Alignment of the heat recovery potential with the local area heat demand for selected industrial entities in the city of Gliwice

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Abstract

Waste heat plays a significant role in obtaining the 4th and 5th generation of District Heating (DH) System in cities. This article presents the possibilities of integrating selected waste heat emitters into DH, with the objective of meeting the demand for heat for the selected residential area (approx. 4000 inhabitants) in the city of Gliwice (180 000 inhabitants). The total heating demand of the studied area was estimated at 19 800 GJ including both space heating and domestic hot water. The maximum thermal power was estimated at approx. 2.45 MW. The demand was calculated on the basis of registered metering values for individual buildings which were processed and summarized due to the lack of collective meters for the district. A detailed data classification, correction and completion procedure was elaborated to deal with non-uniform and low-quality data registration. Two industrial objects with waste heat generation were examined to be integrated with the local DH network. The waste heat generation potential equals 9.0 MW for plant #1 and 0.9 MW for plant #2. Apart from the constant generation declared by the industrial entities, realistic profiles including possible shaft-work and maintenance periods were created. It has been shown that the total heat demand for selected residential areas can be covered by integrating waste heat into the current DH network. Depending on the waste heat generation profile, the local area heat demand can be covered entirely or to a large degree (coverage factor ranges from 72 to 100%). The waste heat utilization factor ranges from 6.3 to 8.3%. To manage the remaining waste heat potential, it is required to build additional district heating pipelines and nodes connecting to the existing network to receive an additional 7.45 MW thermal power. The potential of waste heat recovery is significant at the scale of a medium sized city: integrating two large industrial emitters allows up to 13% decarbonization of heats production in the local district heating plant.

Keywords: waste heat, heat recovery, district heating system, residential sector, energy management

1. Introduction

The contemporary geopolitical crisis turns everyone's attention to the significance of energy resources. Fossil fuels, beyond being harmful to the Earth's climate, reveal our dependence on supply from a limited number of countries. The majority of fossil (and nuclear) fuels is used for the production of electricity or mechanical energy (transportation). Unfortunately, 72% of the primary energy supplied for these two purposes is lost in the conversion processes, and it is dissipated to the surroundings in the form of heat [1].

However, basic human needs, as specified in the Maslow hierarchy [2] comprise the needs of shelter, heat and hygiene, which require proper indoor conditions. In many climatic zones including Poland, this is bound to space heating and the preparation of hot water. These needs are defined at low temperature levels (20°C indoor temperature, and about 55°C for domestic hot water), however, they are mostly covered by fossil fuel combustion, which results in an unnecessary generation of much higher temperatures. In the case of Poland, space heating and domestic hot water production is largely covered by solid fuels (coal and wood) which leads to a severe air pollution in the winter season, and to an unavoidable CO_2 emission.

To address this problem, it is recommended to extend the use of heat pumps, and to promote a new generation of heating systems, integrating various available sources, especially renewable sources and waste heat [3]. The objective set by the European Commission (European Green Deal) is to achieve carbon neutrality, reducing the CO_2 emission to 0 kg/GJ usable heat.

Development of district heating systems is focused on maximizing the efficiency of the DH system and minimizing heat losses by reducing the temperature supply of the heat carrier. Currently, 5 generations of development of district heating systems are known [4], [5]. The first two generations, 1GDH and 2GDH ($1^{st}/2^{nd}$ generation of district heating system), were based on a centralized heat production from fossil fuels and they were characterized by high temperature levels. The feeding temperature in the 1GDH was above 200˚C with steam as a heat carrier, which resulted in large heat losses. Replacing the steam with pressurized hot water enabled reducing the feeding temperature to 100˚C and it constituted a transition to 2GDH. This transition resulted in increasing the efficiency of DH systems and the endurance of DH networks. Implementation of pre-insulated pipes into DH networks allowed a further reduction of the feeding temperature below 100˚C, and the utilization of a greater variety of heat sources including renewable energy sources and high-temperature waste heat from industrial sources, which can be integrated using heat storage if required [6]. These measures define the 3GDH. The fourth generation of DH, 4GDHC is characterized by obtaining the supply temperature in the range of 50–60°C, which enables the utilization of low-temperature waste heat. Moreover, this generation utilizes industrial heat pumps as one of the heat sources. This generation also includes production and distribution of district cooling. The most innovative system is described as 5GDHC (5th generation of district heating and cooling), which ensures less heat loss within the DH network, by obtaining ultra-low feeding temperature below 50°C. This system, compared to previous ones is bi-directional: the production of heat is decentralized, and each consumer can be also a producer.

