The effect of different parameters of the excess heat source on the levelized cost of excess heat

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Abstract

In areas with higher heat demand densities, district heating is the most logical way of achieving heat sector decarbonisation aims, especially when renewable energy or highly efficient cogeneration is used. However, excess heat from industry is also recognized as a valuable source with the high potential for utilization. It increases the economic and environmental viability of the system due to the low operation, investment and conventional energy costs. The main goal of this work was to define the effect of the main factors influencing the levelized cost of excess heat. The paper provided the feasibility of excess heat utilisation in different district heating configurations, including solar collectors, cogeneration, peak load boilers, heat pumps and heat storages, showing that its overall utilisation can be much lower than the expected 100% of the overall availability depending on the configuration. Furthermore, temperature levels of the excess heat source have been considered in the analysis to show changes in levelized cost of excess heat with different temperatures and the necessary preconditions for its utilisation. It has been concluded that it is necessary to reduce the supply temperature of district heating in order to make the low temperature excess heat sources feasible.

Key words: district heating; excess heat; levelized cost of excess heat; feasibility analysis

1. Introduction

Buildings represent a major energy consumer, with around 40% of final energy consumption in Europe. When looking at the source of the consumption in buildings, the heating sector stands out as by far the most energy intensive, with almost 80% of total final energy use [1]. Therefore, one of the most discussed topics in this field lately is the means of producing and supplying this heat to the final consumers. The majority of households and commercial buildings currently use individual heating solutions in the forms of centralized boiler systems on the building level or individual furnaces. These mostly use fossil fuels, e.g. natural gas or fuel oil, and biomass. The negative effects of fossil fuels are well known and while biomass may be considered renewable at certain conditions, its use in individual furnaces, which are often old and inefficient can have a significant negative environmental and health impact on the local level, as discussed in [2]. Therefore, it is necessary to switch to a more sustainable way of heating, and in areas with higher heat demand densities, district heating is an efficient way of supplying heat to the final consumers. On the other hand, in the areas of lower heat demand densities, heat pumps are an ideal solution since they have significantly lower environmental impact than the fossil fuel solutions, as shown in [3]. Currently only 13% of heat supply is covered by these systems on the European level, which makes the potentials for its utilization significant [4].

Various studies have already shown the technical, economic and environmental benefits of increasing the share of district heating, e.g. in [5] where authors concluded that the optimal share for Denmark would be 70% in future energy systems, therefore reducing the CO_2 emissions and costs both directly and indirectly through fuel savings. However, different energy sources can be used for heat production in these systems. Currently, fossil fuels are still broadly used, especially in cogeneration systems as shown in [6]. But in order to comply with the requests of the future energy systems, it is necessary to switch to more sustainable energy sources, as the European Commission recognized in its Strategy on Heating and Cooling [7]. These include renewables, e.g. biomass, solar thermal, geothermal, renewable power-to-heat, as well as excess heat [8]. When compared to the fossil fuel district heating, using renewables results in lower costs and lower environmental impact of the overall system, as shown in [9], which is also one of the main reasons for the consumers to connect to such a system [10]. However, in order to optimize the utilization of variable renewable sources in district heating, thermal storage systems are needed [11], which can have significant space requirements due to their size. This can be solved by using indirect storage systems based on phase change material, which maintain similar performance but reduce the required size by 25% compared to hot water tank storage, as shown in [12].

Even though excess heat might not be renewable at its source, it can be considered as a sustainable option since it would be produced anyway and wasted to the environment. Basically, it presents heat which is produced as a byproduct of some industrial or service sector facility and which would otherwise be wasted into air or water, depending on the cooling system in use. The potential of its utilization is significant, as was shown in [13], where authors debate that the available amount of excess heat on the European level is high enough to cover the demands of buildings in residential and service sector. These results were further complemented with numerous other analyses of potentials on the national or regional level, e.g. industrial excess heat in China [14], Japan [15] or EU-28 [16]. Different tools can be used for such purposes, as was shown in [17] where authors develop a tool for urban excess heat recovery potential. Moreover, the economic benefits of excess heat integration in district heating systems have been shown in numerous studies. In [18], the system analysis of excess heat in Sweden has been implemented, providing the optimization model for system cost minimization and proving the feasibility of such a configuration in the analysed scenarios. Additionally, in [19] the environmental advantages alongside the economic ones have been highlighted for the case of excess heat utilization in district heating, showing also an increase in production of the jointly operated cogeneration units. On the other hand, in [20] the authors have focused on the investment costs of the excess heat utilization from an industrial cluster, providing optimal production from each of the facilities. Furthermore, an analysis on the impact of its utilization on CO_2 emissions and the energy system as a whole has been performed on the case of one region in Sweden [21], showing the reduction of fossil fuel usage and consequently the environmental impact of the energy system.

Regarding the different aspects of the investment into the excess heat utilization equipment, in [22] authors have performed the analysis of its utilization in the new district heating system by using the levelized cost of excess heat method to determine the maximum feasible distances of the potential excess heat source from the demand. Moreover, the heat transport costs in the case of the long distance heat transmission have been analysed in [23], showing that the maximum distances are proportional to the square root of the heat quantity. Other researches have also taken into account the investment costs for connecting the available excess heat sources with the demands, as was shown for the case of Denmark [24] and the temperature level of sources, concluding that in more than 50% of cases heat can be used directly with no need for a heat pump [25].

In order to provide an analysis of the energy system on the hourly level, different tools can be used. One of them is energyPRO, which has already been used in numerous studies and is used in the present study. For example, in [26] it was used to evaluate the effects of integrating new heat pumps and solar collectors into the existing district heating system in Helsinki, in terms of emission reductions and economic benefits. Furthermore, it has also been used to analyse the integration of booster heat pumps in the low temperature district heating systems [27], to develop scenarios for the city of Pecs in terms of electricity, heating and transport sectors [28], as well as analyse different combinations of production technologies in the flexible district heating system in the Baltics in order to calculate the lowest levelized cost of heat [29].The idea of this paper is to complement the research from [22] with the analysis of the effect of different factors of the excess heat source on the levelized cost of excess heat (LCOEH). Levelized cost of heat (LCOH) has been used in various studies, e.g. for analysing the potential for heat production and heat savings in Europe [30], calculating the feasibility of the Fresnel solar system [31] and it was shown in [22] that it is a valid method to analyse the feasibility of excess heat utilization in district heating systems. Therefore, there is a need to define the correlation of its temperature level with the different elements of LCOEH. Another relevant factor which was analysed is the capacity factor of the excess heat utilization, when its variable availability is taken into account.

