in a particular climatic area [16]. A consumption of another one should be limited for certain reasons. For example, the limitation of biomass consumption for heating in 100% renewable energy systems was examined in Denmark [17]. The case study shows that district heating enables to reduce the consumption of biomass by using another renewables (large-scale solar thermal or heat pumps) instead of individual heating technologies. Another research of energy system in Denmark [18] was committed for optimisation between investments in individual heating plants or in expansion of the district heating networks, depending on investment costs, density of heat demand of the potential areas and their distance to existing district heating networks. It was concluded that district heating can cost-effectively contribute to the sustainability and security of supply of future energy systems by facilitating use of heat, which may otherwise be wasted, such as waste heat from power production and heat from solar heaters. Also, district heating can assist as energy storage for the energy system. Furthermore, the case study of energy system in Norway – the country of the hydropower, demonstrated that the municipality under the study [19] has a good potential for the deployment of district heating. Introducing district heating in this municipality could help reduce the community's power dependency, promote the use of biomass in Norway and improve the local environment by replacing inefficient wood combustion which gives high values of particulate emissions and other harmful compounds. Therefore, information is important to correct the general public perception regarding the use of electricity for heating purposes in Norway. The otherwise view is presented for Germany [20], where the most district heat was sold in EU during 2011. The study presents the consequences for district heating and natural gas grids when aiming towards 100% electricity supply with renewables. The impact of a comprehensive passive house standard was analysed and the growing role of decentralised combined heat and power as well as heat pumps was estimated. Also, the impact of heat demand reduction due to higher energy efficiency in buildings on heat and electricity production in Sweden district heating system was investigated by using the energy system optimization model [21]. The results showed that heat demand reductions primarily decrease heat-only production. The electricity-to-heat output ratio for the system was increased for heat demand reductions up to 30%. Local and global CO_2 emissions were reduced. If co-produced electricity replaced electricity from coal-fired condensing power plants, a 20% heat demand reduction was optimal for decreasing global CO_2 emissions in the analysed district heating system. Another study of almost the same authors [22] showed that despite fears that heat demand reductions will decrease co-generation of clean electricity and cause increased global emissions, the results showed that anticipated heat demand changes do not increase the studied system's primary energy use or global CO_2 emissions. Therefore, it can be stated that building energy efficiency measures do have a mainly beneficial impact on the operation of district heating systems. The extensive review of district heating was carried out by Canadian authors [23]. They stated that district systems are flexible in terms of the sources they can accommodate of heating and cooling media, and can thus contribute to reducing fossil fuel use, can be environmentally beneficial and cost effective. The research proved the potential for expanding district energy to integrated larger thermal networks.

Another important aspect of district heating efficiency is concerned with technological features of its supply side – the pipelines quality and operation. The main factor evaluating this efficiency is heat and pressure losses in network [24]. Generally district heating networks are not designed for low building heat demands. High distribution heat losses reduce the benefits of district heating when connecting low energy buildings. In this case, flow temperature reduction is one of the possible solutions. Canadian study [25] proved that the medium supply temperature district heating (70 °C÷90 °C) had better energy delivery performance than high-temperature district heating (>100 °C), decreasing the heat loss by approximately 40%. The low-temperature networks (<60 °C) achieved even lower heat losses, but they required additional capital investment. Also, the use of twin pipes for heat distribution and service piping should be preferred in urban areas where possible, and the use of single pipes should be left to media pipe sizes larger than DN 200. On the one hand, to avoid corrosion of the biomass boilers, the water temperature of the return line should be above 70 °C [26], but on the other hand the implementation of high efficiency economisers requires much lower temperatures.

There are two major problems with the heating system in Lithuania [2] – inefficiency at the point of consumption in buildings and mainly fossil fuels use for energy production. Share of renewables in gross final energy consumption in Lithuania was 20.3% in 2011 [27], when the target for 2020 is 23%. For this reason, the share of district heat produced from renewable energy sources in the heat balance should be increased at least up to 60%, and the share of renewable energy sources in households in the balance of energy sources used for heating – at least up to 80% [28].

The review of the studies shows that district heating is effective energy system for the settlements with high density heat consumers, implementing local renewable sources and optimising their utilisation. However, there is no single way to solve the problem of energy supply for heating under different climate conditions, the renewables accessibility and heat consumption features. This research is intended to evaluate the possibilities to modernise the existing heat supply of Lithuanian resort town Birštonas by integration renewable sources in the district heating system on purpose to reach CO_2 neutral system.