In the case of Poland, transition from the current level of 2–3 GDHC towards higher levels (4-5) provides a simultaneous solution to 3 major problems in the local heating sector [7]:

1. decarbonization - the Polish heating sector currently emits about $68 \cdot 10^6$ Mg CO_2 per year. From a strictly economic point of view, each Mg is burdened by about €80/Mg emission allowance - compared to €20/Mg in 2019.
2. energy safety - following the closure of several major coal mines, and accounting for the current breakdown of Russia-UE economic relations, Poland has now a shortage of $11 \cdot 10^6$ Mg of coal (about 40% of the sectoral demand), while the price of coal still available has risen from $60 to $320/Mg.
3. air pollution - in winter, Poland suffers from severe air pollution, in many cities (including e.g., Kraków) the allowable levels of PM10 are exceeded for 150 days/year [8]. Air pollution is mostly bound to individual solid fuel boilers, i.e., houses not connected to district heating.

To upgrade the generation of DH networks, it is essential to integrate the available waste heat. Until now, waste heat recovery was frequently neglected due to the availability of relatively cheap fuels (coal and gas). Investment costs for waste heat integration were often too high to provide economic feasibility. The new, challenging macroeconomic situation is likely to quickly change this perspective.

The objective of this paper is to demonstrate the availability of waste heat on the local energy market, and to provide the first estimation of its possible integration into the district heating system.

2. The case of Gliwice

2.1 General information

Gliwice is a middle-sized city of approx. 180 000 inhabitants, situated in the highly industrialized area of Upper Silesia, Poland. The city hosts several industrial factories (i.a. 'Huta Łabędy' steelworks, 'Bumar' heavy vehicles factory) as well as the newer Katowice Special Economic Area (KSSE, since 1996), including various branches of industry; many of them are related to the car manufacturing sector (Opel Manufacturing Poland being the leading entity in the area).

The city administration estimates the total thermal demand as 1139.5 MW for space heating and 93.2 MW for domestic hot water (2020). Within these figures, 448.8

MW space heating and 65.9 MW hot water demand is generated by the residential sector. A substantial part of the demand is covered by the local District Heating Plant (installed thermal power 360.5 MW); the contracted thermal power was 320.7 MW, of which 186.2 MW for the residential sector. Accordingly, the demand coverage factor is 26.0% for all sectors, and 36.2% for the residential sector. The remaining heating demand is covered by individual boilers supplied mostly with coal and natural gas, other fuels (oil, wood, biomass pellets), and electricity (heat pumps and direct electric heating). Detailed statistics for the city of Gliwice are not available.

2.2 Industries selected for waste heat recovery

Following a recommendation by the local DH plant and network operator, two industrial objects for waste heat recovery have been identified:

1. Company #1 producing spark plugs for engines. Waste heat thermal power: 9.0 MW.
2. Company #2 (planned, industrial automatics). The company is planning to install its own gas engine generator unit. The produced heat will not be used by the company and can be treated as waste heat. Waste heat thermal power: 0.9 MW (constant generation with 3 weeks service period).

Both companies declared constant heat generation. Still, some modified profiles have been proposed in section 3.3 as possible realistic scenarios.