2. Method

Levelized cost of energy calculates the minimum price at which the unit of energy should be sold in order to break even at the end of the project lifetime. Hence, it takes into account all the cash flows during the lifetime of the production unit. The main parts used for the calculation of LCOH are the discounted capital costs, operation and maintenance costs and fuel costs [22], as can be seen in Equation 1.

$$\mathrm{LCOH} = \frac{I_c \cdot CRF \cdot (1 - TD_{pv})}{8760 \cdot i \cdot (1 - T)} + \frac{O_{total}}{8760 \cdot i} + c_{fuel} \ [€/kWh] \qquad \text{Equation 1}$$

It must be noted that the presented form of the Equation 1 uses specific values for each of the parameters and not the overall value in order to make it more general, easy to use and applicable to the technology itself and not the specific system. The same form has been used also for the calculations of LCOEH.

The main parameters of the LCOH from Equation 1 are the specific Investment costsI_c $(€/kW)$, the Capital Recovery Factor (CRF) which is used for discounting the investment by taking into account the discount rate and the overall lifetime of the equipment, the capacity factor i, the specific annual operation and maintenance costs O_{total} and the specific fuel costs c_{fuel}. As mentioned, all of these parameters are specific values per unit of heat.

However, the excess heat utilization itself incurs different costs than the usual heat production units. These can vary depending on the temperature level of the source, as well as the overall capacity factor. In case the temperature of the excess heat is high enough for the direct utilization, the LCOH consists of the capital costs for the heat exchanger, its operation and maintenance costs as well as the excess heat procurement costs. Since the temperature is high enough, there is no need for the use of heat pumps. Nonetheless, when the source temperatures are not high enough, it is necessary to increase the temperature level by using the heat pumps, which incurs additional costs. Furthermore, the capacity factor of excess heat can vary significantly due to mismatch between available supply and the demand in different configurations of the system. All these factors have been analysed in this paper in different steps.

First, by using the energyPRO software, different configurations of the system have been modelled in order to determine the capacity factor of excess heat, considering the variability of its availability. LCOEH has then been calculated for each of the scenarios in order to show the effect of different configurations on the feasibility of excess heat integration. Furthermore, the effect of the temperature level of the excess heat source on the LCOEH was analysed, as well as the effect of the temperature of the end users. These were compared with LCOEH of the excess heat source where no heat pump is needed and the LCOH of the standard district heating production unit, i.e. the natural gas boiler. Finally, the change in maximum distance of the available excess heat with the different temperature levels is shown.

2.1. Capacity factor of the excess heat utilization

In most of the previous researches, excess heat has been considered as a source with the constant availability, supplying all of its heat to the district heating network. Yet, most of the time this is not the case. The availability often varies depending on the number of shifts of the industrial facility, as has been shown in [24], ranging from full capacity during the day and lower capacity during the night and the weekends. Due to that, the actual capacity factor of the excess heat utilization, which is a significant factor in the calculation of LCOEH, can be much lower than the expected 100%.

In order to take that into the account and calculate the realistic capacity factor, the hourly simulation of the system operation has to be performed. For that, energyPRO software was used [32]. It optimizes the operation of the heat production units by taking into account the input data on operation costs, revenues and the selected priorities. The output is the production of each unit, CO_2 emissions, number of hours of operation on the annual level, costs, etc. The model uses analytical optimisation in order to calculate the operation of each production unit in the time horizon of one year. This is done by calculating the priority number for each production unit in each time step by taking into account the operation costs and revenues. Then the unit with lowest priority number is put in operation, continuing with second lowest and so on, until the whole demand has been met.

Technical constraints of each unit are also taken into account. An example of the block diagram of the energyPRO model is shown in Figure 1. It presents a model developed for Scenario 1, which will be described in the next subsection. As can be seen, the model has an intuitive and simple graphical interface, where blocks represent energy demands, heat/electricity production units and storage systems. Each of these blocks are modelled by providing input data on the specifics, such as production unit efficiencies, unit specifications, hourly demands, etc. Then the connections between them are modelled by selecting the appropriate operation strategy.

In order to model different scenarios, various technical and economic data needed to be acquired. Since energyPRO optimizes the operation of the system based on the operational costs, the required input data included fixed and variable operation and maintenance (O&M) costs, fuel costs, as well as income from heat and electricity production. O&M costs were taken from [33], while the fuel costs were taken from [34]. The revenues from heat and electricity sales depend on the local framework. Since the numerical example is analysed for the city of Ozalj, as will be elaborated in more detail later, the heat price has been taken the same as for the nearby city of Karlovac at 66.6 €/MWh [22], while the electricity prices have been taken from the Croatian Power Exchange market [35].

