Valuation of Novel Waste Heat Sources and a Path Towards Adoption

Preprint

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Presented at the 2022 ACEEE Summer Study on Energy Efficiency in Buildings
Pacific Grove, California
August 21-26, 2022

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Contract No. DE-AC36-08GO28308

Conference Paper
NREL/CP-5500-83352
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Suggested Citation
Manuel Lammle, Amy Allen, Gregor Henze,and Shanti Pless. 2022. *Valuation of Novel Waste Heat Sources and a Path Towards Adoption: Preprint*. Golden, CO: National Renewable Energy Laboratory. NREL/CP-5500-83352. https://www.nrel.gov/docs/fy22osti/83352.pdf.

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National Renewable Energy Laboratory
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303-275-3000 • www.nrel.gov

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This work was authored in part by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Advanced Manufacturing Office. The views expressed herein do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

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Valuation of Novel Waste Heat Sources and a Path Towards Adoption

ABSTRACT

It is recognized that beneficial electrification of most space heating will be necessary to avert the worst consequences of climate change. Fifth generation district heating and cooling (5GHDC) networks operate at near-ambient temperatures and thus facilitate heating electrification, as well as the use of waste heat sources at a wide range of temperatures. In this paper, we analyze the potential of waste heat to supply the required heat to these networks and describe the business models that could expand the use of these waste heat sources. Showcase single family and commercial districts in the US are discussed to demonstrate emerging technologies, district infrastructure approaches, and third-party thermal utility funding models for these leading 5GHDC networks.

As part of this work, heat flow and temperature profiles from five different types of waste heat sources are analyzed. An example district is used to examine the integration potential and to quantify the potential reduction in energy consumption. The results indicate that 5GDHC networks are highly suitable systems for utilizing low to moderate temperature waste heat sources. In the studied district, waste heat can cover a share of up to 66% of the heat supplied to the ambient loop and reduce the overall electricity consumption for heating by up to 51%, depending on the characteristics of the specific power, temperature, and type waste heat source. Through their moderate operating temperatures and use of waste heat sources combined with third party financed infrastructure, 5GDHC districts have significant potential to reduce carbon emissions associated with space conditioning.

INTRODUCTION

Bidirectional thermal networks are a technology to supply heating and cooling to districts within a two-pipe network. In contrast to conventional heating networks, these networks operate at ultra-low temperatures near ambient, which is why they are often denoted as fifth-generation district heating and cooling (5GDHC) networks. Major advantages of these networks are seen in the possibility to supply cooling and heating with the same technologies and to enable full electrification via sector coupling. As 5GDHC networks operate at low near-ambient temperatures, they allow an efficient integration of renewable and low carbon energy sources, especially waste heat from low temperature sources which otherwise would be difficult to utilize (Lund et al. (2014)).

As a result of their moderate network temperatures, 5GDHC systems leverage water-source heat pumps at connected buildings to further temper the water to meet the buildings' loads (Buffa et al. 2019). 5GDHC systems facilitate bidirectional thermal flow through the synergistic exchange of heat among connected buildings, offsetting the load on primary equipment and creating the potential for energy savings relative to earlier generations of district thermal energy systems with separate heating and cooling networks (von Rhein et al. 2019). 5GDHC systems can operate in configurations with bidirectional or unidirectional mass flow (Sulzer et al. 2018). In appropriate applications, 5GDHC systems have been shown to offer reductions in source energy use intensity for HVAC of 21-25% relative to code-compliant, building-level systems (Allen et al. 2021).

The integration of low temperature waste heat in district heating networks has been discussed in several previous research endeavors. Fang et al. (2013) analyzed industrial process heat and suggested a holistic approach to efficiently integrate low-grade waste heat into district heating networks. Wahlroos et al. (2018) specifically addressed waste heat utilization of data centers in Northern Europe and their integration in district heating networks. Xu et al. (2019) developed graphical analysis methods, similar to a pinch point analysis, for designing waste heat recovery systems and suggested using thermal storage, thermal transportation, and high temperature heat pumps to solve mismatches between the waste heat source and user side in time, location and temperature levels. Sandvall et al. (2021) analyzed the utilization of urban excess waste heat sources, such as data centers, metro stations, sewage systems, and service sector buildings' cooling systems, employing central heat pumps to increase temperature levels to the required temperature levels of district heating networks.