3. Methods & Data

3.1 Remarks on input data quality

Industrial data concerning various energy quantities (power production, demand), process parameters (temperature, pressure) can be available in an extremely wide range of quality, spatial and temporal resolution. The previously published data classification [9] into 3 quality classes, can be extended as follows:

- Class 1A: High-frequency data available in short, equal time steps, e.g., 8760 hours/year
- Class 1B: High-frequency data available in irregular or quasi-regular time steps, e.g.

04/12/2022 10:48:03	1198.72 kW
04/12/2022 10:52:13	1211.09 kW
04/12/2022 11:12:07	1007.38 kW

- Class 2: Low-frequency data available in longer times steps:

2a: once per day (daily sum or average)
2b: once per month (monthly sum or average)

- Class 3: Nominal data without any temporal distribution.

Class 1 data allows one to precisely identify the profile of the given process along the time axis. In sub-case 1A this profile is obtained directly, in sub-case 1B it requires additional data processing. For both classes, it is possible to identify the maximum and average values of the given variable. Class 2 data provides a very raw estimation of the temporal profile, and it fails to identify maximum values. Class 3, in contrast, can sometimes provide some information on maximum values based on the nominal data, e.g., knowing the nominal power of a boiler and its technical specification it is possible to identify the maximum power.

Data used for this work have been classified as Class 1B (heat demand) and Class 3 (waste thermal power). Details on data processing are given in the subsequent sections 3.3.

3.2 Geographic position of industrial objects vs plan of the residential area

Close to the industry waste heat sources: WH#1 and WH#2, there is a residential area comprising 38 multifamily apartment buildings (Figure 1).

Figure 1: Location of waste heat sources WH#1, WH#2 and the residential area.

The waste heat emitter #1 (9 MW, existing) is located about 2.2 km from the residential area, while the smaller emitter #2 (0.9 MW, planned) is located in between. This provides an opportunity to build an integrated connection pipeline.

The existing local district heating network inside the residential area is supplied from the Gliwice DH Plant by 2x DN200 main pipelines and is composed of around 3250 m distribution pipelines.

3.3 Thermal load of adjacent heating nodes (measurement data, weather data)

To evaluate the possibility of covering the local heat demand by the identified waste heat, it is first necessary to calculate the existing demand and its variation in time. This step requires the processing of measurement data available in the heating nodes of the residential buildings.

Based on the type of this data, the residential buildings have been classified in two main groups:

- A - separate measurement of heat demand for space heating ($\dot{Q}_{sh}$) and domestic hot water ($\dot{Q}_{dhw}$) *
- B - combined measurement of heat demand for space heating ($\dot{Q}_{sh}$) and domestic hot water ($\dot{Q}_{dhw}$)

* Due to the low resolution of the meter recording heat demand for domestic hot water purposes, it was impossible to create hourly profiles of $\dot{Q}_{dhw}$. The demand was estimated based on Eq. (1), [10].

$$\dot{Q}_{dhw} = \frac{1}{3600}\dot{m}_{dhw} N c_p \Delta t_{dhw} \tag{1}$$

where: $\dot{m}_{dhw}$- average hourly demand for domestic hot water per person, 1.7 kg/h [11],
N- number of people using the same heat node (assumed 3·number of apartments),

c_p - specific heat, 4.19 kg/(kJ K), Δt_{dhw} - temperature difference of hot and cold water, 30 K.

Next, the buildings were also classified into 4 categories depending on the quality of the registered data:

- TYPE 1: high resolution, complete data record during all year,
- TYPE 2: high resolution, incomplete data record - no measurements at the beginning/ in the middle/in the end of the recorded period,
- TYPE 3: low resolution of register data - unable to calculate hourly heat demand,
- TYPE 4: complete lack of data.

The division of buildings by measurement data type is presented in Fig.2.