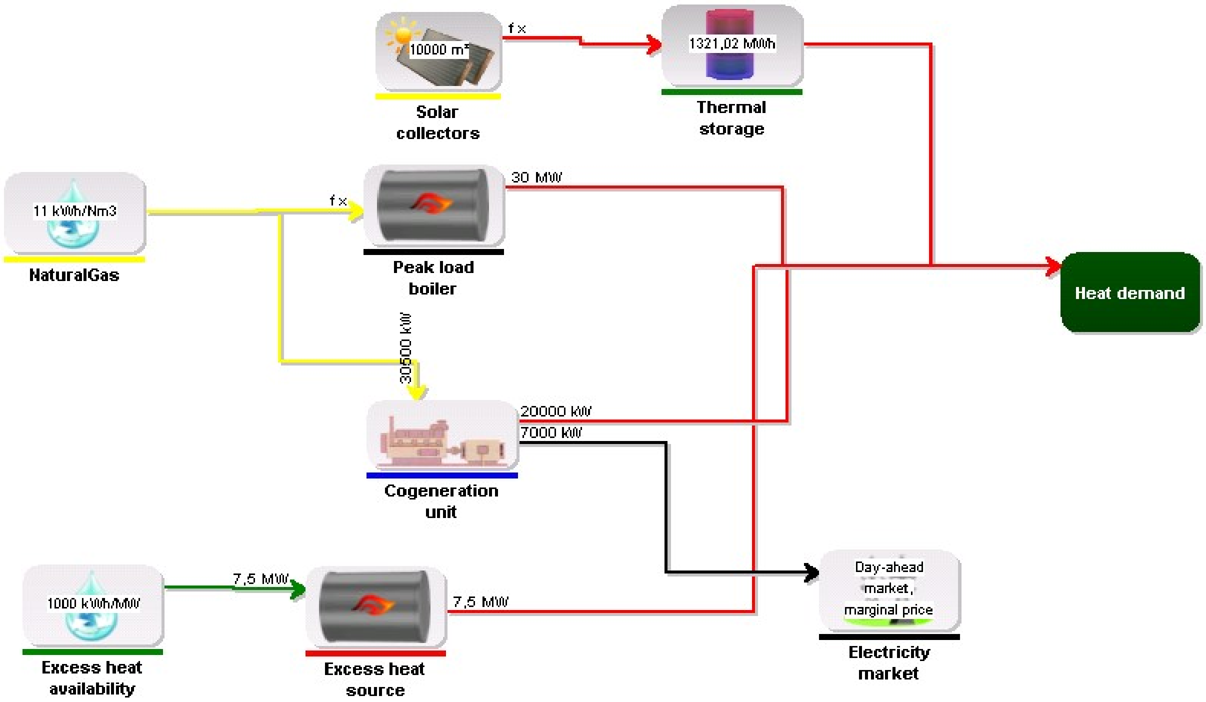

Figure 1. The interface of the model developed for Scenario 1 in energyPRO

For a given maximum excess heat supply its distribution is shown in Figure 2, based on [24]. It reflects well the operation of the manufacturing industry and therefore the availability of excess heat from such a source as well. The distribution is shown for one typical week, which repeats throughout the year. Furthermore, the analysis needs to include the calculation of the hourly heat demand, which is in this case done by the degree-hour method.

The capacity factor will definitely depend on the heat generation mix, i.e. what other technologies supply heat to the district heating network. In cases when e.g. solar thermal supplies heat during the summer months, the capacity factor will be lower due to the inability to supply heat during this time. In order to measure its impact, a scenario analysis has been performed, taking into account different combinations of technologies. Finally, the results from the energyPRO modelling serve as an input for the LCOEH calculation. It must be noted that the results are highly case sensitive, despite considering different heat generation mixes.

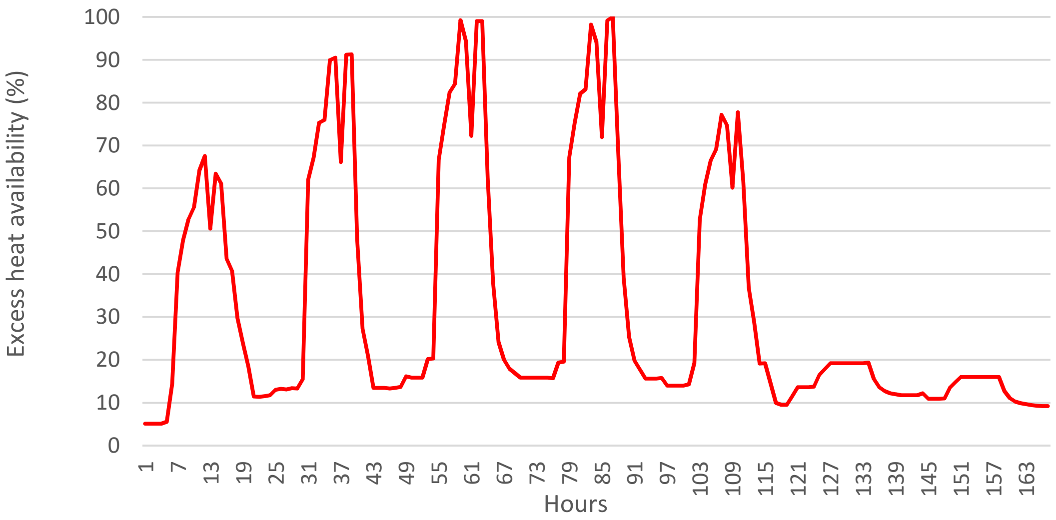

Figure 2 Hourly variation of excess heat availability through the time horizon of one week

2.2.1. Numerical example

In order to model the scenarios, the numerical example has been analysed by using the data for the city of Ozalj, a small rural city in the north-west Croatia, with the population of 1,880. The input data on heat demands and capacities of heat production technologies have been taken from the previous research [22], as well as from the CoolHeating project [36], where the detailed survey of the population has been carried out, providing a comprehensive insight into the energy consumption of the citizens. By using these data, heat demand has been calculated and it amounts to 69.4 GWh. The procedure is explained in more detail in previous research [22]. It has then been elaborated on the hourly level by using the degree hour method. This way, the peak load of the system can be determined, which amounts to 41.5 MW. Here it must be noted that the city completely relies on the individual heating solutions at the moment.

However, as the part of the aforementioned CoolHeating project, a technical concept has been developed for the city, which included the combination of a peak load boiler, cogeneration unit, solar thermal collectors and thermal storage system. These were sized in such a way that the cogeneration units are able to operate as the baseload, peak load boilers cover only the peaks during the winter, while solar collectors area was designed by taking into account the available land area owned by the municipality. This configuration is expected to be built in near future.

On the other hand, certain industrial facilities, mainly manufacturing industry, are present in the relative proximity of the city. By taking into account the data from the excess heat source potentials map [37], it has been concluded that there is significant excess heat potential to be analysed. It must be noted that no real time data on the hourly availability of the excess heat from the mentioned source could be obtained. For that reason, the availability has been approximated by using the variation presented in Figure 2.

Since the method presented in this paper is focused on the LCOH, its use is more suitable for the analysis of the new system implementation. That is why this city, with its newly developed district heating concept has been chosen as the numerical example.

2.2.2. Scenarios

As has been elaborated, technical configurations of the reference system have been selected based on the developed technical concept for the city, as a part of the Horizon2020 project CoolHeating. The available excess heat supply from the manufacturing industry nearby the city has been assumed at 20 GWh annually, considering data from the excess heat source potentials map [37] and the previous results from [22].