2. Methodology

This article analysis focusses mainly on biomass and solar energy transformation technologies: solar collectors and use of biomass for direct heat production. Several district heating system (further referred to as DHS) modernization variants of different renewable energy technologies integration possibilities were investigated. The main goal is to find energy efficient, environmentally and economically feasible solution for small DHS by ensuring the same level of comfort for end users. For more detailed analysis, Birštonas (Lithuania) district heating system was chosen. The size of the system, normalised annual heat demand, the number of heating degree days, and the actual balance of different types of fuel could be referred to any small district heating system from cold climate zone.

EnergyPRO imitation model was used to analyse all different modernization variants for Birštonas DHS. EnergyPRO is a Windows-based modelling software package for combined techno-economic analysis and optimisation of both cogeneration and trigeneration projects as well as other types of complex energy projects with a combined supply of electricity and thermal energy (steam, hot water or cooling) from multiple energy producing units. When using energyPRO, it is possible to include the benefits of thermal storage. Based on the inputs, the unique programming in energyPRO optimises the operations of the plant against technical and financial parameters to provide a detailed specification for the provision of the defined energy demands, including heating, cooling and electricity use. The software enables the user to calculate and produce a report for the emissions (CO_2, NO_X, SO_2, etc.) by the proposed project [29].

EnergyPRO modelling shows heat production (primary energy demand) according to the end user's demand for different production unit. CO_2 emissions are calculated according to emission factors for different fuel types. Economic evaluation includes investments for different modernisation measures/technologies and presents annual variable and fixed costs for the analysed DHS. The main purpose is pointed to environmental evaluation of the heat supply alternatives. However, energy and economic calculations have also been performed. Therefore, a concept of the multi-criteria analysis (3E factor approach) [7] is implemented for estimation of the miscellaneous alternative selections. The non-dimensional values of primary energy, CO_2 emissions and expenses are calculated in accordance with equation:

$$x = 1 - \frac{X_{max} - X_n}{X_{max}} . \quad (1)$$

The optimal (3E factor) result is calculated on the assumption that all criteria are equally important:

$$3E = \frac{x_{pe} + x_{co2} + x_{ex}}{3} \rightarrow min . \quad (2)$$

3. Research object

Birštonas municipality is located in the centre of the southern part of Lithuania with area of 124 km^2. 82% of the municipality's area is in the territory of the Regional Park of the Great Nemunas Loops. The municipality consists of Birštonas town and Birštonas eldership.

The space heating in the municipality is divided between consumers that receive heat from district heating network and those who have individual (decentralised) heating. District heating is present in Birštonas city only, while in other parts of the municipality individual heating is used.

District heating company JSC "Birštono šiluma" is the only district heat supplier operating in Birštonas town. Total installed capacity reaches 22 MW of which 4 MW come from biomass and 18 MW – from natural gas boilers. The total length of district heating network is 8.4 km. The average heat losses in the network were about 20% (4,100 MWh/year) in 2009–2012 [30]. The annual heat production and demand duration curve of the analysed DHS is presented in the Fig. 1. The share of renewables of produced energy comprises of 77%. According to [30] JSC "Birštono šiluma" in 2012 supplied heat for 103 buildings, 66 of which are residential. The total heated area is 54,718 m^2.