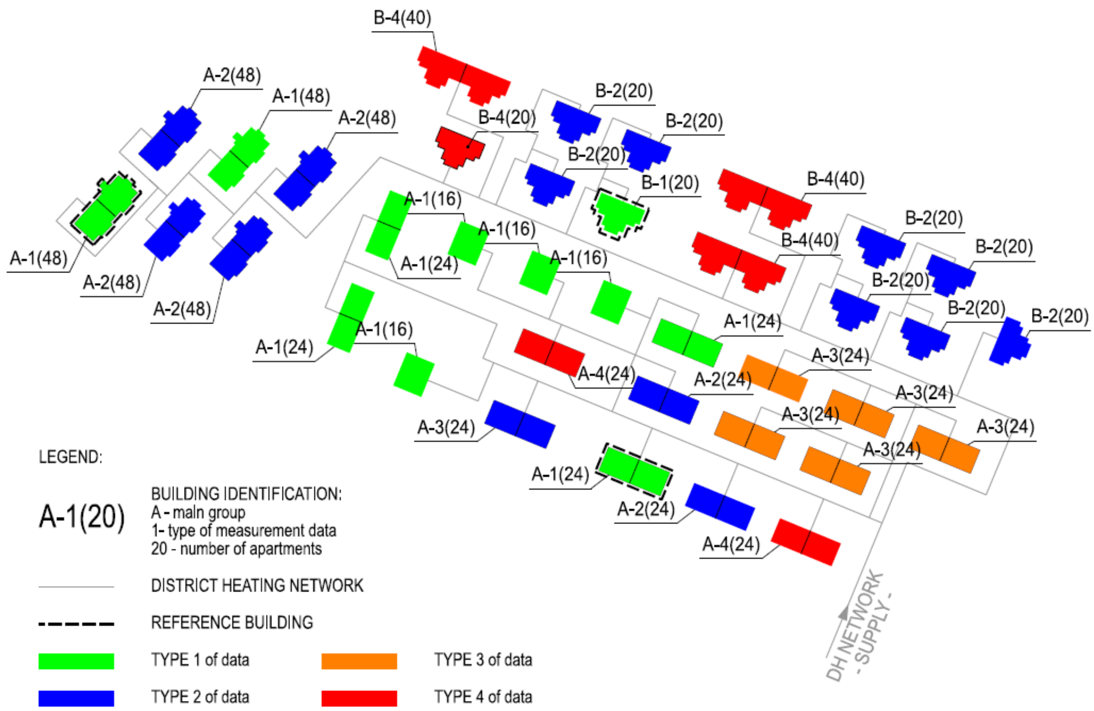

Figure 2: Classification of buildings based on the type/quality of registration data

Raw measurement data was available in an extremely disorganized format, with data spread over multiple worksheets (738 files for 38 buildings), which required collection and ordering by time using a dedicated VBA macro. Following the initial data processing step, the obtained format for the source measurement data type 1 is shown in Table 1.

Table 1: Example of registration data format type A-1

Data, hour	Counter registration: Energy, GJ
01.01.2021 00:00	529.93
01.01.2021 00:02	529.94
...	...
01.01.2021 23:11	530.29
...	...

The measurement data were registered in irregular intervals and included lots of gaps. Therefore, the data was regularized through another VBA macro, performing the following functions:

1. Calculating the hourly-average demand if the resolution is higher than 1/hour.
2. Completing the missing (blank) data based on values available for other objects:

Incorrect data adjustment, e.g., negative heat gain, erroneous number, counter reset etc.