List of technologies used in the scenarios and their capacities are shown in Table 1. The basic reference scenario includes a peak load boiler, a cogeneration unit, solar collectors and the thermal storage. As described in the previous subsection, this configuration represents a technical concept developed for the city of Ozalj as a part of the CoolHeating project and it is planned to be built in the city in near future. The capacities in the reference scenario have been selected in order to meet the overall heating demand of the city, taking into account the technical constraints of each technology, as well as land use constraints for solar thermal and thermal storage. Other scenarios included different variations of technologies with the addition of excess heat source in each scenario, in order to utilize its potential from the manufacturing industry in the proximity of the city. Therefore, in Scenario 1, the effect of adding the excess heat to the current technical concept is modelled. In Scenario 2, an additional storage facility for the excess heat is added, based on the results from Scenario 1.

Furthermore, this excess heat configuration is also modelled in Scenario 3, where no solar thermal utilisation exists and no storage is used for excess heat, with the rest of the demand being covered by peak load boiler and the cogeneration unit. In scenario 4, storage for excess heat is added again to the configuration from Scenario 3. Finally, in Scenario 5, a large heat pump is added before the main supply to the already existing configuration to analyse the utilisation of excess heat in such a heat generation mix. The main output of the scenarios are different capacity factors of the excess heat in these configurations, i.e. its overall amount of heat utilised, compared to the maximum available amount. Then, these data were used to calculate the LCOEH of each scenario, by using the formula from [22] in order to compare different configurations. The LCOEH calculations for the scenarios took into account only the direct excess heat utilization and incorporated the costs of the storage system in the method.

Table 1. Capacities of different technologies used in the scenarios

	Reference	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**
Natural gas boiler (MW)	31	31	31	31	31	31
Natural gas cogeneration (MW)	20	20	20	20	20	20
Solar collectors (m^2)	10,000	10,000	10,000	-	-	-
Seasonal thermal storage (MWh)	1,320✓	1,320	1,320	-	-	-
Excess heat (MWh)	-	20,000	20,000	20,000	20,000	20,000

Thermal storage for excess heat (MWh)	-	-	1,100	-	1,100	1,100
Heat pump (MW_{th})	-	-	-	-	-	6.2

Since the maximum available excess heat amount can usually cover only a certain share of the overall demand, a peak load boiler and a cogeneration unit have been used in all the scenarios. Maximum availability of the excess heat source has been held constant throughout the scenarios, while the heat pump has been modelled in such a way that it has approximately the same heat output as solar collectors, in order to be able to compare with that scenario. The capacity of the thermal storage unit for the excess heat has been modelled at 1,100 MWh for Scenario 2. Thermal storage units are modelled in energyPRO by selecting the available volume, the temperature difference from top to bottom, which was set to 40°C and the minimum content, which was set at 5% of the capacity. Also, the model requires data to calculate the losses, which include the ambient temperature, insulation thickness and the thermal conductivity of the insulation material. The same capacities have been kept for Scenario 4 and 5 in order to enable an easier comparison of the results. All the heat production units in Scenarios 1-5 have been modelled prior to the supply line of the district heating network and therefore no booster units have been included in the analysis.

2.2. Different temperature levels of excess heat

Many industries and especially service sector facilities produce the low temperature excess heat, which cannot be used directly and therefore requires the use of a heat pump. For the simplification reasons, it is assumed that in case the heat pump is used, there is no need for an additional heat exchanger, i.e. the quality of steam or water is high enough for the direct contact with the evaporator. The threshold for using the heat pump is defined by the needed supply temperature of the district heating system, as well as the temperature level of the excess heat source. Most elements in the LCOH remain the same, however an additional cost is added due to the use of a heat pump, i.e. the cost of electricity for using this device, as can be seen in Equation 2.

$$\text{LCOEH} = \frac{I_{HP} \cdot CRF \cdot (1 - TD_{pv})}{8760 \cdot i \cdot (1 - T)} + \frac{O_{HP,total}}{8760 \cdot i} + c_{excess\,heat} + c_{el,th} \; [€/kWh] \qquad \text{Equation 2}$$

Nevertheless, the electricity cost needs to be presented per unit of heat, since the LCOH calculates the production cost for one unit of heat. In order to do that, the coefficient of performance (COP) of the heat pump must be calculated, since it is the correlating factor between the electricity consumption and heat production, as shown in Equation 3. This is introduced in order to take into account the fact that with the decreasing temperature of the excess heat source and thus the increasing temperature difference between the source and the district heating supply, the COP of the heat pump decreases. This leads to higher electricity costs for the operation of the heat pump.

$$c_{el,th} = \frac{c_{el}}{COP} \; [€/kWh_{th}] \qquad \text{Equation 3}$$

It is well known that the COP of a heat pump depends significantly on the temperature of the heat source. Therefore, when an ambient source is used (e.g. ambient air, sea water, etc.) it can change drastically throughout the year. However, when excess heat is used, it is assumed that it has a constant temperature during the year and therefore no annual changes of COP occur. Nonetheless, the difference between the required supply and the excess heat source temperature can vary significantly, effecting the COP and consequently the cost of electricity per unit of heat. For the purpose of this research, the COP was calculated by using the Carnot COP and the efficiency of heat pump which was assumed at 60% [38], as shown in Equation 4 and Equation 5.

$$COP_{Carnot} = \frac{T_{DH}}{T_{DH} - T_{EH}} \qquad \text{Equation 4}$$

$$COP = \eta \cdot COP_{Carnot} \qquad \text{Equation 5}$$

Therefore, by implementing the Equation 2, the correlation between the temperature level of the excess heat source and the LCOEH can be calculated and plotted. However, another parameter influences the results of the calculation significantly, the capacity factor of the excess heat utilization. This will be further elaborated in the next subsection. It needs to be emphasized that all the capital and the operation and maintenance costs have been taken from the same source [33] in order to make the comparison between different cases possible and valid.

2.3. Maximum distance of the excess heat source from the demand

In order to show the effect of the temperature level of the excess heat source on the overall feasibility of its utilization in the district heating system, the maximum distance from the demand is calculated, based on the method described in [22]. That way, the cost of pipes is also considered since it is a significant contributor to the overall costs of the excess heat utilization. This is due to the fact that most of the industrial sources are located further from the demand, and therefore a distribution network needs to be built to the nearest district heating pipe.

