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Residential Heat Supply by Waste-Heat Re-Use: Sources, Supply Potential and Demand Coverage—A Case Study

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Abstract: This paper deals with climate change mitigation and addresses waste heat reuse as a measure which is until now considered only to a limited extent. The City of Vienna serves as a case study to explore potentials to improve the urban heat supply using waste heat as an additional energy source. As no observation data about waste heat and detailed heating demand is available, this data is derived from proxy data for estimating waste heat reuse potential and residential heating demand patterns. Heat requirements for manufacturing and service provision is explored and, based on the distribution of the companies within the city, mapped as waste heat sources. Employees per company serves as proxy data to allocate the heat volume. Waste heat share and temperature ranges is reviewed from literature. Heating demand is mapped based on floor space of the buildings by age class and building type. Merging supply and demand maps allows to quantify the residential heating demand coverage through local waste heat in the potential supply areas within different distance ranges and housing density classes. In high density housing areas, only a small share of the demand can be covered by waste heat supply even within 250 m distance from sources due to few companies which could provide waste heat. In medium to low density housing areas in Vienna's outer districts with more industry, a higher share of residential heating demand near the sources can be covered by waste heat within a 250 m distance. Within a 500 m distance, around half of the residential heating demand can be covered only in low density housing areas near the waste heat sources.

Keywords: sustainable cities; renewable energy sources; waste heat use; waste heat distribution; heating demand distribution; heat supply-demand mapping

1. Introduction

Climate change is triggered through accelerated greenhouse gas (GHG) emission into the atmosphere. Reducing GHG requires a change of energy consumption and supply towards alternative energy carriers, moving from fossil fuel supplies to renewable energy sources [1]. Heating and cooling accounts for 50% of the EU's energy consumption and the total urban consumption is expected to grow due to growing urbanization Renewables account for just 18% of this. While urban manufacturing is causing heat emission, neighbouring housing areas require energy for heating and cooling [2–4]. Cascading energy use by re-use of industrial and commercial waste heat is an effective option to reduce GHG emissions in urban environments. There exist various demonstration projects on urban district heating system improvement, as shown by the EU-FP7 project CELSIUS where the Consortium Cities are deploying 12 technically and economically innovative demonstrations [5] or by UNEP's District Energy Report describing a collection of 45 case studies [6]. However, they usually deal with single demonstration projects like waste incineration, sewage waste heat recovery, combined heat and power (CHP)-plants or similar, but do not deal with distributed industrial and commercial waste heat use in an entire city.

This article examines the entire commercial waste heat potential for the City of Vienna. Like in most cities, Vienna's waste heat potential is unknown, as data on waste heat volume and distribution are not collected. Thus, a method has been developed for identifying sources and allocating waste heat volumes from the specific industrial and commercial enterprises for an entire city. The article does not address technological aspects of waste-heat recovery but concentrates on exploring the waste heat distribution with respect to sources and volumes as well on waste heat utilization to cover residential heat demand in the neighbourhood of sources, avoiding large district heating network extensions by matching sources with potential customer locations (nearby housing areas, new developments).

1.1. Determination of Potential Sources for Waste Heat Recovery

Waste heat is heat generated in processes by way of fuel combustion or chemical reactions that is emitted to the environment. Waste heat sources can be production machines or plants, hot air appliances and furnaces for drying, wastewater from cleaning, washing, dyeing or cooling processes, but also cooling systems, motors or the heated exhaust air arising in production halls and office areas [7].

Process heat is required in very different production processes in industry as well as in trade and storage, e.g., for the production of steam or hot gas/hot air for drying processes, for washing or electroplating, for evaporation or for distillation. Further applications are the provision of hot air or hot water, for heating feed materials, for thermal separation processes or pasteurization. Other important sources are found in cleaning processes that occur during the production process: for example, cleaning bottles and other containers before filling beverages and food, as well as cleaning and steam sterilization in biotechnological production plants or breweries. In cooling processes, waste heat is a cooling load. Significant sources are data centers, as well as cooling houses and ice factories requiring heat for cooling. [7].

Only a few robust studies and references (e.g., [7–10]) are available that have reviewed waste heat potentials in industry. Because of target group-related and technological obstacles, potentials are currently only used to a small extent. Issues include structural, financial, information-related, legal and operational, in particular logistical obstacles (e.g., the spatial and temporal consistency of heat supply and demand). Particular concerns have also been raised regarding production safety as well as amortization expectations. On the other hand, energy prices, a stronger penetration of energy management systems, but also an image gain and a personal commitment from management and energy representatives are encouraging.

1.2. Heat-Requiring Processes and Temperature Levels

Waste heat can only be utilized if surplus heat can be provided. The different temperature levels have to be considered (see Figure 1) as they require different treatments to extract waste heat.

In the various production processes heat demand of the different industries lies between 60 °C (cleaning processes) and over 1000 °C (products of the basic material industry such as iron and steel, cement, glass and ceramics). Chemical industries require temperatures between 100 °C and 500 °C (in some cases up to 1000 °C). In contrast, the consumer goods industry (e.g., textiles, pharmaceuticals, food) as well as the capital goods sector (e.g., automotive and mechanical engineering, electrical engineering) typically require room temperature and low temperature heat for washing and drying processes from 40 to 90 °C (an exception is surface treatment of metals requiring 180 °C for powder coating). Cleaning or sterilization according to production processes requires 121 to 134 °C at least once a week (information on all processes addressed above are compiled from [7]).

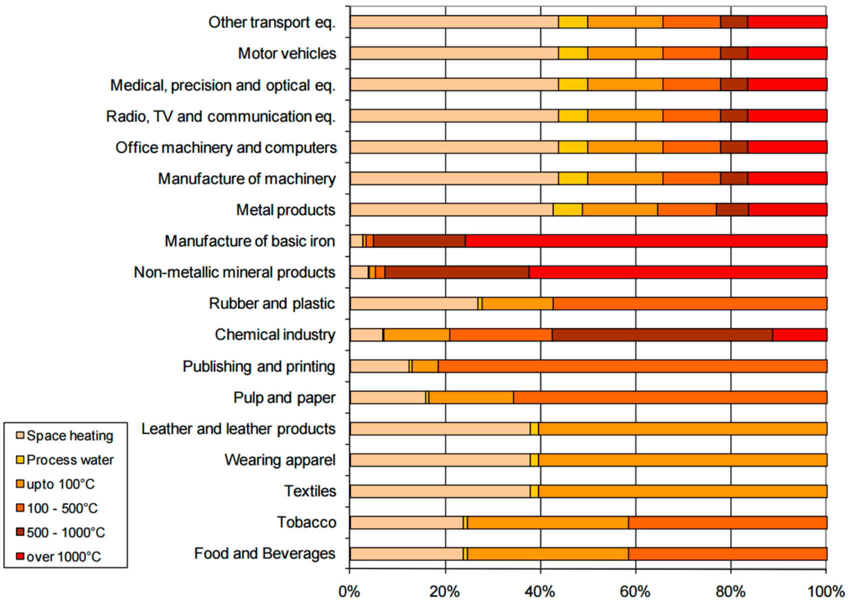

Figure 1. Heat demand by temperature level and industrial industry in Germany (numbers from 2001, provided by [8]).