The completion of data (point 2) was done differently for two cases:

a. Building data type, A-2 or B-2: missing data for some periods. In this case it is possible to copy data from reference buildings (type A-1 or B-1) correcting the profile by the factor determined from the period registered both for the studied and the reference building, Eq. (2):

$$\bigwedge_{i:\left(\dot{Q}_{sh,A-2}\right)_i^{OLD}=0} \left(\dot{Q}_{sh,A-2}\right)_i^{NEW} = \left(\dot{Q}_{sh}\right)_{i,REF} \cdot \frac{\sum_{i:\,\dot{Q}_{sh,i}\neq 0} \dot{Q}_{sh,i}}{\sum_{i:\,\dot{Q}_{sh,i}\neq 0} \left(\dot{Q}_{sh}\right)_{i,REF}} \quad (2)$$

where: $\left(\dot{Q}_{sh,A-2}\right)^{OLD}$ - registered demand for space heating for buildings type A-2, MW, $\left(\dot{Q}_{sh,A-2}\right)^{NEW}$ - revised demand for space heating for buildings type A-2, MW, $\left(\dot{Q}_{sh}\right)_{REF}$- demand for space heating for reference buildings, MW

A similar operation has been performed for buildings type B-2. In this case the demand for domestic hot water has also been included. The reference buildings are indicated in the map (Fig. 2).

b. Building data type, A-3, B-3, A-4 and B-4: the existing data is not provided or not sufficient. In this case, the data is directly copied from the reference building with the factor 1, since the reference building has the same number of apartments.

The example of revised data is presented in
Fig. 3.

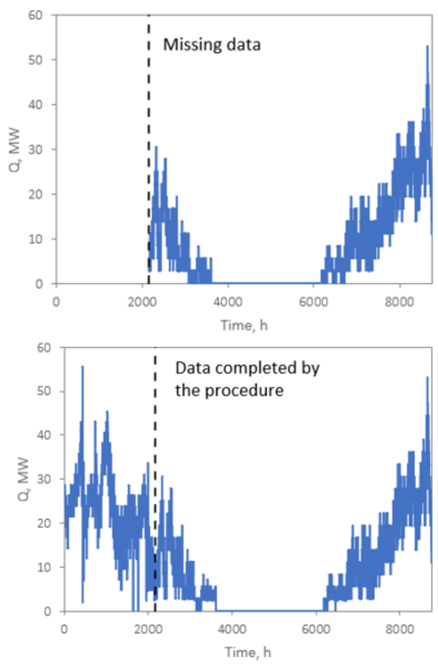

Figure 3: Example of the data completion procedure.

Once the registration data for all buildings have been completed, the total heat demand of the residential area has been calculated as a sum of all completed and corrected data for individual buildings, with a resolution of 8760 hours per year, Eq. (3):

$$Q_{sh+dhw} = \sum_{j=1}^{38}\left(\sum_{i=1}^{8760}(\dot{Q}_{sh,i} + \dot{Q}_{dhw,i})\Delta\tau\right)_j = 19\,800\text{ GJ} \quad (3)$$

where: $\dot{Q}_{sh}$ - heating demand for space heating, GW, $\dot{Q}_{dhw}$ - heating demand for preparing domestic hot water, GW, Q_{sh+dhw} - total heat demand for residential area, GJ, $\Delta\tau$ - time interval, 3600 s

3.4 Waste heat generation

Based on the information provided by companies #1 and #2 the total waste heat thermal power equals 9+0,9=9,9 MW at constant rate. Due to the poor quality of input data on waste heat generation, several possible scenarios were introduced to make the assumptions more realistic. These scenarios are presented in Fig. 4 (red line).

The scenarios have been built by introducing a time scaling function y(t), defined as follows:

- Scenario a, Eq.(4):

$$y(t) = 1 = const. \quad (4)$$

- Scenario b, Eq.(5):

$$y(t) = \begin{cases} 1 & \text{for time } 6:00 - 22:00 \\ 0 & \text{elsewhere} \end{cases} \quad (5)$$

- Scenario c, Eq.(6):

$$y(t) = \begin{cases} 0 & \text{for 168 h per year} \\ 1 & \text{elsewhere} \end{cases} \quad (6)$$

Following 3 scenarios were based on the genuine annual engine operation on the gas compressor station. The running period of the engine equal 1800 h was selected and re-scaled for the all year round, as presented in the Fig. 4.

