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EXCESS HEAT UTILISATION COMBINED WITH THERMAL STORAGE INTEGRATION IN DISTRICT HEATING SYSTEMS USING RENEWABLES

by

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District heating systems already play an important role in increasing the sustainability of the heating sector and decreasing its environmental impact. However, a high share of these systems is old and inefficient and therefore needs to change towards the 4th generation district heating, which will incorporate various energy sources, including renewables and excess heat of different origins. Especially excess heat from industrial and service sector facilities is an interesting source since its potential has already been proven to be highly significant, with some researches showing that it could cover the heat demand of the entire residential and service sector in Europe. However, most analyses of its utilisation in district heating are not done on the hourly level, therefore not taking into account the variability of its availability. For that reason, the main goal of this work was to analyse the integration of industrial excess heat into the district heating system consisting of different configurations, including the zero fuel cost technologies like solar thermal. Furthermore, cogeneration units were a part of every simulated configuration, providing the link to the power sector. Excess heat was shown to decrease the operation of peak load boiler and cogeneration, that way decreasing the costs and environmental effect of the system. However, since its hourly availability differs from the heat demand, thermal storage needs to be implemented in order to increase the utilisation of this source. The analysis was performed on the hourly level in the energyPRO software.

Keywords: *district heating, excess heat, hourly analysis, energyPRO, thermal storage*

Introduction

Heating and cooling sector is one of Europe's most energy-intensive sectors, which is responsible for around 50% of its final energy consumption [1]. Due to the high use of fossil fuels in covering the heating demand, this also leads to a high environmental impact of this sector. However, this could be substantially reduced if district heating (DH) systems are used at a much higher level in the future energy systems, which was shown in [2] proving significant cost, CO_2 emission and fuel use reductions when the share of DH is increased from the current 13% of the European heat demand [3]. Nonetheless, in order to provide such benefits, these systems must transform into the 4th generation and integrate much higher shares of

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renewables and excess heat [4]. Significant research has been already performed on the topic of the integration of renewables in DH, showing benefits of different combinations including solar thermal and thermal storage [5], adding biomass to the previous combination [6], as well as combining heat pumps with solar thermal [7], but also using geothermal energy [8]. These systems provide substantial benefits from both the economic and the environmental point of view, as was shown for five different cities in southeastern Europe [9], but also in [10]. This proves to be one of the main reasons for customer connection to DH, as shown in [11]. It can be concluded that when using intermittent heat production technologies, it is crucial to utilise thermal storage units, which should often have a seasonal character [12]. The importance of thermal storage has been proven in numerous articles, *e.g.* in [13] where authors provide a model for determining thermal storage optimal capacity, with the addition of optimal sizing of conventional sources and solar thermal and in [14] which shows the necessity of thermal storage when power to heat technologies are utilised in a smart energy system. They do, however, have certain space restrictions due to their size and therefore should be planned carefully, considering different options like phase change material indirect storage systems [15], which have also been analysed in combination with heat pumps [16].

From the perspective of sustainable heat sources for DH, excess heat from industrial and service sector facilities is especially interesting and has significant potential on both regional and national levels, as has been shown in numerous studies focusing on industrial excess heat utilisation in Japan [17], China [18], and the EU [19]. Despite a high amount of research being done on the topic of the potential of this source, its variability is rarely taken into account, which can have a high effect on the overall utilisation of this source. Therefore, this paper discusses rates of utilisation of excess heat in different configurations of the system, when the variability of excess heat availability and its mismatch with the heat demand is considered. Specifically, the contribution of this paper is in analysing the integration of thermal storage with various capacities to increase the utilisation of variable excess heat, while still remaining an economical solution.

Method

In order to analyse the different effects of excess heat utilisation in the DH system, scenario analysis has been performed. The idea was to study the integration of excess heat into the system which consists of the most common, conventional heat production units, *i.e.* natural gas cogeneration and peak load boilers, but also of zero marginal cost, renewable technologies, *i.e.* solar thermal collectors. In order to do that, a numerical example has been analysed, which will be elaborated further in the following subsections. By considering cogeneration, a link is made to the power sector since the operation of these units depends on the market prices of electricity. On the other hand, by including solar thermal in the calculations, the competing technology in terms of low marginal costs is also considered providing a full picture of the effect of excess heat integration on different heat production units. It must be noted that the analysis has been performed from the perspective of energy planning, not integrating the excess heat into the existing system but rather into the planned system, therefore being able to change the parameters of the fossil fuel units such as the required capacity of the peak load boiler.