This temperature distribution provides information about the temperature level of the resulting waste heat as well as the possible in-house application possibilities. The appropriate waste heat recovery technology must be selected from a cost perspective. Four types of waste heat utilization can be identified [11–13]:

- process-internal heat recovery: waste heat used in the various processes,
- in-house use: waste heat can be used in other processes, for heating, etc.,
- in-house conversion: waste heat converted into cold or electricity,
- external use: waste heat fed into nearby companies, households' heating systems or district heating networks.

High-grade thermal energy emissions are typically caused by processes that are usually not located within urban areas: e.g., iron and steel- or cement-production. However, lower-grade heat emissions in urban areas can be frequently found in production processes as well as in cooling processes (see [13]). Such lower temperature waste heat sources may serve as heat supply for heating purposes in urban environments by feeding it into municipal district heating networks or by utilize waste heat locally by installing micro-grids linked to adjacent building blocks.

2. Materials and Methods

2.1. Test Case Vienna—Overview

The City of Vienna serves as case study to identify the waste heat use potential. Vienna has about 1.8 M inhabitants living in 182,000 buildings, occupying around 1 M flats. Since the year 2000, the total population has risen by around 200,000 people. Currently it is estimated that the city will grow yearly by 30,000 inhabitants. In Vienna, around 630,000 employees are working in 92,000 companies. According to the urban development plan 2025 the target to provide 120,000 flats until 2025 should be achieved [14].

The gross domestic energy consumption in Vienna amounts to 43,073 GWh. According to the energy balance, the final energy consumption is 39,092 GWh, which is made up more than one-third by oil, followed by electric energy with 21% and by district heating with 17%. The highest end energy consumption is the transport sector with 36%, followed by households with 24%, public and private service providers with 24% and the manufacturing sector with 8% (data from 2013 [15]). Vienna can supply around 12% of the energy demand from local sources, while 88% is based on imports. The total heating consumption in Vienna is 19,949 GWh (data from 2013 [15]). 40.8% is covered with gas boilers, followed by district heating with 32.9%, electrical heating with 17.4%, oil with 3.3%, biological materials with 2.5%, firewood with 2%, ambient heat with 0.9% and coal with 0.2%. Room heating is with 73.9% the biggest consumer, followed by cooking and hot water with 19.9%, steam with 3.5% and industrial ovens with 2.7%. Assessing only the room heating energy (14,736 GWh), gas (41.5%) and district heating (39.8%) provide more than 80% of Vienna's room heating energy consumption [15].

Heat distributed through the Vienna district heating network (length: 1200 km) is provided by several heating plants. The two largest ones are fueled by waste incineration supported by gas, others by gas and one by wood-chips. All use CHP technology for producing power as well as heat, which is a disadvantage in the summer season, when only little heat is required. The system has been established decades ago so the system is to some extent outdated, working with high temperatures ranging between 90 and 160 °C. Besides heat, Vienna's largest heat provider, "Fernwärme Wien", has so far established 12 district cooling networks in Vienna, however typically there are only specific building types (e.g., hospital campuses, shopping centers) or a few building blocks (offices) connected [16].

As waste heat and heating demand observation data is not available, workarounds must be carried out, using spatially explicit proxy data related to heat consumption and heating demand. Figure 2 depicts the modelling approach.

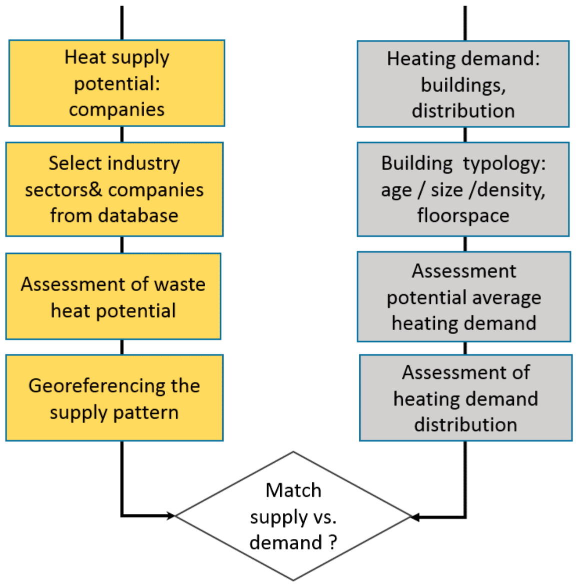

Figure 2. Concept to identify and allocate waste heat potentials, heating demand and related matches [17].

2.2. *Production-Related Heat Requirements and Waste Heat Shares of the Relevant Industries*

The relevant industry sectors have been identified based on a literature review. The required heat volume and temperature ranges to assess the waste heat potential have been extracted for different production processes and services. Table 1 presents the relevant industries, their production processes and temperature ranges.

Table 1. Selected industries as potential heat sources by process and temperature range (own compilation, data extracted from [18,19]).

Business	Process	Temperature [°C]	Business	Process	Temperature [°C]
Food Industry	Drying	30–90	**Chemical Industry**	Cooking	95–105
	Washing	40–80		Distill	110–300
	Pasteurizing	80–110		various chemical processes	120–180
	Cooking	95–105	**Wood Industry**	Drying	50–100
	Sterilizing	140–150		Pressing	125–175
	Heat Treatment	40–60		Steaming	120
	Baking	150–250	**Pulp and Paper Industry**	Cooking	100
Brewery	Cooking	100		Thickening	130
	Sterilizing	120		Drying	100
Textile Industry	Washing	40–80	**Manufacture of motor vehicles**	Drying of paint	200
	Bleeching	60–100	**Manufacture of machinery**	Drying of paint	120
	Coloring	100–160	**Foundry**	Melting	1000–1600
	Drying	100	**Plastics Processing**	Processing of various plastics	100–300

The average heat consumption by an employee is the basis for estimating the overall industrial energy demand and thus the waste heat potential. Table 2 shows the annual heat demand volume in MWh by employee for the relevant industries for low, medium and high temperature. The temperature ranges are important for waste heat recovery and have therefore divided into temperature classes [19]:

- Low temperature (LT) (35–100 °C): is directly usable in low temperature systems (e.g., underfloor heating) or can be raised to higher temperature levels by heat pumps. Waste heat below 35 °C was not considered as a useful source.
- Medium temperature (MT) (100–500 °C): lower ranges can be directly fed into a district heating system higher ones can be used for conversion into electrical energy.
- High temperature (HT) (>500 °C) can be directly used for conversion into electrical energy or must be cooled for feeding into a heating network.

As no empirical data on waste heat shares are available in Vienna, numbers have been extracted from literature, which show a broad range of results. Table 3 gives an overview of the waste heat shares by industry sector. Bold letters mark the finally applied value "share used".

All numbers must be considered to be rather vague: processing temperature does not always correspond to waste heat temperature, and number of working hours and thus heat availability varies between industrial sectors and companies.

Table 2. Heat demand by employee for relevant industries by company size classes (N of employees (EMP)), (own compilation, data extracted from [10]).