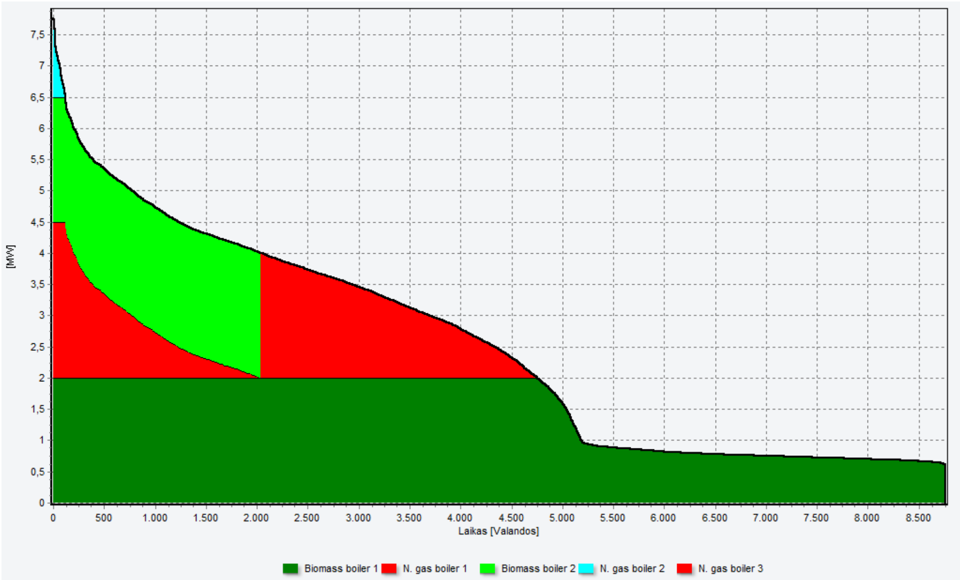

Fig. 1. Annual heat load duration curve with production boilers in analysed DHS

Fig. 1 shows that heat generation priority is given to the biomass boiler 1 (installed capacity 2.0 MW in 2003) and it generates the biggest part (about 60%) of total annual heat demand, second biomass boiler 2 (installed capacity 2.0 MW year of construction 2003) covers about 18% of total annual heat demand. Two natural gas boilers (one of 2.5 MW of installed capacity build in 2001 and another – of 7.75 MW and build in 1981) are peek boilers and they generate about 23% of total annual heat demand in the analysed DHS.

4. Case study and results

The analysed variants could be grouped in two sets. In the first set (I-IV variants), energy demand for heating, ventilation and domestic hot water preparation remains the same during the analysed 20 years period. In the second set (V-VII variants), it is assumed that investments into building modernization will take place and possible realistic savings for heating and ventilation will reach 50%. In order to ensure flexible and efficient work of biomass boilers, new accumulation storage with 40.8 MWh (volume 1,100 m^3, temperatures $80^oC/40$ °C, heat losses 20%) storage capacity was suggested for all the analysed DHS modernization variants.

Reference variant. Reference variant describes the existing DHS energy production and consumption variant with two biomass boilers (total installed capacity of 4.0 MW) and three natural gas boilers (total installed capacity of 18.0 MW).

4.1. Biomass integration possibilities for DHS

Variant I (new 2.5 MW biomass boiler). In variant I, an integration of new biomass boiler for heat production in Birštonas DHS was introduced. In this case, new 2.5 MW (total efficiency 85%) biomass boiler was suggested. This new boiler is more efficient than other two old ones therefore it has a priority and operates most time of the year. All three biomass boilers cover total energy demand in Birštonas DHS. Two of three natural gas boilers could be decommissioned; just the newest one natural gas boiler is left for backup and high peak heat production. All three biomass boilers are connected to new 1,100 m^3 accumulation storage. This allows generating heat in more stable and efficient way.

Variant II (new 2.0 MW biomass boiler with 0.5 MW economiser). In variant II, an integration of new biomass boiler with economiser for heat production in Birštonas DHS was analysed. In this case, new 2.0 MW (total efficiency 85%) biomass boiler with 0.5 MW economiser was suggested. This new boiler has a primary priority and operates most time of the year. Like in variant I, just one old natural gas boiler is left for heat production. All three biomass boilers are connected to new 1,100 m^3 accumulation storage.

Variant V (modernisation of the buildings and 0.5 MW new economiser). Almost all buildings in the analysed DHS are old (built before 1993) and they do not meet new standards and requirements. In this variant, modernization of all buildings is investigated. It is assumed that heat demand for heating and ventilations resulting of modernisation will be 50% (7,350 MWh/year) lower than in the reference variant. After modernisation heat duration curve shows that heat capacity will also drop and only new additional 0.5 MW heat capacity economiser could cover all heat demand.

4.2. Solar energy integration in DHS

Variant III (new large scale flat plate 3,400 m^2 solar collectors field). This variant is similar to variants I and II but in this case instead of new biomass boiler a new large scale flat plate solar collector's plant is suggested. These solar thermal collectors are built near Birštonas district heating company on a field and are connected to return pipe of district heating network. The total area of integrated solar collectors is 3,400 m^2. All biomass boilers and solar collectors' plant are connected to new 1,100 m^3 accumulation storage. Solar collectors cover as much as possible heat demand during the summertime, a surplus heat which is generated during daytime is stored in accumulation storage, during the night heat demand for domestic hot water (DHW) system and losses in the network are covered from accumulation storage. Biomass boiler covers heat demand when heat from solar collectors and accumulation storage is not enough.