The system has been modelled in the energyPRO software [20], which is an analytical optimisation model providing optimal operation of the system for the given heat demand in the time frame of one year. The time step for the analysis has been selected at one hour. In order to model the system, data on technology operation costs, fuel costs, as well as revenues from heat and electricity sales, is needed. Heat production capacities need to be predefined, and specific technical data of each technology need to be inserted in the model, including the technical constraints of each unit. The optimisation is performed in several steps. First, the priority number is assigned by the model to each technology based on the costs and revenues in each time step. Then the unit with the lowest priority number is put in operation, moving forwards with second lowest and continuing until the whole demand has been met.

The energyPRO software has been used as the primary tool for energy system analysis in numerous research articles already, *e.g.* analysing emission reductions and economic benefits of combining solar thermal with heat pumps in Helsinki DH [7], analysing booster heat pumps integration in DH with low system temperatures [21], developing scenarios and integrating various energy sectors, including electricity, heating and transport, as shown for the case of Pecs [22], investigating levelized cost of heat for the flexible DH in Baltics through the analysis of different combinations of production technologies [23], and many others.

Scenarios

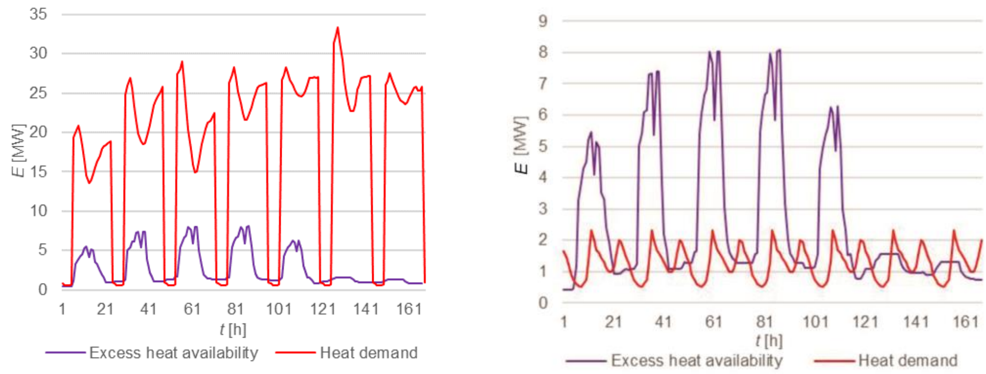
As mentioned earlier, the main idea of the scenario analysis was to research the utilisation rate of excess heat, as well as the effect it has on the operation of other heat production technologies in the system, while taking into account the hourly variability of the source. For that reason, a numerical example has been studied. It is based on the data acquired through the CoolHeating project for the city of Ozalj in central Croatia [9], which details the heat demand and potential revenues, *i.e.* energy prices. Therefore, the scenarios developed as a part of this research will be compared with the Reference scenario, a starting point for this analysis which presents a technical concept developed for the city as a part of the CoolHeating project.

However, it must be noted that the Reference scenario is non-existent at this point, but is rather a highly developed technical concept, which has been discussed with the city and should be implemented in the coming years. It consists of a 20 MW natural gas cogeneration (CHP) unit, a 30 MW natural gas peak load boiler, as well as 10^5 m^2 of solar collectors, combined with a 30000 m^3 thermal storage system. All of these units would cover the heat demand of the city, which equals to 66.4 GWh and would transfer heat to the consumers through 16 586 m of pipes. This represents a trench length, *i.e.* only the length of the flow pipe, which is needed for additional calculations. Furthermore, in order to calculate the required amount of energy which would need to be produced in these units, heat losses need to be analysed. They have been calculated by using the empirical formula, based on real DH grids in Austria [24], which requires data on the annual grid density. It has been calculated at 4004 kWh/m/a. The losses have therefore been calculated at 3029 MWh/a, resulting in overall required heat production from DH units of 69.4 GWh.