	Low-Temp. Process Heat	**Medium-Temp. Process Heat**	**High-Temp. Process Heat**
	<100 °C	100–500 °C	>500 °C
	MWh_{th}/(EMP * a)	MWh_{th}/(EMP * a)	MWh_{th}/(EMP * a)
Bakery			
up to 10 EMP	0.31	5	0
up to 100 EMP	0.48	8.33	0
up to 200 EMP *	0.76	13.24	0
up to 300 EMP *	1.05	18.16	0
up to 400 EMP *	1.33	23.07	0
more than 500 EMP	1.9	32.9	0
Brewery			
up to 10 EMP	51	12	0
up to 100 EMP	79.1	19.4	0
up to 200 EMP *	91.95	22.5	0
more than 500 EMP	104.8	25.6	0
Chemical Factory			
up to 50 EMP	31	48	0
up to 1000 EMP	48	127	0
more than 1000 EMP	31	48	127
Printing House			
up to 10 EMP	0	0	0
up to 100 EMP	0	34.5	0
up to 200 EMP *	0	38.6	0
up to 300 EMP *	0	39	0
more than 500 EMP	0	55.2	0

	Low-Temp. Process Heat	**Medium-Temp. Process Heat**	**High-Temp. Process Heat**
	<100 °C	100–500 °C	>500 °C
	MWh_{th}/(EMP * a)	MWh_{th}/(EMP * a)	MWh_{th}/(EMP * a)
Manufacture of Motor Vehicles			
up to 1000 EMP	3	3	5
up to 10,000 EMP	3	3	5
more than 10,000 EMP	3	3	5
Foundry			
up to 25 EMP	0	0	40
up to 100 EMP	0	0	48
more than 500 EMP	0	0	55
Plastics Processing			
up to 10 EMP	0	660	0
up to 100 EMP	0	907	0
more than 100 EMP	0	1081	0
Malthouse			
up to 10 EMP	1030	0	0
up to 100 EMP	1133	0	0
up to 200 EMP *	1184.50	0	0
more than 500 EMP	1236	0	0
Dairy			
up to 10 EMP	41	0	0
up to 100 EMP	50	5	0
up to 200 EMP *	54.7	5.45	0
more than 500 EMP	59.4	5.9	0

* Own calculation, interpolated.

Table 3. Waste heat shares by industry and process (own compilation, data extracted from: [20–25]).

Business	Subcategories	Share Source 1	Share Source 2	Share Used Value	Reference Unit	Source 1	Source 2
Chemistry	-	2%–5%	-	**3.5%**	of total energy consumption	Blesl et al. (2011): [20]	-
Printing	-	15%	-	**15.0%**	of total energy consumption	KPC (2012): [21]	-
Kitchen	-	6%	25%	**15.5%**	of total energy consumption	Waldhoff et al. (2014): [22]	KPC (2012): [21]
Plastics Processing	-	3%	-	**3%**	of total energy consumption	Waldhoff et al. (2014): [22]	-
Paint Shop	-	25%	30%	**27.5%**	of total energy consumption	KPC (2012): [21]	calculated from Emikat and Litzellachner (2009) [25]
Food-Retail	-	-	-	**no appraisal possible**	-	-	-
Food-Bakery	-	44%	-	**44%**	of process heat consumption	Gewerbegas (online)	-
Food-Production	Brewery	6%	25%	**15.5%**	of total energy consumption	Waldhoff et al. (2014): [22]	KPC (2012): [21]
	Butcher	15%–20%	-	**17.5%**	of process heat consumption	Brandstätter (2008): [24]	-
	Malthouse	-	-	**value known**	-	-	-
	Dairy	6%	25%	**15.5%**	of total energy consumption	Waldhoff et al. (2014): [22]	KPC (2012): [21]
Other-Metal	Foundry	25% (iron and steel production)	30% (metal production)	**27.5%**	of total energy consumption	KPC (2012): [21]	Waldhoff et al. (2014): [22]
	Manufacture of fabricated metal products	3%	-	**3%**	of total energy consumption	Waldhoff et al. (2014): [22]	-
	Surface Technology	3%	-	**3%**	of total energy consumption	Waldhoff et al. (2014): [22]	-
Other-Production	Manufacture of machinery	3%	10%	**6.5%**	of total energy consumption	Waldhoff et al. (2014): [22]	KPC (2012): [21]
	Manufacture of vehicles	10%	-	**10%**	of total energy consumption	KPC (2012): [21]	-
Laundry	-	5%	-	**5.0%**	of process heat consumption	Litzellachner (2009): [25]	-

2.3. Residential Heating Energy Demand

Residential heating energy demand depends mostly on the quality of the construction and building architecture, which in turn is influenced by various factors: The building shape and compactness define the volume to surface ratio—a higher surface area generally relates to higher transmission heat losses through the external envelope. Smaller, detached houses are in this context less energy efficient than row houses or larger block of flats with otherwise the same properties. Choices of material, structural build-up as well as air-tightness of the building also significantly affect the transmission, ventilation and infiltration heat losses. According to available statistical data, numbers on building stock characteristics, building type, size and age are the most important attributes to provide rough estimates for the heating energy demand. The building age indicates the building standards in terms of economics, technology and legislation during the time of construction and is thus a crucial indicator for a rough estimation.

Heating demand is calculated from statistical data on housing stock, considering floor space, building age and building type. Statistical entities are 250 × 250 m cells, which provide statistical data in a spatial explicit way. The number of flats by size-class allow estimating the floor space amount in m^2, building numbers by age-class, and by building type allow the definition of heating demand factors for floor-space related to buildings by age and type to estimate and allocate heating demand totals.

Adjusted to Vienna's framework settings, heating demand per m^2 for those building types are taken from the Austrian subset of the European TABULA study [26]. Heating demand/m^2 floor space distinguished by building age- and building size-classes allow an estimation of the heating demand pattern in the entire city.

Figure 3 shows the typical heating demand ranges by age-class for multi-story buildings in Austria and thus Vienna. The annual heating demand is highest for buildings constructed before World War II and until the 1960ies ranging from 150 to 270 kWh/m^2. Low energy buildings erected since 2000 show annual heating demands between 30 and 100 kWh/m^2 [26].

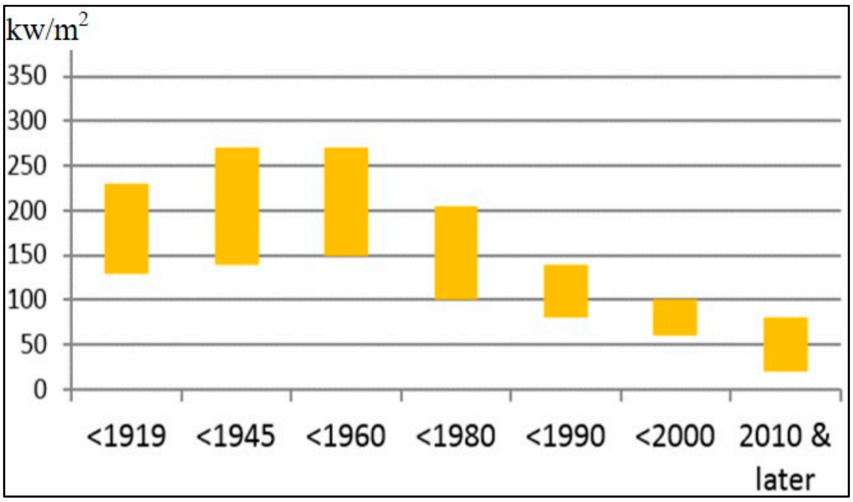

Figure 3. Annual heating demand ranges in kW/m2 of multi-story buildings by age-class in Vienna (own compilation, extracted from [26]).