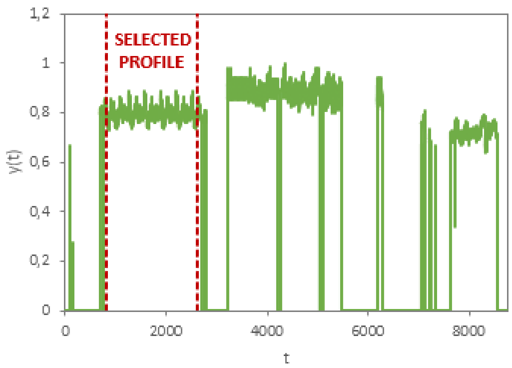

Figure 4: Genuine engine work converted to a simplified profile.

- Scenario a, Eq. (7):

$$y(t) = \frac{\dot{Q}_{reg}}{\dot{Q}_{reg,\max}} \text{ where } \dot{Q}_{reg,\max} = 337 \text{ kW} \tag{7}$$

- Scenario b, Eq. (8):

$$y(t) = \begin{cases} \dfrac{\dot{Q}_{reg}}{\dot{Q}_{reg,\max}} & \text{for time } 6:00 - 22:00 \\ 0 & \text{elsewhere} \end{cases} \tag{8}$$

- Scenario c, Eq. (9):

$$y(t) = \begin{cases} 0 & \text{for 168 h per year} \\ \dfrac{\dot{Q}_{reg}}{\dot{Q}_{reg,\max}} & \text{elsewhere} \end{cases} \tag{9}$$

The following indicators have been defined for the purposes of assessing the efficiency of waste heat utilization:

- Waste heat recovery factor f_{WHR}, Eq. (10):

$$f_{WHR} = \frac{\sum_{i=1}^{8760}\left(\dot{Q}_{received}\right)_i}{\sum_{i=1}^{8760}\left(\dot{Q}_{wh}\right)_i} \cdot 100\% \tag{10}$$

- Demand coverage factor f_{DC}, Eq. (11):

$$f_{DC} = \frac{\sum_{i=1}^{8760}\left(\dot{Q}_{received}\right)_i}{\sum_{i=1}^{8760}\left(\dot{Q}_{sh+dhw}\right)_i} \cdot 100\% \tag{11}$$

where: $\dot{Q}_{wh}$ - waste heat generation depending on the production profile, MW, $\dot{Q}_{sh+dhw}$- total heat demand for residential area, MW, $\dot{Q}_{received}$ - received waste heat depending on the waste heat production profile, defined by the technical possibility of heat exchange between the waste heat and the consumer demand, i.e., is directly defined by the lower of two values, Eq. (12), MW

$$\left(\dot{Q}_{received}\right)_i = \min\left(\left(\dot{Q}_{wh}\right)_i ; \left(\dot{Q}_{sh+dhw}\right)_i\right) \tag{12}$$

Eqs. 10 and 11 do not contain the time interval $\Delta\tau$ which simplifies dividing.

System energy effects were calculated for the local residential area based on the received heat calculated from Eq.12 and, additionally, also for the total waste heat generation assuming that it can entirely be integrated into the district heating network of Gliwice.

Fossil fuel savings were determined based on the quantity of waste heat and the average efficiency of the current district heating plant fueled with hard coal. They can be expressed as chemical energy savings:

$$E_{ch} = \frac{Q}{\eta} \quad (13)$$

The efficiency of heat generation in district heating plant was assumed to be 85%.

And then converted into the mass of fuel saved based on the LHV:

$$p = \frac{Q}{LHV} \quad (14)$$

The LHV of coal was assumed to be 20.4 MJ/kg

Finally, avoided CO_2 emission was determined:

$$m_{CO_2} = Q \cdot WE_{CO_2} \quad (15)$$

The emission factor WE_{CO2} was equal 94.81 kg CO_2/GJ (KOBIZE report for Poland).