By researching available excess heat facilities in the area, it has been concluded that a ceramic industry is operating in the relative vicinity of the city, with significant amounts of excess heat available, based on the excess heat sources map [25]. It has already been shown in [26] that the ceramic industry has high potentials for excess heat recovery, due to the high temperatures used in its processes. The overall excess heat potential from this specific ceramic industry facility amounts to 46 GWh. However, this presents a theoretically maximum excess heat availability calculated from the total CO_2 emissions of the facility, which is probably much lower in reality and therefore a more conservative value has been taken for further analysis, at 50% of the maximum value, *i.e.* 23 GWh.

In the next step, it was necessary to define the hourly availability of the excess heat source. By reviewing the existing literature, it can be concluded that the ceramic industry usually operates on a two or three-shift schedule throughout the year [27], but it is assumed that higher quantities of excess heat are produced during the working days than during the weekends. The source has been modelled in energyPRO by taking into account the assumption that its temperature is high enough in order to be utilised directly in the system, through the means of the heat exchanger and without having to use the heat pump. This assumption is logical since the source of excess heat is the ceramic industry which produces high temperature heat, as already mentioned.

The availability of ceramic industry excess heat is based on [27] and is shown in fig. 1. In order to put the variability of excess heat availability into perspective, it has been plotted alongside heat demand for a standard winter and summer week. It must be noted that the excess heat availability has been assumed the same for every week throughout the year, *i.e.* without any seasonal changes. It can already be noticed that excess heat availability and heat demand are in a significant mismatch in different seasons of the year. This will be further discussed in the results section.



(a) **(b)**

Figure 1. Excess heat availability and heat demand in a standard week in winter (a) and summer (b)

Due to these evident differences, it is evident that a thermal storage system has to be implemented at the excess heat site, in order to increase the utilisation of this source. Therefore, two scenarios have been modelled, Scenario 1 where excess heat is integrated into the system from the Reference scenario without using a thermal storage unit and Scenario 2, where a thermal storage unit is also added.

For that purpose, a series of simulations have been carried out with different capacities of thermal storage ranging from 2000 m^3 to 2.2×10^5 m^3 in order to calculate the best solution regarding thermal storage integration, when the economics of the overall system are taken into account. Then the dynamics of the system have been shown for the selected capacity of storage. Thermal storage units with lower capacities have been modelled as a steel tank, with the temperature difference from top to bottom of 40 °C, and the utilisation rate of 95%. The losses have been modelled, taking into account the storage height, insulation thickness and thermal conductivity of the insulation material (polyurethane foam), as well as the ambient temperature.

On the other hand, thermal storages with higher capacities have been modelled as a large pit unit, usually constructed to serve as seasonal storage. Technical details of all the three scenarios can be seen in tab. 1. The required input data for the model, other than technology capacities and technical constraints of the units, include the hourly electricity price, which is taken from the Croatian power exchange [28], hourly weather data, including solar irradiation and temperature, which is directly incorporated in the model for a selected location, the natural gas price at 0.3 €/m^3 [29], as well as fixed and variable operation and maintenance costs for each technology, which have been taken from [30].

Table 1. Technical details of different technologies used in the scenarios

	Reference scenario	Scenario 1	Scenario 2
P_{NGB} [MW]	30	26	27
P_{CHP} [MW]	20	20	20
A_{ST} [m^2]	10^4	10^4	10^4
V_{TS} [m^3]	3×10^4	3×10^4	3×10^4
$Q_{\mathrm{EH,\,max}}$ [GWh]	–	23	23
V_{TSEH} [m^3]	–	–	$2000 - 2.2 \times 10^5$

The capacities are selected in such a way that the cogeneration covers the baseload, while the peak loads are covered by the peak load boiler. Solar collectors operate mostly during the summer and cover the domestic hot water demands, while seasonal thermal storage is used in order to increase the share of solar thermal in the overall heat production. Throughout the scenarios, the cogeneration and solar collector capacities have been held constant, while the peak load boiler capacity has been decreased with the introduction of excess heat to the minimal level while still covering the demand.