Comparing the number of buildings by age-class in Vienna shows a high share of buildings with relatively low energy efficiency. According to the Austrian Building Register, Vienna had 182,620 buildings in 2015, where 26% of these were erected between 1919 and 1960 and another 20% between 1961 and 1980, as depicted in the following Figure 4. Since the last years, the number of new buildings is expected to grow faster, so the share of highly efficient buildings will rise.

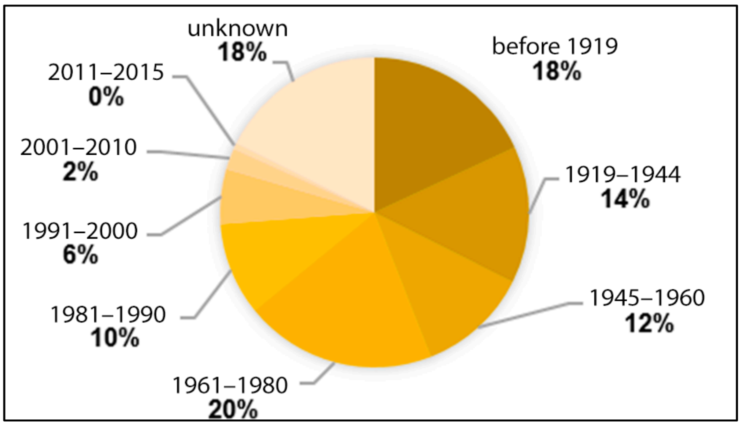

Figure 4. Age-class distribution of all buildings in Vienna (numbers extracted from [17]).

There is no central database available documenting the refurbishment in the individual buildings. Several sources, however, conclude that the refurbishment rate in Austria is currently around 1%. Due to the fragmented data on actual refurbishment measures and achieved reduction of heating energy demand, this factor has been neglected in this study. Since the recast of the Energy Performance of the EU Buildings Directive [27], and the enforced legislation in the member states on provision of energy certificates, in the future, there should be more documented refurbishment actions and subsequent data for heating energy demand via the mandatory energy certificate.

3. Results

3.1. Waste Heat Supply Potential Allocation

To relate the industrial heat consumption to locations, the entire energy consumption by industry sector from Energy Statistics is divided by the employee numbers of the particular sector to get sectoral heat consumption quotas by employee. These allow the sectoral energy demand total to be distributed between the various industry sites of the particular sector in Vienna by using the address and employee numbers of each company. (Only companies with a turnover of two million Euro have been included in the set of potential waste heat sources, assuming that smaller companies do not require a sufficient heat volume for their production activities to be considered as an appropriate waste heat source.)

Data centers have been added as a very relevant heat supply source. The rapid growth of IT applications demand distributed storage and cloud services have resulted in a huge increase in data centers running 24 h a day, 365 days a year. They consume a huge amount of energy, where the majority of the electricity used is converted into heat, which must be cooled to avoid damage to the equipment [28]. The energy requirement for cooling the plants ranges between 30% and 50% of the energy consumption of a data center [29]. Here a large amount of waste heat can be extracted from cooling loads, occurring during the entire year. In case of air-cooled data centers, the waste heat temperature is about 45 °C, in case of water-cooled about 60 °C [28]. As the employee numbers are not an appropriate proxy, the load volumes for each of the data centers have been derived through internet searches to find the size and capacity of the centers (e.g., through floor space).

In total around 108,000 work sites have been screened for Vienna and out of those, approximately 180 work sites have been selected as large potential sources. Various sites have not been considered as waste heat sources due to little expected heat volume (indicated through a turnover of less than two million Euro as mentioned earlier) or short processing time and thus short waste heat availability (which is the case for various production sectors). The following Table 4 shows the total results of the estimated usable waste heat potential in Vienna by industry sector. These numbers, derived by company and aggregated by 250 × 250 m cells (see Figure 5), serve as base for the waste heat potential allocation.

Table 4. Usable waste heat potential from Vienna industries by sectors (own compilation).

Business	Subcategory	Low Temperature (35–100 °C) [GWh]	Medium Temperature (100–500 °C) [GWh]	High Temperature (>500 °C) [GWh]
Chemistry		-	3.7	-
Printing		-	8.2	-
Kitchen		-	57.0	-
Plastics Processing		-	29.0	-
Paint Shop		-	6.7	-
Food-Bakery		0.3	26.5	-
Food-Retail		-	-	-
Food-Production		5.0	6.8	-
	Butcher	-	*6.2*	-
Data Center		383.3	-	-
Other-Metal		-	1.5	2.8
	Manufacture of fabricated metal products	-	*1.3*	-
	Surface Technology	-	*0.2*	-
	Foundry	-	-	*2.8*
Other-Production		10.8	24.8	-
	Manufacture of machinery	-	*4.7*	-
	Manufacture of vehicles	*4.5*	*0.1*	-
Laundry		3.1	-	-
Result		**402.4**	**164.3**	**2.8**

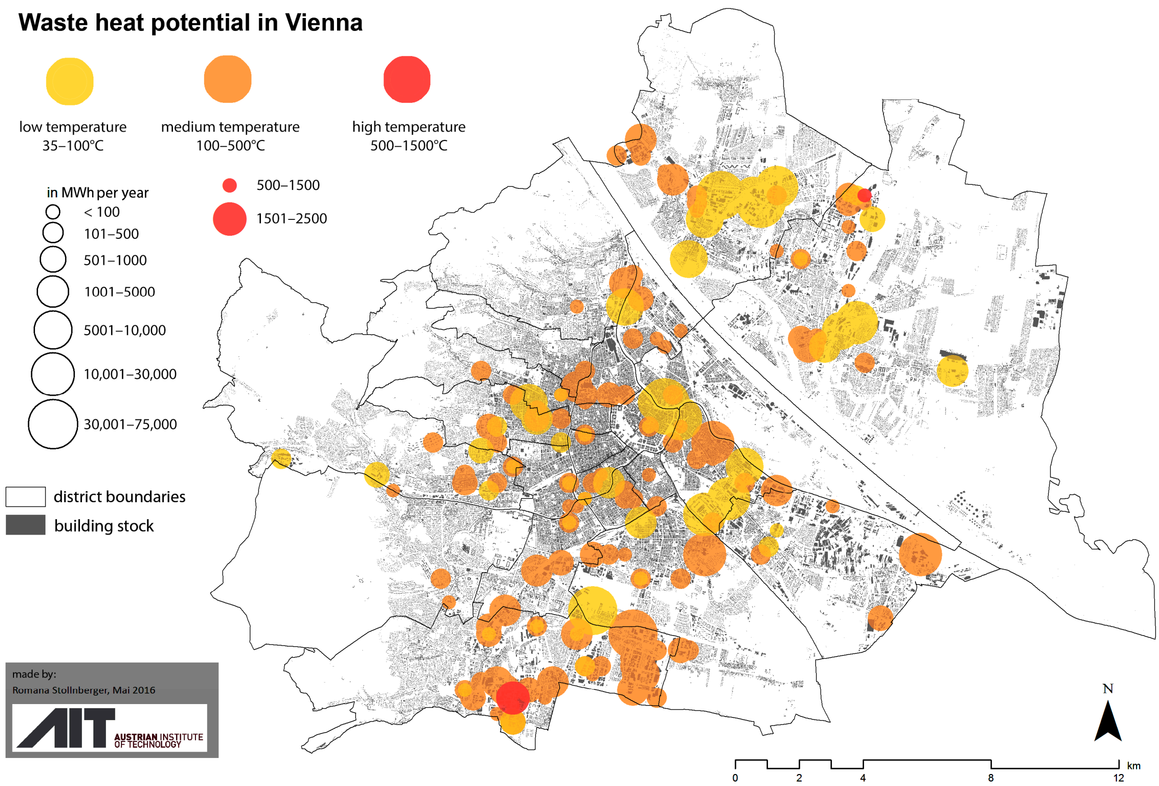

Figure 5. Annual industrial waste heat potential distribution in Vienna from the most relevant sectors [17].