Eqs. 13-15 contain the general term 'waste heat' Q which can refer to the locally received heat or to the total waste heat generation (see table 2 for results).

4. Results

The generated profiles of waste heat thermal power and the calculated profile for the total heat demand of the residential area are presented in Fig. 6.

Table 2 presents synthetic results of the waste heat recovery, balancing the waste heat available (using 6 availability patterns) and the estimated local heat demand of the residential area.

It can be seen that the majority of waste heat is still free for utilization, and it can be supplied to other consumers, in particular to the main urban district heating pipeline. On the demand side, the coverage of the local demand is either complete (100%), or close to this factor.

As it can be seen in Fig. 6, in the basic scenario (a) the generated constant flux is always higher than the local area heat demand. It is also the case for the fluctuating operating mode (d). If the source of waste heat is subject to a daily shift schedule or to a seasonal maintenance, then the demand coverage is not complete, and some back-up heat supply is required.

Table 2: Synthetic results of the waste heat recovery and the demand coverage for the local case study in Gliwice, Poland. Maximum waste thermal power: 9.9 MW

	Waste heat		Local area indicators		Fossil fuel savings		Avoided CO_2	
Type of heat source profile	Total generation $\dot{Q}_{wh}$	Local area reception $\dot{Q}_{received}$	Waste heat recovery factor f_{WHR}	Demand coverage factor f_{DC}	Total	Local	Total	Local
	GJ		-		Mg of coal		-	
A	**312 206**	**19 795**	6.34%	**100%**	**17 164**	**1 088**	**13.0%**	**0.83%**
B	294 244	19 460	6.48%	72%	16 176	1 070	12.3%	0.81%
C	155 135	14 335	6.61%	98%	8 529	788	6.5%	0.60%
D	248 925	**19 795**	7.95%	**100%**	13 685	**1 088**	10.4%	**0.83%**
E	234 593	19 460	8.13%	72%	12 897	1 070	9.8%	0.81%
F	176 272	14 338	**8.30%**	98%	9 691	788	7.4%	0.60%

5. Summary/Conclusions

Based on the presented results, it can be concluded that waste heat can play a significant role in covering local heat demands. In the studied case, two industrial entities generate much more heat that can be consumed in a local residential district. Although the generated waste heat is sufficient to entirely cover the local heat demand, it is still recommended to provide a back-up source of heat for possible periods of maintenance.

The management of heat production and demand is complex, and in the studied case, the complexity is entirely related to the demand side. While the waste heat generation is constant (or declared constant), the demand suffers from strong seasonal and daily variations.

Moreover, the quality of metering data is mostly insufficient. Only a few buildings are equipped with full, real-time registration of heat demand, which can help to design a control system for waste heat integration in the heating nodes. The remaining houses either have a low resolution of measurements (0.01 GJ is needed for real-time management), or they lack the registration of domestic hot water demand, or they have incomplete data with blank periods, or they do not have any local registration at all.