The system was modelled in energyPRO by using Region module, therefore modelling excess heat and the reference system as separate energyPRO sites, which both supply heat to cover the heat demand. This had to be done in such a way in order to take into account the effect of adding thermal storage on the excess heat side since it is impossible to separate two storage systems if they are modelled in the same energyPRO site. The system schematic presented in the form of the energyPRO block diagram is shown in fig. 2.

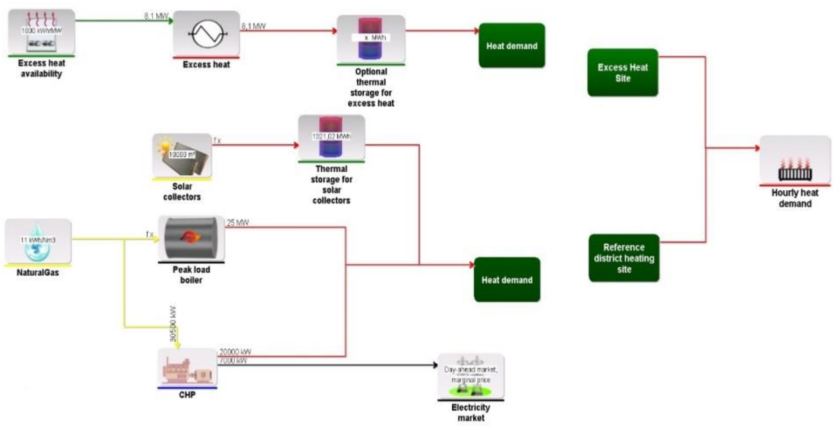


Figure 2. Schematic view of the system modelled in energyPRO

Finally, in order to compare the scenarios from the economic perspective, levelized cost of heat for the whole system has been calculated for each scenario, by using the equation presented in [31]. It has to be pointed out that the boundaries of this approach are that the results are highly case sensitive and input data-sensitive but are therefore used to present a qualitative analysis of the variable excess heat integration into the DH system.

Results

The results of the energyPRO modelling will be shown in this chapter. First, Scenario 1 will be studied in comparison to the Reference scenario. Afterwards, an addition of the thermal storage system for the excess heat in Scenario 2 will be analysed and compared to previous scenarios.

Scenario 1

Scenario 1 is compared to the Reference scenario, where no excess heat is utilised in the DH system. The annual production of heat from different production units can be seen in tab. 2. The results show that by introducing excess heat into the heat generation mix, the required peak load boiler capacity reduces, as well as its production. This results in lower natural gas consumption and consequently, the lower environmental impact of the heating sector. While cogeneration units also produce less heat, the production of solar collectors increases slightly, which will be discussed in the next paragraphs.

Table 2. Production in [GWh/a] of DH system under optimised operations, case studies: Reference scenario and Scenario 1

	Reference scenario	Scenario 1
Q_{NGB}	19.1	13.4
Q_{CHP}	40.7	36.5
Q_{ST}	9.5	9.7
Q_{EH}	–	10.4

However, this also has a negative effect on excess heat integration since only 45% of the available amount has been utilised. The problem is not just during the summer when there are excess amounts of solar energy but also during the heating season in the night. This happens since at that time, the available amount of industrial excess heat is higher than the heat demand, as was shown in fig. 1. Due to the lack of storage in Scenario 1, it is not possible to store this excess production, which is therefore wasted.

The DH production for the Reference scenario and Scenario 1 can be seen in fig. 3 for a typical winter week. The figure shows how excess heat first reduces the operation of a peak load boiler and then the operation of a CHP plant in cases of higher excess heat utilisation. Therefore, the operation of the peak load boiler has reduced from 3336 h/a to 2751 h/a, while for the CHP the reduction was from 2749 h/a to 2548 h/a. This consequently resulted in the reduction of natural gas consumption by 1137798 m^3/a.

Another benefit of the excess heat integration can be seen in fig. 4, which shows the monthly heat production for October when the heating season starts. It can be seen that with excess heat, the peak load boiler turns on approximately one month later in the heating season, allowing the seasonal thermal storage to discharge more slowly. This enables a slightly higher production from solar collectors and again reduces the natural gas consumption.