Figure 5 depicts the waste heat potential distribution in Vienna by temperature range, which allows relating the possible waste heat supply to residential heating demand. The big potential waste heat sources are frequently located in the out skirting areas of Vienna where larger industries are concentrated: in the industrial areas Inzersdorf and Atzgersdorf-Liesing in the South and in the industrial areas of Strebersdorf, Floridsdorf and Kagran in the Northeast and East of Vienna. The remaining waste heat sources are distributed throughout the city, which allows connections to a wider range of residential demand areas.

3.2. Residential Heating Demand Distribution

Building type and age-class distribution of the buildings in Vienna result in different heating demand patterns. Figure 6 depicts the residential heat demand pattern of Vienna as respondent area for waste heat use, reflecting the housing density pattern due to the current building distribution. It seems that the housing areas in the inner districts show the highest heat demand, which can be covered by waste heat.

However, deeper insight regarding the building type distribution is required for a final judgment. Figure 7 thus gives an overview of the building types: the areas marked in blue indicate a higher share of single family or small multi-family houses with little heat density, where a district heating connection is less efficient due to high connection costs. The economics of a connection increases with the attainment of a high heat density. Therefore the connection of multi-family houses has a higher economic feasibility (see [30]). All areas in red indicate areas with large (social) housing blocks heated frequently by central heating systems, suitable to be adapted for district heating connection. (A significant share is already connected to the municipal district heating network.) The central areas of Vienna show high building density but they consist largely of late 19th/early 20th century buildings, where the flats are individually heated and a district heating connection would require a complete change of the buildings' heating systems, which would be difficult to substantiate.

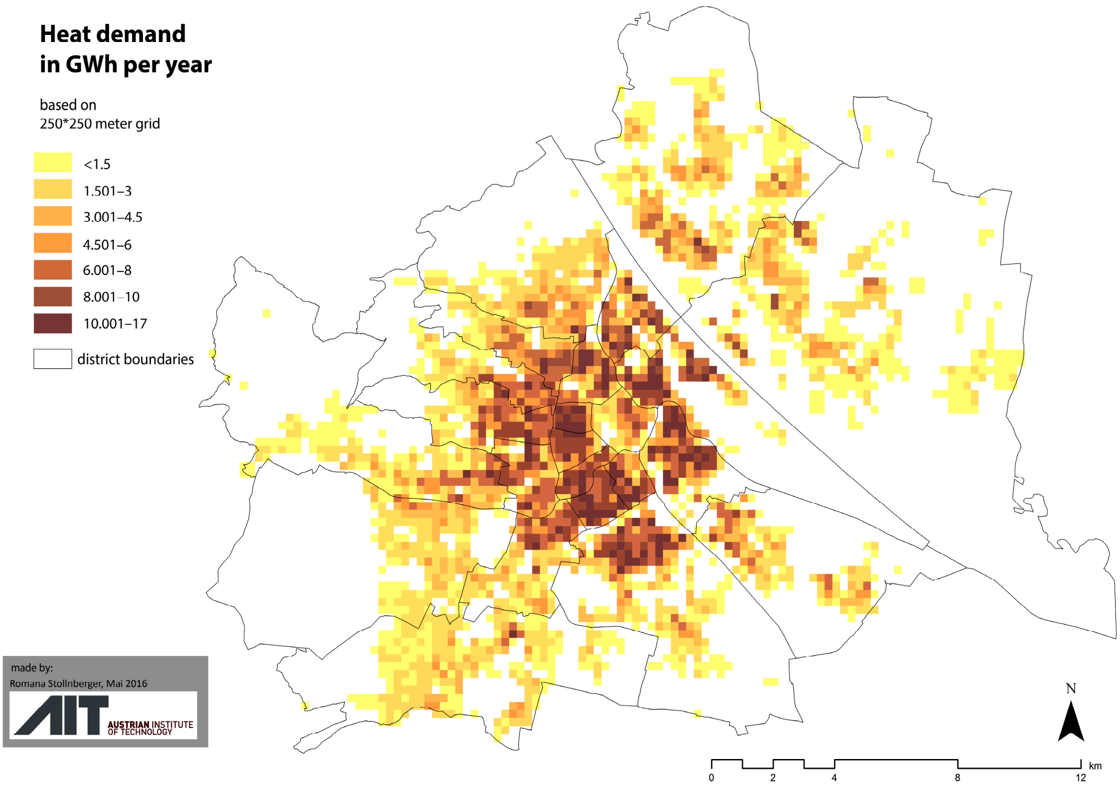

Figure 6. Residential heating demand in Vienna based on building age, type and floor-space related to 250 × 250 m cells [17].

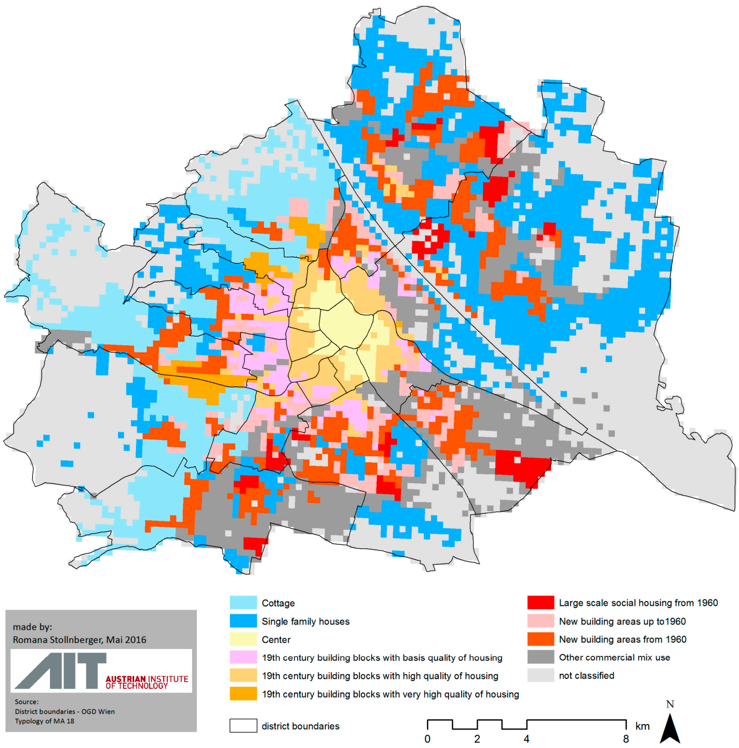

Figure 7. Vienna's building type distribution (own compilation for 250 × 250 m cells, based on [31]).