Variant IV (new decentralised flat plate of 1,700 m^2 solar collectors). This variant is similar to variant III but in this case instead of new centralised large scale solar collector's plant decentralised heat production with solar collectors is suggested. New solar collectors are built on roof of each building and accumulation storage is integrated in the basement. The total area of decentralised flat plate solar collectors is 1,700 m^2, the total volume of accumulation storage tanks is 260 m^3 (storage capacity 6.78 MWh). The size of decentralised solar collectors' system is selected according to the detailed system modelling of reference multi-storey building [14]. In this case, variant when the decentralised solar collectors are on the roof of each building and cover all heat demand during the summertime, DHS will save heat losses during the three months of the summer, but alternative heat source for DHW system is electrical heaters. They are integrated in each accumulation storage. This solution helps to save heat losses in district heating network during the summer period.

Variant VI (modernisation of the buildings, new large scale flat plate of 3,400 m^2 solar collectors field and 0.5 MW new economiser for old boiler). This variant is similar to variant III, but after building stock modernisation only new 0.5 MW economiser is required to cover all heat demand in DHS with biomass.

Variant VII (modernisation of the buildings and new decentralised flat plate of 1,700 m^2 solar collectors). This variant is similar to variant IV, the main difference is that energy demand for heating and ventilation is 50% lower.

4.3. Technical and economic assumptions

Some main technical and economic assumptions were made for Birštonas DHS model according to 2013 December data:

- CO_2 emission from burning natural gas 55.23 tCO_2/TJ;
- Electricity transformation to primary energy factor 2.8;
- Natural gas price 533.3 € /thousand m^3 (57.3 €/MWh);
- Biomass price 104.0 €/t (19.8 €/MWh);
- Electricity price 144.9 €/MWh;
- Fixed costs 395,900 € /Year;
- Relative investments to biomass boilers 0.41 mill. €/MW;
- Relative investments to large flat plate DHS solar collectors 230 €/m^2;
- Relative investments to decentralised flat plate solar collectors 880 €/m^2;
- Relative investments to building stock modernisation 162 €/m^2.

4.4. Modelling results

In order to compare modelled with EnergyPRO results and according to the described technical and economic assumptions calculated results of modernisation variants, 3E multi-criteria evaluation was chosen. The main results, i.e. primary energy demand, CO_2 emission, investments for district heating company (DHC), investments for end users, heat price in DHS with investments and end user expenses are presented in Table 1. For 3E multi-criteria evaluation primary energy, CO_2 emission and relative end user's expenses were used.

Table 1. The results of Birštonas town DHS modernisation variants

Variants	Reference	I (2.5 MW biomass boiler)	II (2.0 MW biomass boiler	III (large solar collectors)	IV (decentralised solar collectors)	V (0.5 MW economiser)	VI (large solar collectors 0.5 MW economiser)	VII (decentralised solar collectors)
Heat demand (MWh/year)	22,000	22,000	22,000	22,000	21,068	14,650	14,650	13,718
Primary energy demand (MWh/year)	26,653	26,103	23,637	22,849	25,739	14,796	13,502	16,788
CO_2 emission (tCO_2/year)	1,073	2.9	1.4	1.5	532.6	0.8	0.9	230.8
Investments for DHC mill. €	1.021	0.912	0.863	0.848	0.910	0.688	0.663	0.705
Investments for end users mill. €					1.496	6.22	6.22	7.71
Heat price in DHS with investments (€/MWh)	61.6	59.0	56.0	54.4	58.5	74.4	75.8	81.7
End user expenses (€/m^2/year)	19.59	18.77	17.80	17.31	21.06	19.35	19.61	23.15