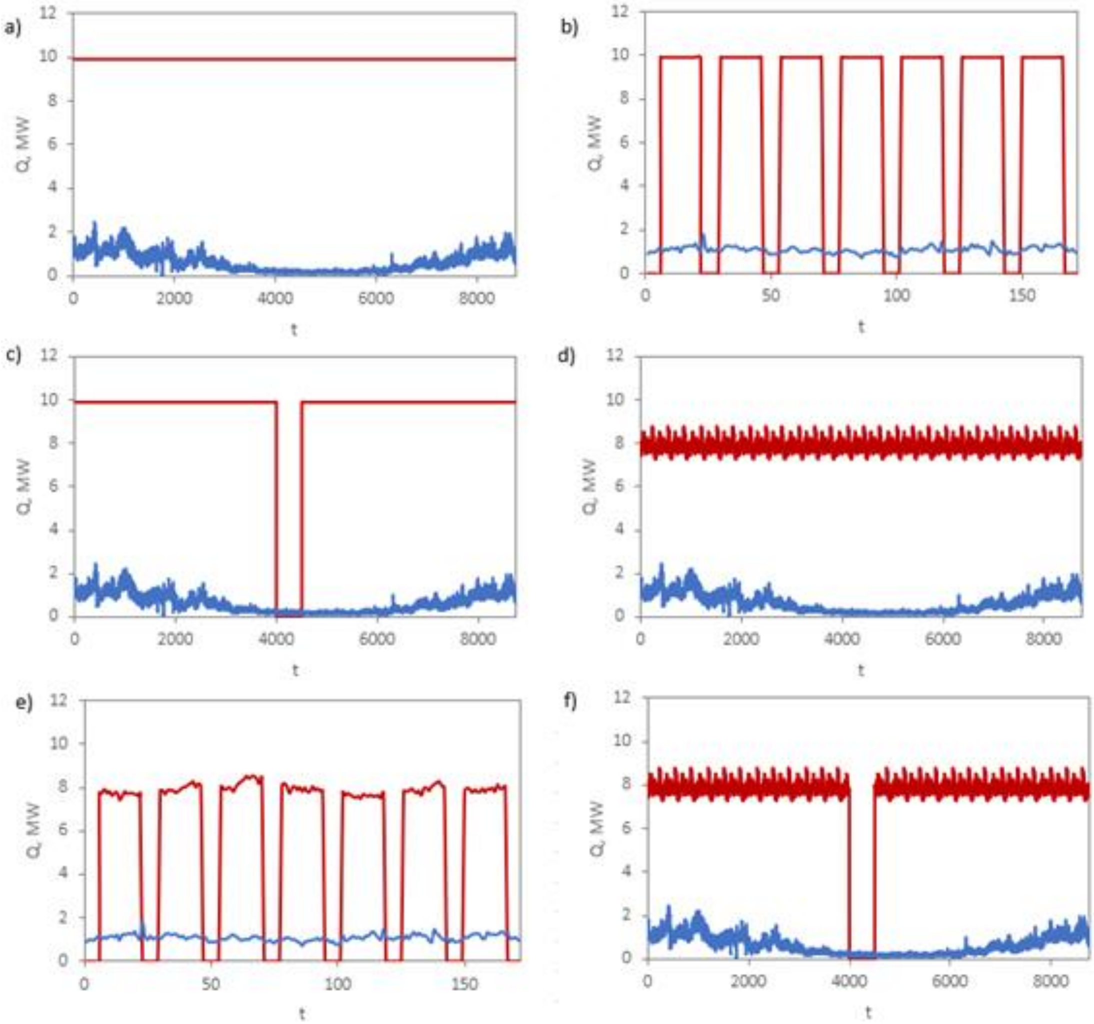

Figure 6: Comparison of the waste heat generation (red line) and the local area demand profiles (blue line). Chosen profiles of waste heat generation: a) constant work b) shift work c) constant work with 7 days maintenance d) simplified engine work e) simplified engine shift work f) simplified engine work with 7 days maintenance

Accordingly, the transition to the 4-5 generation of district heating systems must be related with an improved metering, which receives new function: not only long-time registration and billing, but also real-time data acquisition and system management.

The presented study demonstrates the potential of waste heat in a local environment. It can be seen that one major industrial emitter can entirely cover the heating demand of a local residential area and it can also substantially contribute to heat production in a large-scale district heating plant facilitating its decarbonization.

The studied case represents the first step of work related to the waste heat integration into the local heating systems based on the energy balance. Further work is needed to design the required connection pipelines, to verify the technical availability of heat transfer accounting for temperature levels, and to consider optional profile equalization using a local heat storage unit.

Acknowledgements

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