Besides the already built-up areas, future housing development areas have to be identified to consider future target areas for potential waste heat use; the map in Figure 8 shows those areas with the number of apartments, indicating an increasing heating demand in specific locations.

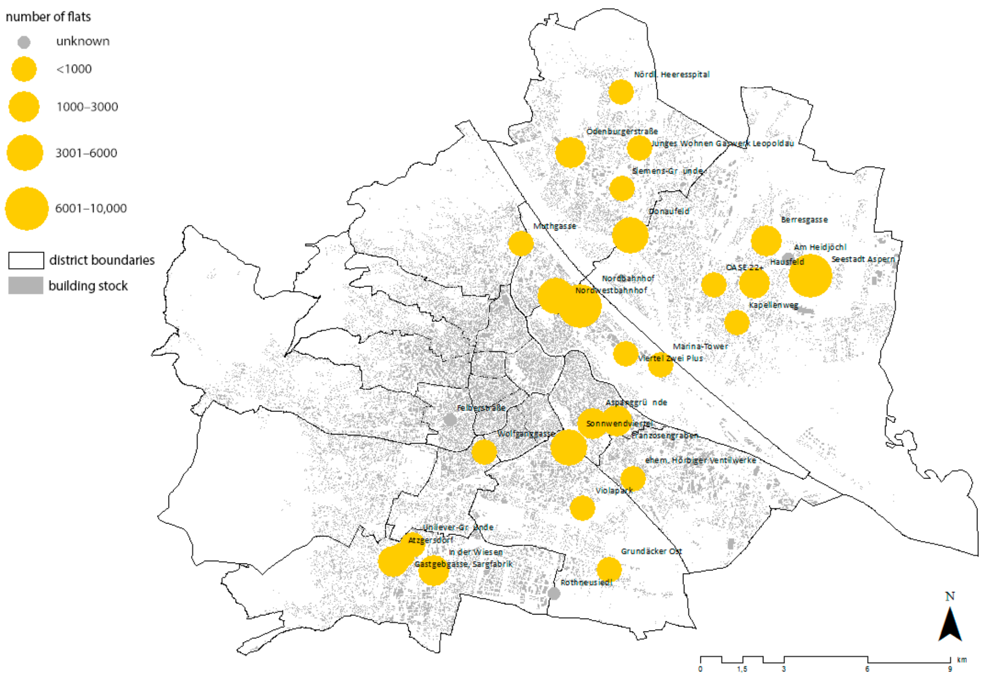

Figure 8. Future urban development sites (compiled from various Vienna Urban Development Strategy documents and press releases on housing development [17]).

3.3. Waste Heat Supply Matching the Demand

According to information from “Fernwärme Wien”, Vienna’s municipal district heating network provider, one meter of district heating pipeline costs up to 1500 EUR. Vienna’s district heating system works with 90 °C or even higher temperature, which does frequently not match with the temperature ranges provide by the waste heat sources. Thus, industrial waste heat was decided to be used through local micro grids, as connection costs to Vienna’s large district heating network would be too high for small heat quantities, while the temperature from the waste heat sources would be frequently too low.

The supply area to be connected with potential demand areas has been examined for two distance ranges: 250 m and 500 m. Figure 9 matches potential waste heat sources with residential heating demand within a 500 m distance around the waste heat sources. The supply areas in the Vienna outskirts which show a surplus against the potential heating demand in the neighbourhood of commercial/industrial sites are marked in green. In the densely built-up inner districts the waste heat supply rate would be comparatively low due to less waste heat volume and higher heating demand (marked in red and orange).

Figure 10 shows supply ranges of 250 m around potential waste heat sources. Within this 250 m supply distance, the locally available waste heat volume could cover the demand of some inner city areas to a higher extent; more supply areas are shown in orange and yellow. On the other hand, some potential waste heat supply areas in the outer districts no longer appear, as no or only little demand is located within the potential supply range. Areas with too little demand to be covered by a potential heat source are low density housing areas: single-family neighbourhoods or few larger housing blocks with no expectation regarding upcoming densification. Using all waste heat would require longer network sections to reach more customers, which would result in in higher connection costs per building. Here the economic feasibility has to be analyzed in detail for selected areas.

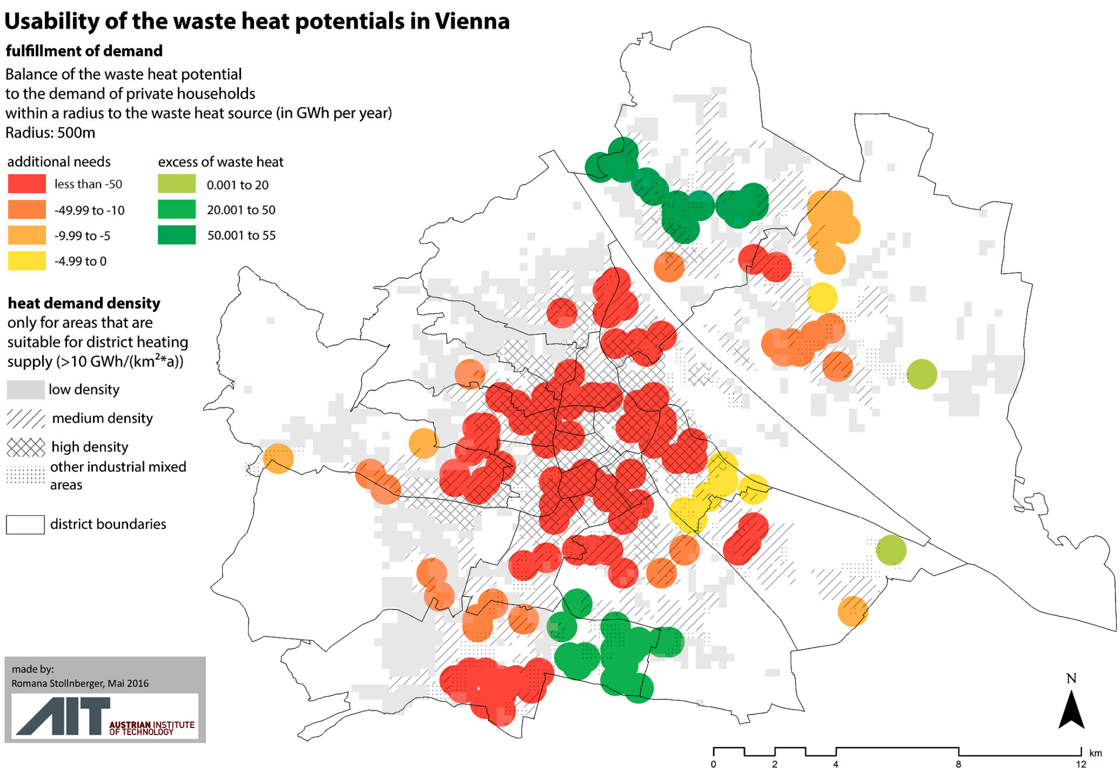

Figure 9. Waste heat supply from commercial sources in Vienna matching the residential heating demand in the neighbourhood (500 m buffers around source areas [17]).