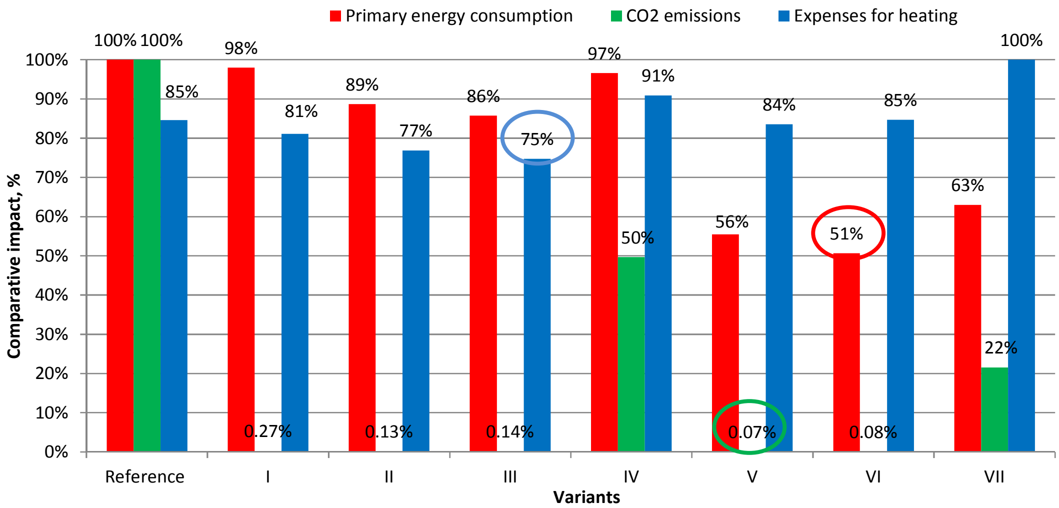

Fig. 2. The non-dimensional (comparative) results of primary energy, CO_2 emission and expenses

Fig. 2 shows that only in two variants (IV and VII) the zero CO_2 emission goal was not achieved. These variants describe the decentralised heat production in flat plate solar collectors on the roofs of the buildings. In these cases in order to decrease heat losses in network, DHS is not operating during three summer months. It helps to save fuel, but some heat demand is covered by electric heaters. Electricity is produced by combusting natural gas in condensing power plants. Table 1 shows that if we take into account investments only for DHS modernisation measures, heat price is higher in building stock modernisation. However, the total end user expenses are lower. It could be explained by the fact that building stock modernisation will reduce heat demand for heating and ventilation by 50% and this will also influence the revenue of district heating company, but the fixed cost for company will remain almost the same. It increases heat price for end users, but the total heat demand will be much lower as well as the relative expenses for 1 m^2 of heated area. In case of primary energy demand comparison, the lowest demand could be found in modernisation variant V (buildings modernisation and 0.5 MW economiser) and VI (buildings modernisation and large flat plate solar collectors with 0.5 MW economiser).

In order to compare the different results of the investigated variants, 3E multi-criteria for each variant was calculated. In this case, the weights for each criterion are equal. Calculation results are presented in the Fig. 3.

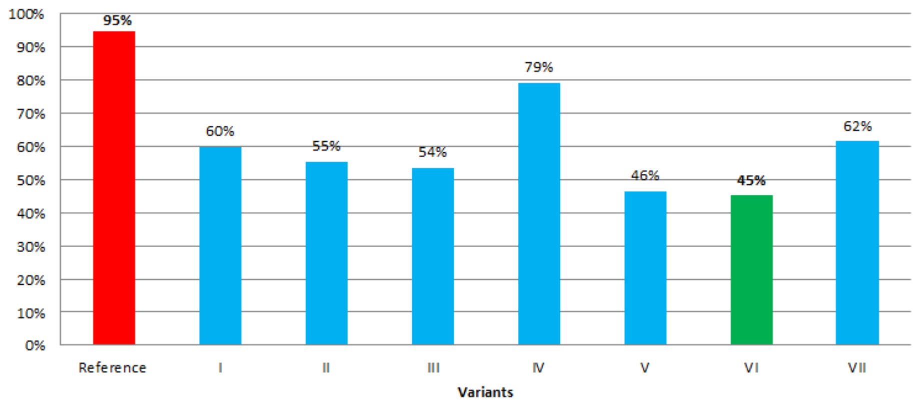

Fig. 3. The results of 3E factors calculation for the variants

Fig. 3 shows that the best variant is VI (buildings modernisation and large flat plate solar collectors with 0.5 MW economiser) but the results of variant V (buildings modernisation and 0.5 MW economiser) are also very close. Naturally, these results will change if the weights for analysed factors are redistributed.

5. Conclusions

There is no single way to solve the problem of sustainable energy supply for heating under different climate conditions, the renewables accessibility and heat consumption features. Therefore, each specific case should be analysed individually with convenient approach.

This case study allows to state that district heating in combination with renewables (biomass and solar energy) is the most environmentally friendly solution for heat supply. The implementation of those systems enables to reach nearly zero

CO_2 emission. In addition, with modernisation of the buildings those improvements could save up to 50% of primary energy and could be still economically attractive in comparison with decentralised heat supply.

The evaluation in terms of 3E multi-criteria shows that the best modernisation variant is VI (buildings modernisation and large flat plate solar collectors with 0.5 MW economiser) but the 3E factor of variant V (buildings modernisation and 0.5 MW economiser) is also very close. More comprehensive multi-criteria evaluation could be carried out in case of the detailed research of weight coefficients for particular criteria. Anyways, the setting of the weights depends on interests of all concerned sides.

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