From these considerations it becomes clear that waste heat recovery from low-grade waste heat sources is most efficient when waste heat is supplied to low-temperature applications. 5GDHC networks are therefore considered a suitable application for low-temperature waste heat recovery, and waste heat utilization can facilitate an energy-efficient and economic operation of these networks.

However, the specifics of integrating waste heat from different types of processes have not yet been studied in detail. In this paper, we therefore analyze the extent to which waste heat can contribute to the required heat supply for these networks and identify innovative development and ownership models that can be leveraged by building owners to more easily implement such district and waste heat recovery systems.

MODEL OF A SHOWCASE DISTRICT FOR A 5GDHC NETWORK

The case study models a small district with seven buildings connected by a bidirectional heating and cooling network. The network topology was optimized in previous work (Allen et al. 2021). The district system is implemented in Dymola/Modelica and annual simulations are performed, on which basis the energetic performance is evaluated.

The building types represented in the prototypical district were selected to correspond generally to buildings present at the chosen location on the campus of the University of Colorado in Boulder, CO, and thus be representative of building types that would typically be located in proximity to each other in an urban district. Based on an evaluation of a metric known as linear heating power demand density, the thermal load density of this collection of buildings is greater than that of some districts with operating ambient loop systems and would thus be considered an appropriate application for such systems (Buffa et al. 2019). Building thermal loads are represented using the U.S. DOE Prototype Building models in EnergyPlus format (U.S. DOE, 2021). A parameter sweep of inputs to the prototype building models is used to create a data set for training random forest metamodels using the framework developed by Long et al. (2021), which predict the buildings' thermal loads as a function of the ambient loop supply temperature.

The 5GDHC network is modeled in Modelica, extending a model from one developed by von Rhein et al. (2019). In the modeled 5GDHC network, a centralized ground source heat pump controls the loop temperature, with the "warm pipe" controlled to a temperature of 26°C and "cool pipe" to 16°C. Each connected building is served by an energy transfer station, which includes heat exchangers and water source heat pumps, which temper the network water to meet the building's thermal loads. Circulation pumps control the flow rate through the energy transfer station to maintain a 10 K temperature differential between the warm pipe and cool pipe of the ambient loop.

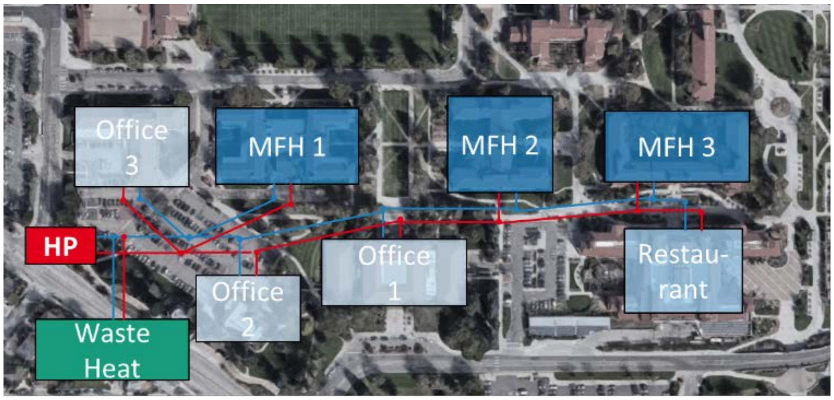

Figure 1: Model district consisting of three residential multi-family buildings (MFH), three office buildings, a restaurant, and a central ground-source heat pump (HP). The waste heat is integrated in the cold return pipe to the central heat pump.

INTEGRATION OF WASTE HEAT SOURCES IN 5GDHC

The viability of integrating waste heat sources in low temperature heating networks depends on the characteristics of the waste heat source and the sink. Depending on the underlying waste heat process, the specific waste heat power and temperature profile is subject to daily, weekly, monthly, or seasonal fluctuations. Therefore, the technical and economic potential for the utilization of waste heat depends on the specific characteristics of the waste heat source. With the goal of comparing the integration of different waste heat sources in 5GDHC networks, we analyze the following waste heat sources and their corresponding profiles:

(1) Water cooled data center: data from the high performance computing data center of the National Renewable Energy Laboratory (NREL) with a relatively continuous waste heat profile and $T_{supply,mean}$ = 36.5°C (NREL 2014, Moore 2016)
(2) Air cooled data center: data from the same data center but measured at air cooling heat exchangers with similar characteristics but lower temperatures of $T_{supply,mean}$ = 30.6°C
(3) Wastewater: open sewage system of an interceptor in Denver with a strong seasonal variations of waste heat and temperature profile with $T_{supply,mean}$ = 20.4°C (Pless 2020)
(4) Refrigeration: compression chillers at a supermarket with daily and seasonal variations at relatively high temperatures in refrigerant ($T_{supply,mean}$ = 67.0°C)
(5) Laundry: open and discontinuous batch process of a German laundry with wastewater at $T_{supply,mean}$ = 28.4°C.

Figure 2 shows the annual, normalized heat flow profile of the five analyzed waste heat sources. The annual waste heat profiles were generated based on measurements in real processes regarding heat flow and supply and return temperatures and subsequent data analysis to create a complete and consistent set of waste heat profile for every hour of the year.

A detailed time-series analysis of these waste heat sources is covered in a separate paper that is currently in preparation. The waste heat profiles, including heat flow rate and supply and return temperatures, can be downloaded from a public GitHub repository.[1]

[1] Public git repository available on https://github.com/mlaemmle/WasteHeatProfiles.git

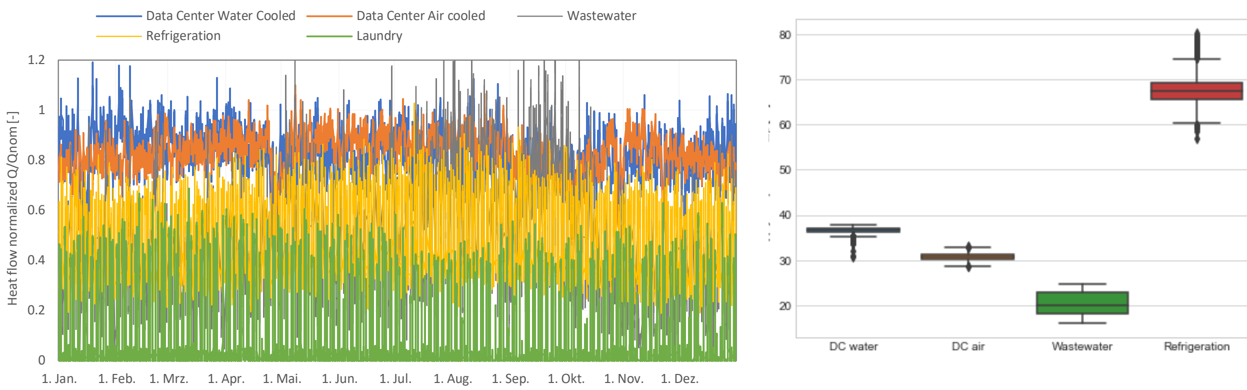

Figure 2: Measured heat flow and temperature profiles of five different types of waste heat sources.

The hydraulic integration of the waste heat source in the 5GDHC network is shown in Figure 3. The optimum integration point from an exergetic point of view is the return pipe to the heat pump: during the heating period, this is the coldest point in the network. The integration of waste heat at this location optimizes the objective to offset heat provided by the central heat pump and thus reduce electricity consumption.

In the simulation model, an approach similar to the energy transfer stations in each building is used for modelling the waste heat integration. A plate heat exchanger decouples the process and the heating circuits hydraulically. The circulation pump in the heating network is controlled in such a way that waste heat is transferred to the heating network only when required, i.e., during heat demand and when supply temperatures of the waste heat source are higher than return temperatures of the network. For this purpose, a PI controller is combined with a rule-based controller to operate the modulating circulation pump for the waste heat integration.

Different types of waste heat sources can be analyzed and compared on a consistent basis with this approach. However, one must differentiate between open and closed waste heat processes. In an open waste heat process, such as wastewater, return temperatures from the waste heat process can be as low as technically possible. Subcooling below the assumed minimum temperature of 15°C as specified in the waste heat profile is therefore possible in open processes. In closed waste heat processes, on the contrary, subcooling below the specified return temperature is not allowed, as the power of the waste heat process is strictly given by the waste heat process.