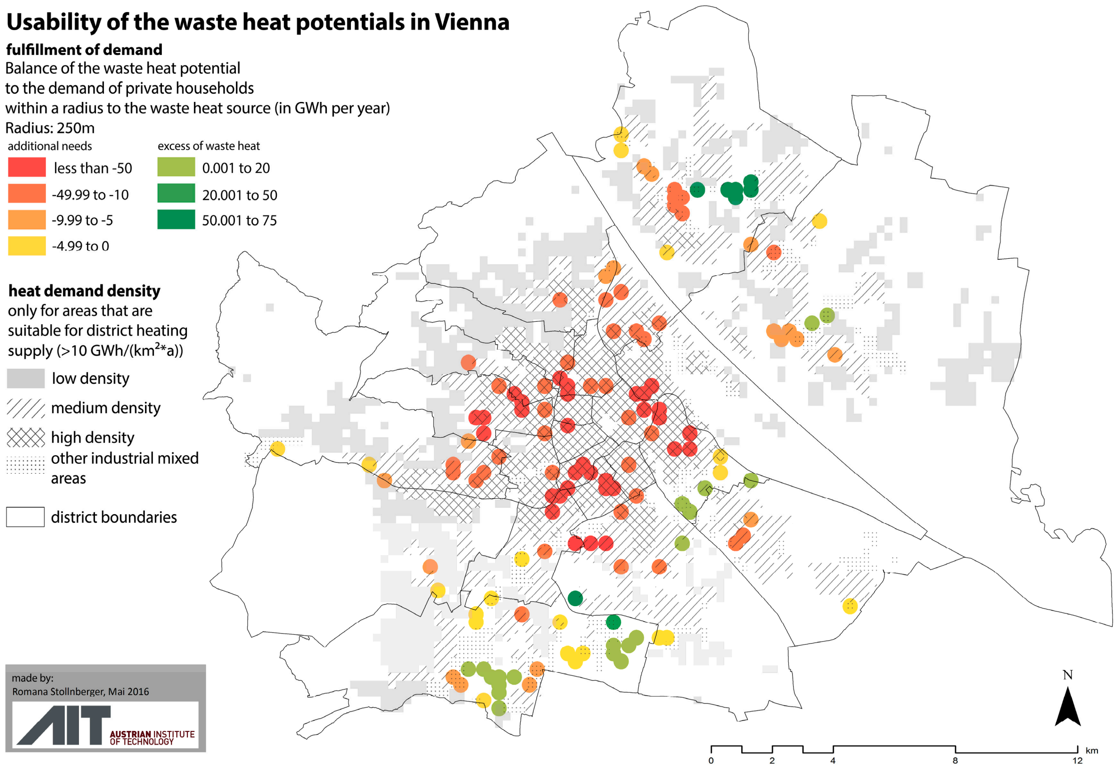

Figure 10. Usable waste heat supply from commercial sources in Vienna matching the residential heating demand in the vicinity (250 m buffers around source areas). Own compilation.

Figure 11 quantifies the results shown in Figures 9 and 10 depicting the average demand coverage through waste heat supply within the supply ranges in four building density classes in Vienna considering a 250 m and a 500 m supply radius. The building density classes are the following: low density (single-family housing neighbourhoods), medium density (large social housing blocks, multi-family houses), high density (19th century building blocks, Vienna Centre) and mixed density areas (commercial and industrial areas with dispersed housing).

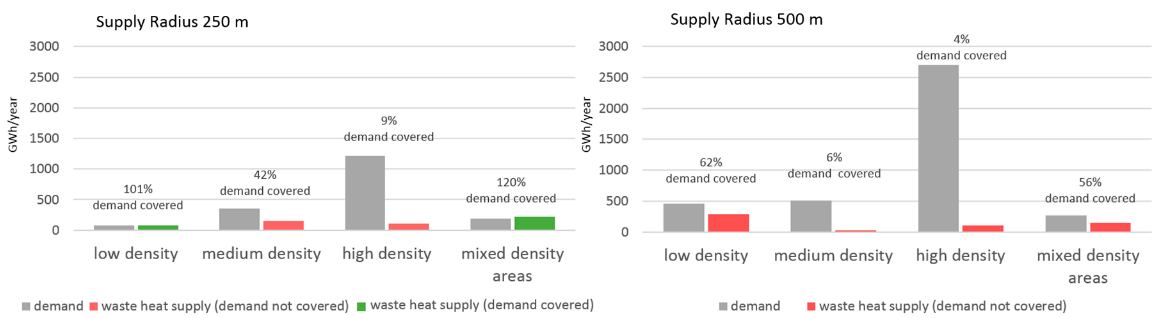

Figure 11. Average heating demand coverage by potential waste heat supply (in GWh/yr) in Vienna related to building density classes. Left: supply radius 250 m, right: supply radius 500 m. Own compilation.

A 500 m supply radius around waste heat sources includes obviously more buildings and related floor space demanding heating than a 250 m supply radius. In low-density housing areas, the heating demand can be fully covered by waste heat within a 250 m supply radius (101%). Within a 500 m supply radius around 62% of the heating demand can be covered by waste heat. In mixed-density areas, 120% of the residential heating demand can be covered within a 250m supply radius and 56% within a

500 m supply radius. In medium-density housing areas, 42% of the heating demand can be covered within a supply radius of 250 m and only six percent within a 500 m supply radius. In high-density housing areas, only nine percent of the heating demand can be covered by waste heat within a 250 m supply radius and only four percent within a 500 m supply radius. Thus, only for low density and mixed density areas with a 500 m supply distance around waste heat sources is it appropriate to use the entire supply potential for heating avoiding waste heat left. In medium- and high-density areas, the heat supply ratio is low due to little local heat volume from industrial and commercial sources compared with much higher local heating demand.

3.4. Exploration of a Priority Area for Local Waste Heat Use

An exemplarily selected priority area for local waste heat use is located in Vienna's Northeast. Figure 12 shows a large surplus of potential waste heat, available due to a lack of a current heating demand in the vicinity.