The maximum distance is calculated by defining the extra revenue of the system which enables the investment into the distribution pipes. The calculation is shown in Equation 6 and is elaborated in detail in [22].

$$\mathrm{R}_{EH} = E_{total} \cdot r_{heat} - (E_{EH} \cdot LCOEH + E_{DH} \cdot LCOH) - l \cdot n \cdot c_{pipes} \quad [€] \qquad \text{Equation 6}$$

By dividing this extra revenue with the discounted cost of pipes, the final result, i.e. the maximum distance can be calculated. This has been calculated for different temperatures of the excess heat source, to show the decrease of the maximum distance with the decrease of the temperature.

3. Results

This section will present the variations of the LCOEH when different configurations of the system, as well as different temperature levels of the excess heat source are taken into account. Furthermore, the effect of variations of the end user temperature levels will be presented and discussed and finally the maximum distance of the source from the demand will be shown for the numerical example.

3.1. Scenario analysis of different system configurations

The production of different units in the scenarios is presented in Table 2. When compared to the Reference scenario, the results of Scenario 1 show that by introducing excess heat into the heat generation mix, the production of the peak load boiler is reduced. The overall benefits of introducing excess heat into the system can be seen in the form of lower natural gas consumption and consequently lower environmental impact of the heating sector. While cogeneration units also produce less heat, the production of solar collectors remains more or less the same, since they have a high priority in the optimization process.

However, this also has a negative effect on the excess heat integration since only around 53% of the available amount has been utilized in this scenario. The problem is not only during the summer when there are excess amounts of solar energy but also during the heating season in the night, when the available amount of excess heat is significantly higher than the heat demand. This leads to the conclusion that storage systems need to be implemented alongside the excess heat facility in order to increase the utilization of excess heat and further reduce the use of fossil fuels in the existing system. For that reason, Scenario 2 analysed the integration of an additional 20 000 m^3 storage system.

Table 2. Production of different units in all the scenarios

	Reference	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**
Natural gas boiler	19.48 GWh	12.76 GWh	10.56 GWh	9.41 GWh	6.57 GWh	5.5 GWh
Natural gas cogeneration	40.43 GWh	36.94 GWh	36.81 GWh	47.14 GWh	45.88 GWh	44.99 GWh
Solar collectors	9.53 GWh	9.7 GWh	9.7 GWh	-	-	-
Excess heat	-	10.61 GWh	12.96 GWh	12.89 GWh	17 GWh	17 GWh
Heat pump	-	-	-	-	-	1.88 GWh
Capacity factor of excess heat	-	53%	64.8%	64.5%	85%	85%

The results of Scenario 2 show that by introducing a thermal storage system at the location of the excess heat source, its utilization can increase to 64.8% of the overall availability with the given size of the storage. For that reason, the utilization of the peak load boiler is further reduced to 10.5 GWh/a, while the production of other units remains mostly the same.

However, the results showed that with further increases of the storage size, the utilization doesn’t increase significantly in the given configuration of the system. This is because of the competition with the solar collectors, which have the lowest cost during the summer and are the only used technology for covering the hot water demand in that period, while at the same time filling the seasonal thermal storage for its utilization in the heating season.

Consequently, a configuration without the solar collectors has also been analysed, first without the heat storage for excess heat (Scenario 3), and then with the storage system (Scenario 4). It can be seen that already in Scenario 3 the excess heat utilisation is rather similar to Scenario 2, showing increased feasibility of this source when it is not competing with solar thermal.

However, there is still a need for thermal storage unit if higher utilisation rates are to be achieved. By using the same storage size as in Scenario 2, 85% of the available excess heat can be utilised in Scenario 4, while a 92 000 m^3 seasonal thermal storage has to be used if 100% of available excess heat should be utilised.

Finally, the results from Scenario 5, where the heat pump is added to the configuration from Scenario 4, show that it doesn't affect the excess heat utilisation by a large margin, since its operating costs are higher than for the excess heat most of the times. Therefore, it wouldn't be feasible to implement a heat pump in such a configuration when its high investments are taken into account.

The LCOEH has been calculated for each of the scenarios and the results can be seen in Figure 3. It is the lowest for Scenario 3 since it has the highest excess heat utilisation rate without using the storage system. However, it can be seen that it is not much higher in Scenario 1 when no storage is used. When the costs of storage are taken into account, LCOEH is increased up to 0.023 €/kWh for Scenario 2, but in Scenarios 4 and 5 it is rather similar to Scenario 1, at 0.0189 €/kWh. For further analysis, the configuration of the scenario with lowest LCOEH will be taken into account, i.e. Scenario 3.