However, despite all the benefits of the excess heat integration into the DH system, when the variable availability of this source is taken into account, the results show that less than 50% of the available excess heat can actually be utilised, as previously discussed. This leads to the conclusion that storage systems need to be implemented alongside the excess heat facility in order to increase the utilisation 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 storage system for excess heat.

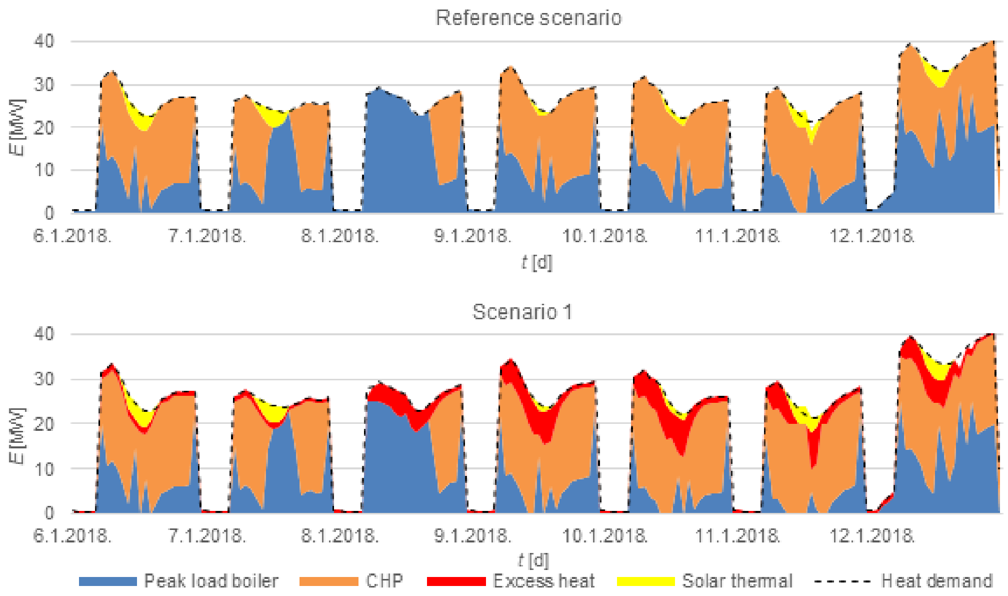


Figure 3. Thermal load of optimised operations in DH system during the typical winter week, case studies: Reference scenario and Scenario 1 (*for color image see journal web site*)

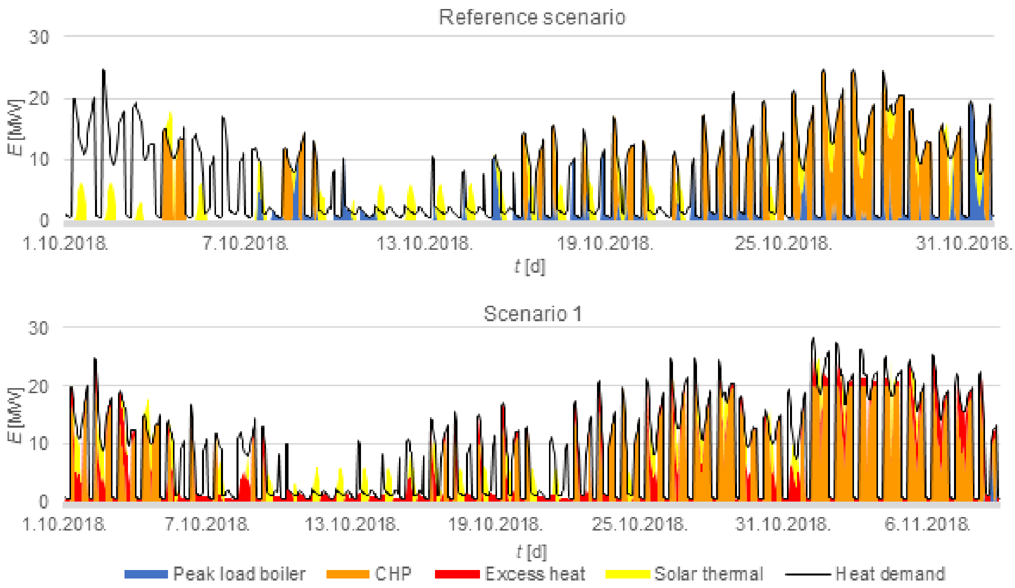


Figure 4. Thermal load of optimised operations in DH system in October, case studies: Reference scenario and Scenario 1 (*for color image see journal web site*)