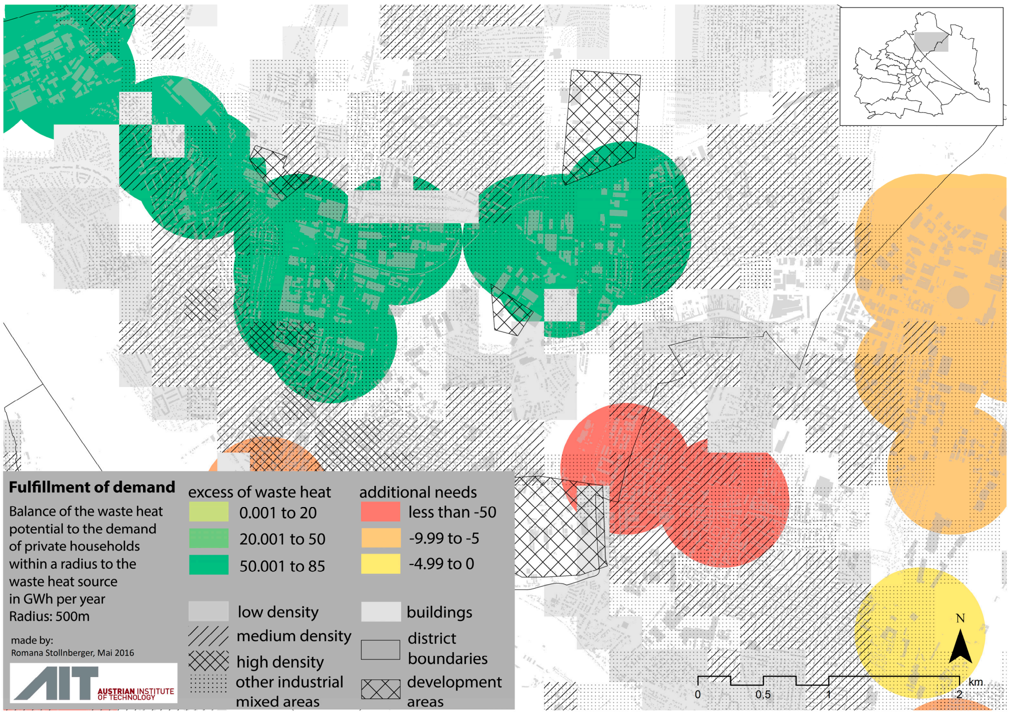

Figure 12. Possible new development areas within the priority area Floridsdorf to be supplied by nearby waste heat sources marked as hatched polygons, own compilation.

As the waste heat potential lies largely in the temperature range between 35 and 100 °C this supply could be ideally fed into a new local low temperature heating micro-grid. Negotiations between a data center, as potential heat supplier, and a housing developer, who plans to establish a new social housing project in the neighbourhood of the data center, have been established, also involving Vienna's major district heating network operator, "Fernwärme Wien". Appropriate temperature levels and the commercial viability of the project were discussed in late 2016. The annual cooling load of the data center is 6800 MWh. The social housing development with 170,000 m^2 floor space let expect an annual heat load of 5300 kW. The temperature provided by the data centers' cooling system is 16 °C that would require heat pump to raise the temperature to 63 °C. The costs for heat supply using the local waste heat combined with a central heat pump system accounts for 6.3 ct/kWh. (Due to competition reasons, the network operator of the municipal district heating network did not provide cost data for heat supply. Thus, a comparison between local supply costs and municipal district heating supply costs was not possible.) In late 2016, negotiations have started, regarding waste heat selling, construction and maintenance of such a local heating network and the legal situation concerning right of way permissions for the pipe network connecting the potential supplier with the potential customer.

4. Discussion

Focusing on cities as a whole has increased in the last years due to the advance of the topics of smart cities. By connecting the various sectors in the cities—buildings, energy infrastructure, mobility, and industry—efficiency can increase more substantially rather than focusing on single sectors individually. Since cities play a crucial role in the reduction of greenhouse gas emissions, optimisation processes, which consider whole districts up to the entire city, must be further exploited. The connection of buildings with electrical and thermal grids has for a long period of time been largely one-directional as energy was delivered from the power stations to the consumers. With the increase of decentralized renewable energy production, consumers can also become "producers" and supply surplus energy back to the grid.

Buildings at large can also substantially contribute to load-shifting potentials in a city. Equipped with thermally and electrically based systems and the potential to shift loads between electrical and thermal energy (e.g., by the integration of heat pumps or CHPs) buildings offer a tremendous storage capacity. Pre-heating and/or pre-cooling of buildings allows for load shifts and the opportunity to use energy when it is abundantly available (e.g., during daytime, when renewable energy by photovoltaic power is high) and to reduce the current demand when energy is scarce. Especially in areas where most buildings are constructed with heavyweight materials (masonry, concrete), the thermal storage capacity could be used at large for load shifting in dense areas. Connected to thermal and electrical grids these potentials should be exploited to increase energy efficiency and reduce fossil based energy consumption.

The topic of smart grids is heavily researched, as electricity networks are increasingly reaching their load limits and must further deal with the rise in volatile feed-in of decentralized renewable energy.

On the thermal side, however, smart thermal grids are only slowly on the rise. Small scale feed-in of heat into thermal networks is still relatively rare and district heating utilities are usually providers of energy only.

This paper examines, with Vienna as an example, the theoretical potential of using waste heat on a larger scale. On the one hand, the heating energy demand is on the rise as the city is growing in population. Thus, even though the building standards in terms of energy efficiency have significantly increased over the last thirty years, the total heating energy demand is still increasing. On the other hand, there are a number of industries located in the city, which could offer decentralized heat supply, as waste heat through cascading use of their average energy consumption.

As the paper describes, in theory a matching between industrial waste heat and residential heating demand can be beneficial as there is a significant overlap in terms of location of demand and supply. In practice, however, there are still some challenges, which would need to be resolved:

- Smart thermal grids: Load shifting of thermal energy requires a smart thermal network including storage solutions, as capacity, pressure and temperature would need to be managed for the network to be able to deal with these variable loads. Cascading use of thermal energy could be exploited if the network is able to balance feed-in and supply.
- Smart expansion of district-heating networks: Currently district heating expansion is to some extent blocked, as new buildings require less (thermal) energy due to stricter building regulations. Small passive houses with a heating demand of below 15kWh/m^2/year cannot be economically feasible connected to the network, as the yearly heating demand is too low to justify the connection costs. New connections must be planned in cooperation with new large housing developments by including local supply sources to increase efficiency.

- Business models: Business models and legal framework conditions would require improvement to allow individuals serving as heat suppliers enabling marketable models where small scale industries can easily sell their energy from waste heat to residential customers.

5. Conclusions and Outlook

Implementation of a smart and sustainable city requires, with respect to energy efficiency improvement, a combination of factors such as retrofitting of old buildings and the construction of new ones towards an energy efficient housing stock, the use of renewable energies or the development of a multi-modal transport system. In terms of strategic planning, it is necessary to harmonize the goals of energy efficiency and increasing renewable supply among other urban development objectives (inter alia social mix, urban quality).

Waste heat detection and re-use is one key topic with respect to energy planning in line with spatial planning. Waste heat from small scale urban industries still provides a yet unmapped potential to meet the heating energy demands of residential quarters. As cities should be optimized as a whole by exploiting synergies between various urban sectors, the overall energy efficiency could be substantially increased and energy demand from non-renewables sources decreased if connections between the described sectors are undertaken. However, this is a theoretical example, which needs to be further reviewed for a practical market application.

Given that there is a substantial rise in the share of renewables from electrical systems, such as wind power or photovoltaic, and a decline in renewables from thermal systems, waste heat could also be converted into power; thus, load shifting between buildings can be more easily undertaken with the use of the electrical rather than thermal grids. As buildings offer a tremendous capacity for load shifting based on their electrically and thermally powered building systems as well as their inherent storage capacity of the (mostly heavyweight) construction materials, optimization potentials must be increasingly exploited. Further research is required to investigate the feasibility of small-scale waste heat to be converted and connected to electrical systems with the incurred conversion losses and/or high-grade thermal systems. Also, the number of companies that could provide waste heat could be extended to include not only the large enterprises (with a turnover above two million EUR) but also smaller ones from sectors with high energy consumption.

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