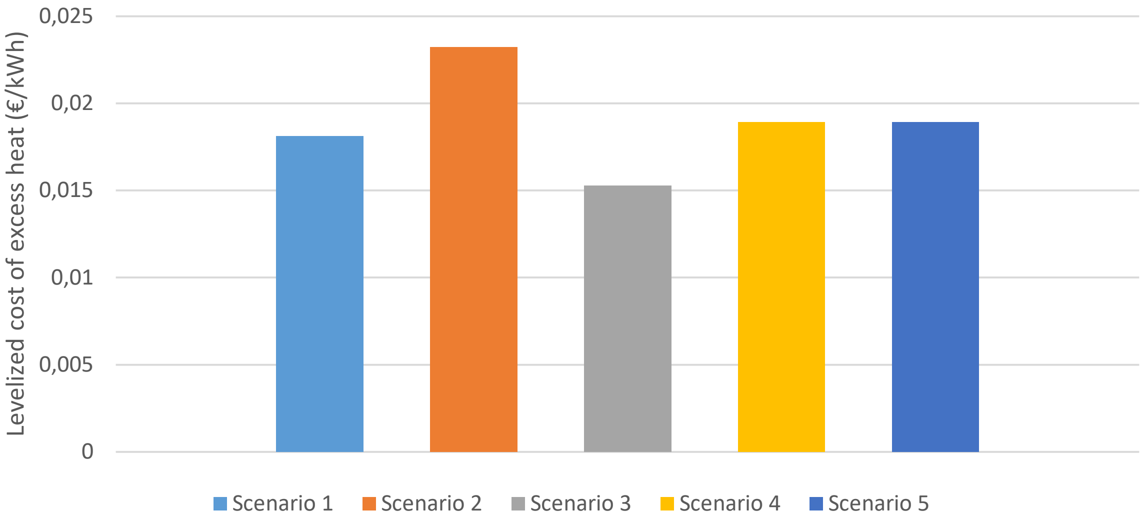

Figure 3 Levelized cost of excess heat for each of the scenarios

3.2. Temperature variations

When all the input data are determined and inserted into the Equation 2, the variation of the LCOEH with the different temperatures of the excess heat source can be calculated. The results are shown in Figure 4. Here it must be noted that the capacity factor has been recalculated in energyPRO for each of the temperature levels, therefore considering the decreasing utilisation of excess heat when lower COP is achieved. The required district heating supply temperature T_{DH} has been selected at 90°C, while the minimum temperature difference between EH source and the district heating supply temperature at 5°C.

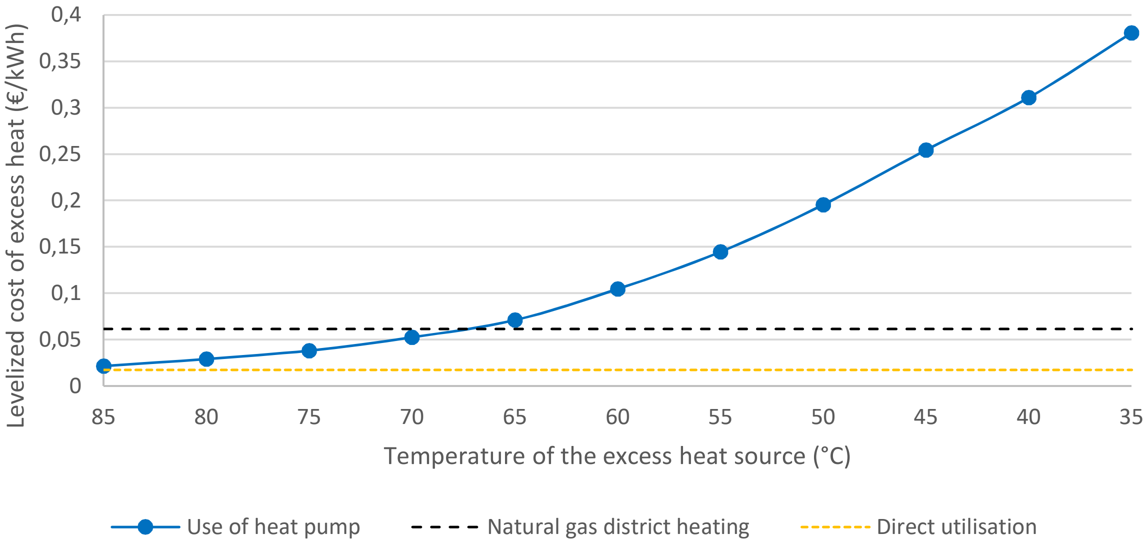

Figure 4 The effect of the temperature level of excess heat source on the LCOEH

As expected, the LCOEH is the lowest in case when no heat pump is used, i.e. that excess heat is used directly, with only the need for a heat exchanger. In Figure 4, this cost is presented as a horizontal line in order to act as a graphical threshold to better read the results. Nonetheless, this value is acquired only for the temperature of the excess heat source above 95°C in order to satisfy the minimum temperature difference between EH source and district heating supply temperature. Furthermore, when the temperature of the excess heat source is lower than the required temperature for direct utilization, heat pump is implemented, and the costs increase. Up until 66°C, the LCOEH is still lower than the LCOH for the natural gas district heating system, which has been taken as a reference system due to its simplicity. After this point, the temperature is too low for the industrial or service sector excess heat to be a competitive heat source for district heating.

Nevertheless, the supply temperature for a district heating network has been selected rather high in this analysis. These temperature levels can be expected in the countries of South-east Europe, where the building stock is old and inefficient and therefore high temperature heating is needed. Still, the legislation of the European Union facilitates the implementation of energy efficiency measures in buildings to lower their consumption and consequently lower the needed temperature of the buildings heating system. These are suitable to connect to a low temperature 4th generation district heating system [39], with supply temperatures as low as 50°C.

Therefore, the needed temperature of the end user has also been taken into account in the analysis. The results are shown in Figure 5.

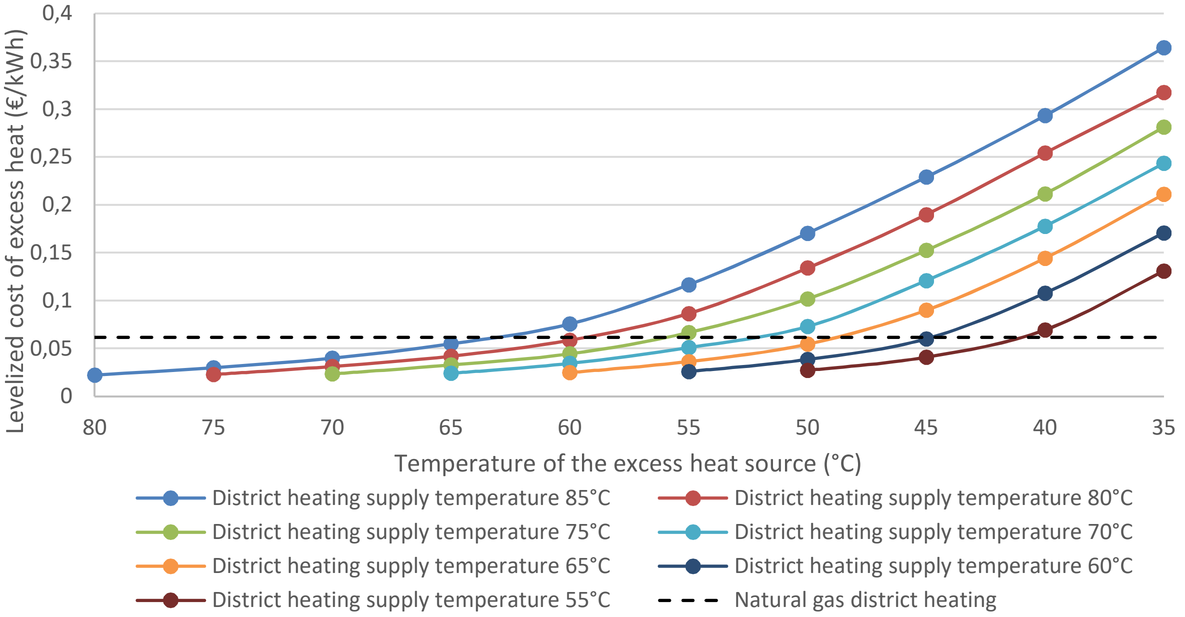

Figure 5 The effect of lowering the needed supply temperature in a district heating system on LCOEH of excess heat sources on different temperature levels