Scenario 2

In order to determine the best solution in terms of thermal storage capacity for the excess heat source, a series of simulations have been carried out in energyPRO integrating different storage capacities from small buffer tanks to large pit storages. Then, the levelized

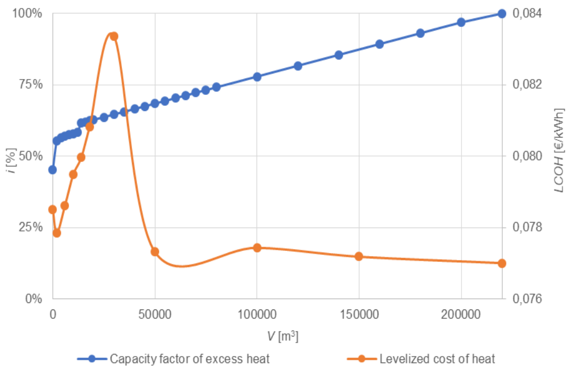


Figure 5. Thermal and economic analysis of the whole system operations for different capacities of thermal storage in Scenario 2

cost of heat has been calculated for the whole system, taking into account the results from these simulations. The resulting capacity factor of the industrial excess heat source, as well as the economics of the system when different thermal storage sizes are integrated into the system, can be seen in fig. 5.

It can be concluded that in order to utilise all of the available excess heat, a large underground thermal storage is needed, in this case with a capacity of 2.2 $\times 10^5$ m^3, which equals to 9690 MWh. However, if this cannot be achieved due to space restrictions, relatively high capacity factors can still be achieved by implementing a smaller buffer tank, since the highest increases in the capacity factor occur at smaller capacities due to the most significant difference from the reference state, *i.e.* no thermal storage. Nonetheless, these showed to be more expensive solutions, as underground thermal storage units have a much lower specific investment cost than the buffer tanks.

Moreover, when the levelized cost of heat for the Reference scenario is calculated, it equals to 0.079 €/kWh, which shows that by using the underground thermal storage and therefore achieving a high capacity factor of excess heat, significant economic benefits can be achieved, as an addition to the environmental benefits. From fig. 5 it can be seen that lower costs of the system can also be achieved in Scenario 1, when no thermal storage is used, but also in cases of smaller buffer tanks, which increase the capacity factor significantly when compared to Scenario 1. However, when a higher-capacity buffer tank is used, the levelized cost of heat of the system increases above the levels of Reference scenario. Still, the increase is low, since the cost is only 5% higher at peak value than in the Reference scenario, which is negligible when compared to the environmental benefits of using the excess heat source. This is especially significant when the fact that excess heat can be considered as a carbon-neutral source is taken into account. This statement can be made since excess heat presents the heat that would be wasted otherwise, and its emissions are already accounted at the side of the industrial facility.

Since the least cost solution from fig. 5 is the 2.2 $\times 10^5$ m^3 thermal storage, which enables the total utilisation of excess heat, these results will be elaborated in more detail in the next paragraphs.

Table 3. Production in [GWh/a] of DH system under optimised operations, case studies: Scenario 1 and Scenario 2

	Scenario 1	Scenario 2
Q_{NGB}	13.4	6.7
Q_{CHP}	36.5	30.6
Q_{ST}	9.7	9.7
Q_{EH}	10.4	22.9

When the results for a 2.2 $\times 10^5$ m^3 thermal storage are calculated, it can be concluded that the utilisation of the peak load boiler is further reduced to 6.7 GWh/a, the utilisation of the CHP unit to 30.6 GWh, while the production of solar collectors remains the same as in Scenario 1, as can be seen in tab. 3. This again leads to lower natural gas consumption by 1454395 m^3/a, as well as lower environmental effect of the heating sector.