The diagram shows that in the case of lower temperatures at the end user, the feasibility of excess heat utilization increases for the lower temperatures of the source. Therefore, the threshold for the competitiveness of excess heat reduces from 63°C for the supply temperature of 85°C to 41°C for the supply temperature of 55°C. Furthermore, it can be seen that for the same temperature of excess heat source, the LCOEH decreases significantly with lower supply temperatures. For example, for the source temperature of 50°C the LCOEH reduces from 0.17 €/kWh if the supply temperature is 85°C to 0.027 €/kWh if the supply temperature is 55°C.

By taking into account the data from Figure 5, the borderline feasibility of excess heat utilisation can be plotted for different district heating supply temperatures in order to achieve better visualisation of the results. This is presented in Figure 6 and shows the decreasing trend with lower district heating supply temperatures.

This on the one hand shows the necessity of increasing the efficiency of the buildings sector and therefore reducing the temperatures, both on the district heating network side and the end user side. On the other hand, it is inevitable that the heating system will gradually transform to low temperature in the next decades and therefore the feasibility of excess heat utilization in district heating will increase significantly.

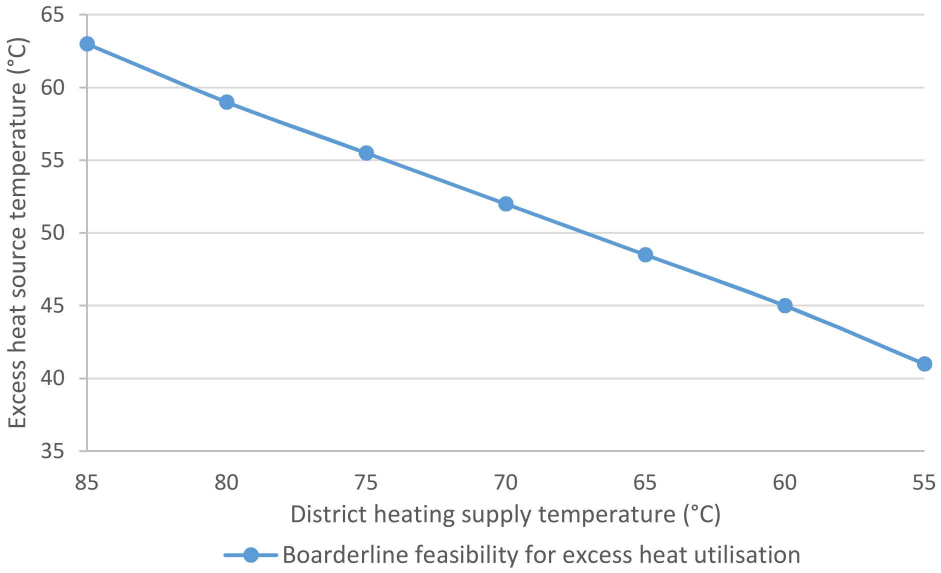

Figure 6 Decrease of the borderline feasibility excess heat source temperature with the district heating supply temperature

3.3 Maximum feasible distance of the excess heat source

The maximum feasible distance of the potential excess heat source has been analysed both for different temperatures of the excess heat source and the different district heating supply temperatures, which are influenced by the required temperature at the end users side. The analysis has been performed for a specific case in Croatia, the city of Ozalj as was described in the Methods section. The excess heat procurement costs were assumed at 1€/MWh and the pipe costs at 400 €/m.

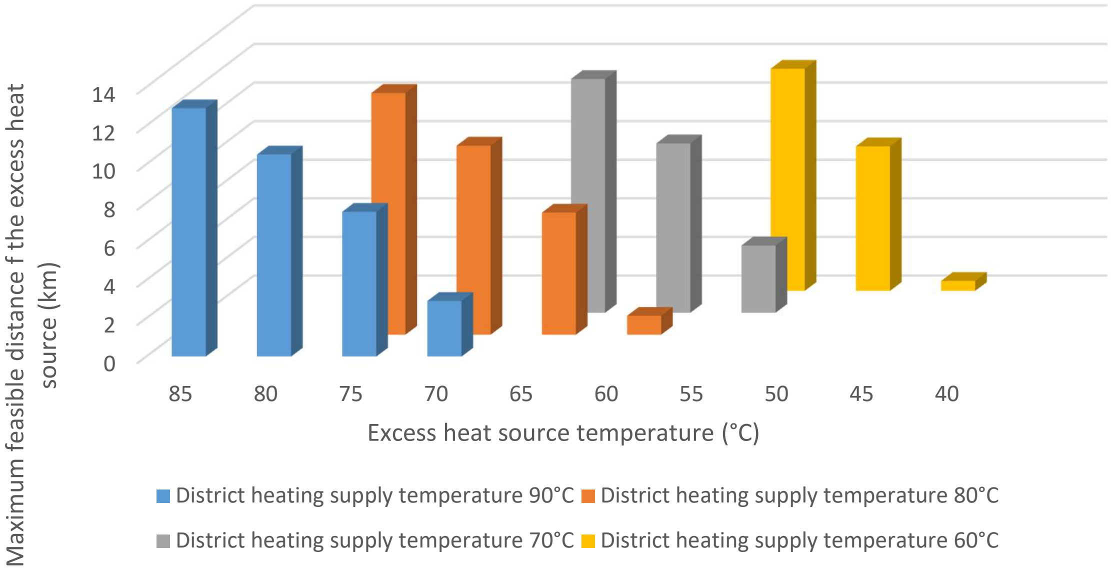

Figure 7 Variations of maximum feasible distance of the potential excess heat source with the temperature of the excess heat source and the district heating supply temperature

The results correlate with the variation of LCOEH with decreasing temperature level of the excess heat source. Therefore, it can be seen that the maximum feasible distance decreases in the case when temperature of the excess heat is lower. If the supply temperature is assumed at 90°C, the results show that at the excess heat source temperature of 70°C, it would be feasible to utilize it only in cases when the source is located at the close proximity of the primary district heating network, i.e. at the city itself.