The production of different units for Scenario 2 in a typical winter and summer week is shown in fig. 6. It can be seen that in winter, the utilisation of excess heat increases both during the night hours, as well as during the day due to the implementation of the storage system. However, this only provides minor increases in the capacity factor of the excess heat source, which can already be achieved by buffer tanks with significantly lower capacities.

Figure 6. Thermal load of optimised operations in the DH system during the typical winter week: case study Scenario 2 (*for color image see journal web site*)

The highest increase in utilisation is therefore seen in the summer months when the heating demand reduces significantly, and the excess heat is being stored in the thermal storage system. In cases of lower capacity storage, it would charge rather quickly at the beginning of summer and could not store any additional heat coming from the industrial excess heat source throughout the rest of the summer. 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 utilisation in the heating season. It can be concluded that when excess heat is integrated into the system with solar collectors, such as the analysed configuration, the seasonal thermal storage is required in order to utilise the source entirely and store all of the produced excess heat during the summer when solar collectors have higher priority.

The operation of excess heat thermal storage can be seen in fig. 7. The figure shows its seasonality since the daily operation has relatively small variations in comparison to the seasonal ones. This would also mean that the industries which have reduced operation during the summer months would be an ideal source of excess heat in cases when there are space restrictions and no seasonal thermal storage can be built.

Conclusions

This paper showed how the excess heat integration depends significantly on different conditions in the system when its variable availability is taken into account. The analysed case integrated excess heat into the system with solar thermal collectors who were the primary technology for supplying heat during the summer. By integrating excess heat, the solar thermal production did not reduce, as it has lower operating costs and therefore has the priority of operation. It even increased slightly since the excess heat integration enables slower discharging of the thermal storage for solar collectors in the autumn and hence their higher production. On the other hand, the operation of peak load boilers reduced significantly in all the scenarios, with the slight reductions of CHP operation as well. This resulted in much lower CO_2 emissions of the heating sector, due to the reduced consumption of natural gas.

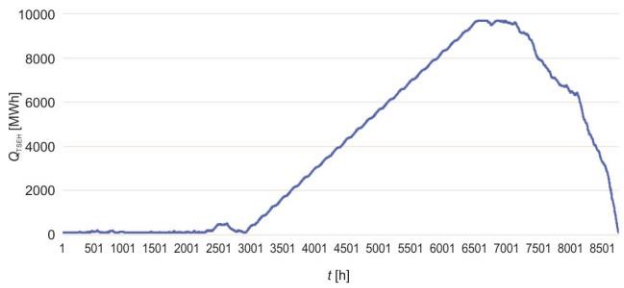


Figure 7. Excess heat thermal storage operation

However, it was shown that the maximum amount of excess heat that could be utilised is 45% for the analysed case, due to low heat demand in the night and the priority of solar in the summer. The reduction due to low night-time demands is applicable to the majority of cases in central and northern Europe, which have variable demands. For that reason, the effect of integrating a storage system at the excess heat production side was analysed by implementing multiple simulations with different storage capacities. The analysis showed that the storage actually has a seasonal character since the daily variations have a much lower effect, in cases when solar thermal is used alongside excess heat. Therefore, in order to utilise all of the available excess heat, an underground pit seasonal storage needs to be implemented. This also showed to be the economically optimal solution since it has the lowest overall levelized cost of heat. Nonetheless, if it is not possible to build such a storage unit, smaller buffer tanks can also be incorporated since they also achieve significant increases in the capacity factor for excess heat, while remaining an economically viable solution. It can be concluded from the presented research that the variability of excess heat should always be taken into account when hourly analyses are implemented since it affects the results significantly and that thermal storage must be used alongside excess heat source in order to increase its utilisation since it is a variable source, similar to intermittent renewable sources.

Acknowledgment

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Nomenclature

A – area [m^2]
i – capacity factor of excess heat [%]
E – thermal load [MW]
LCOH – levelized cost of heat [€kWh^{-1}]
P – installed capacity of different production units [MW]
Q – heat produced by different production units or stored in the thermal storage unit [GWh]
t – time [h]
V – capacity of thermal storage unit [m^3]

Subscripts or superscripts

CHP – combined heat and power
EH – excess heat

NGB – natural gas boiler
ST – solar thermal collectors
TS – thermal storage
TSEH – thermal storage for excess heat

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