However, if the system were to be transformed to the 4th generation network in terms of supply temperatures, lower temperature excess heat sources could be utilized. Hence, the results show that in the case of the supply temperature of 60°C, 40°C excess heat source could be utilized in cases when such a source is located more at the proximity of the primary network. Furthermore, in case when the supply temperature is 90°C, the maximum distance of the excess heat source is 12.9 km at 85°C excess heat source temperature. Nonetheless, when the supply temperature is lowered, similar distances can be achieved with excess heat source temperature of 55°C. The results are graphically presented in Figure 7.

4. Conclusions

Utilizing excess heat from various industrial or service sector sources in the district heating systems depends significantly on different factors. In this work, the dependence of the capacity factor on the system configuration, as well as the temperature level differences of the source have been taken into account in order to present their influence on the LCOEH. This is a continuation of the previous work [22], which already proved that this method can be used as a criterion for excess heat utilization in district heating systems by calculating the maximum distance of the potential source from the demand.

Even though most of the calculations are usually made on the annual level, assuming that the availability of the excess heat source is constant throughout the year, this is frequently not the case. For this reason, the availability curve of this source was modelled by taking the data from literature in order to calculate its capacity factor, as one of the crucial parameters for the LCOEH calculation. Furthermore, different configurations of the system have been taken into account by implementing the scenario analysis. The calculations have been performed by using energyPRO, an energy system operation optimization tool. The results have shown that the configuration of the system has a significant impact on the excess heat utilisation, with the capacity factor ranging from 53% in Scenario 1 to 85% in Scenarios 4 and 5. It can be concluded that the storage system is needed if high utilisation rates of the excess heat should be achieved, mostly due to the mismatch between its availability and the overall heat demand. Nonetheless, this increases the LCOEH and therefore the cost optimal combination of storage and excess heat needs to be analysed in detail.

In further research, the effect of the decreasing temperature of the excess heat source on the LCOEH has been studied. In cases when this temperature is above the required supply temperature of the district heating network, this heat can be utilized directly, without the need for a heat pump. The investments are required only for the heat exchanger, while the operational costs consist of the excess heat procurement costs and the operation and maintenance. However, when the temperature of the excess heat source is lower than the needed supply temperature, the use of the heat pump is required substituting the investment and operation and maintenance costs of the heat exchanger with those of the heat pump and adding the additional cost of electricity needed for the heat pump, expressed by the unit of heat.

The results have shown that the LCOEH increases significantly with the lower temperature of the excess heat source. In the case when the supply temperature amounts to 90°C, LCOEH rises above the LCOH of the natural gas boiler district heating system at the temperature of the excess heat source of 66°C. However, another important parameter which greatly influences the results is the supply temperature of district heating, i.e. the needed temperature at the end use side. It has been shown in this research that the threshold for the competitiveness of excess heat (i.e. the temperature when the LCOEH reaches the LCOH of the gas boiler district heating) reduces from 63°C for the supply temperature of 85°C to 41°C for the supply temperature of 55°C. Furthermore, for the source temperature of 50°C the LCOEH reduces from 0.17 €/kWh if the supply temperature is 85°C to 0.027 €/kWh if the supply temperature is 55°C, showing the benefits of decreasing the temperatures at the end use side. This shows that even though the low temperature excess heat may not be feasible in this moment for the use in high temperature networks, its feasibility will significantly increase when the system is transformed towards the 4th generation of district heating with low supply and return temperatures.

Finally, the research has been validated by using the method from [22], i.e. by calculating the maximum feasible distance of the potential excess heat source from the demand, taking into account that the larger sources are usually located further from the populated areas. The results show that in the case of the supply temperature of 60°C, 40°C excess heat source could be utilized in cases when such a source is located in the proximity of the primary network. Furthermore, lowering the supply temperature results in achieving similar maximum distances both for the excess heat source temperature of 85°C, when the supply temperature is 90°C and 55°C when it is 60°C.

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Nomenclature

LCOH	Levelized cost of heat [€/kWh]
I_c	Capital cost of the production facility [€/kW]
CRF	Capital recovery factor which discounts the investment
T	Tax rate
D_{pv}	Present value of depreciation
i	Capacity factor of the production facility
O_{total}	Total operation and maintenance costs [€/kW]
c_{fuel}	Cost of fuel being used [€/kWh].
LCOEH	Levelized cost of excess heat [€/kWh]
I_{HE}	Investment cost for the heat exchangers [€/kW]
$O_{HE,total}$	Operation and maintenance costs for the heat exchangers [€/kW]
$c_{excess\ heat}$	Excess heat procurement costs [€/kWh]
I_{HP}	Investment cost for the heat pump [€/kW]
$O_{HP,total}$	Operation and maintenance costs for the heat pumps [€/kW]

$c_{el,th}$	Electricity costs of heat pump operation per unit of heat [€/kWh]
c_{el}	Electricity costs [€/kWh]
COP	Coefficient of performance
COP_{Carnot}	Carnot coefficient of performance
T_{DH}	Supply temperature of the district heating system [°C]
T_{EH}	Temperature of the excess heat source [°C]
η	Efficiency of the heat pump
R_{EH}	Extra revenue which can be used to finance the construction of the distribution network [€]
E_{total}	Total heat demand of the area for which it would be feasible to connect to a natural gas district heating system [kWh]
r_{heat}	Price of heat [€/kWh]
E_{EH}	Available excess heat [kWh]
E_{DH}	Remaining heat demand being covered by the natural gas district heating [kWh]
l	Average length of distribution network in a 100x100 m area [m]
n	Number of 100x100 m areas
c_{pipes}	Discounted cost of pipes [€/m]

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