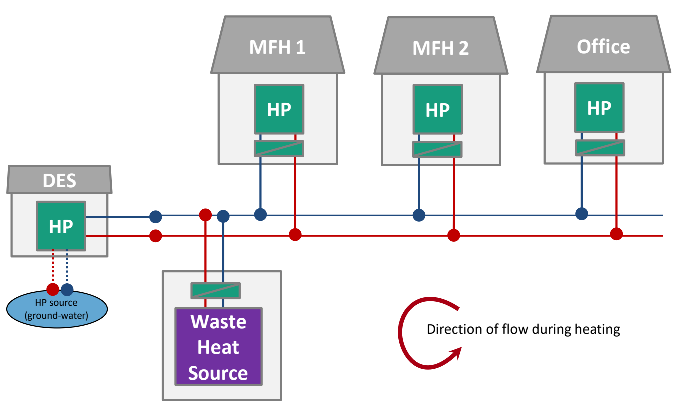

Figure 3: Hydraulic integration of a waste heat source in the 5GDHC network by an increase of return temperatures to the DES.

SIMULATION RESULTS OF INTEGRATING WASTE HEAT INTO 5GDHCN

Thermal and electrical energy balance of a 5GDHC network with integrated waste heat

The basic concept of integrating waste heat into 5GDHC networks and its effect on the energy balance is illustrated in *Figure 4*. For this case study, we consider the waste heat profile of a water-cooled data center and assume that the annually available waste heat $Q_{WH,available}$ is equal to the building's annual heat consumption $Q_{building}$. Due to the seasonal variations of the heating load, with a peak heat load of $\dot{Q}_{building} = 631\ kW$, this corresponds to a nominal power of the waste heat source of $\dot{Q}_{WH,nominal} = 38\ kW$.

As a result of the differing seasonal profiles, the waste heat source can cover only a certain fraction of the overall heat demand. During summer, when demand for space heating is zero, the waste heat cannot be used. During the transitional period, there are days where most of the district's heat demand is supplied by the waste heat source. During winter, however, the power of the waste heat source is insufficient to cover the district's heat demand. Therefore, the district energy system (DES) supplies the required heat via the compression heat pumps that utilize electricity ($E_{HP,DES}$) to leverage ambient heat sources ($Q_{ambient,DES}$).

Moreover, the waste heat sources with their low temperature levels are only capable of substituting the heat supplied by the DES. The temperatures in the 5GDHC network only range between 16°C and 26°C. An additional compression step by the decentral heat pumps in each building is therefore required to supply the required temperature levels of the buildings.

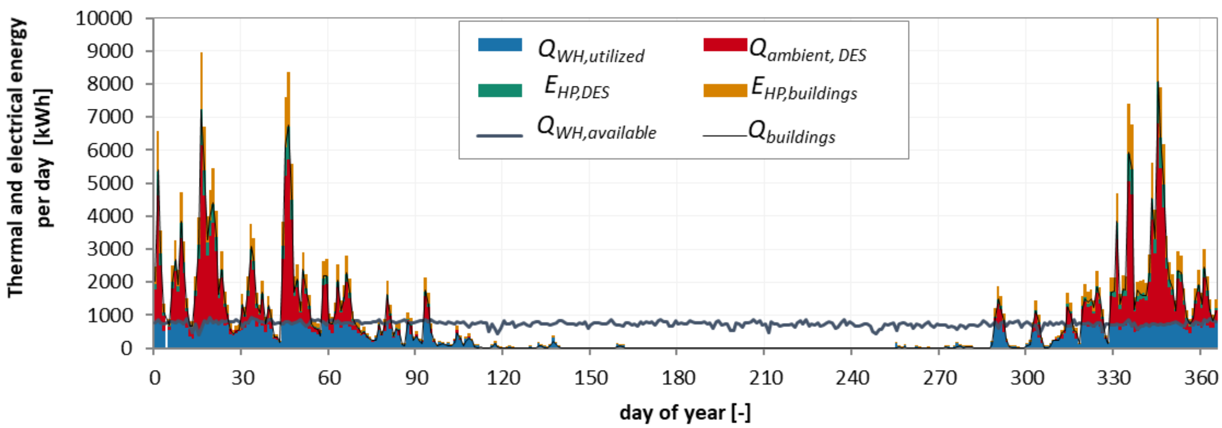

Figure 4: Daily thermal and electrical energy balance for district heating.

These considerations lead to the definition of the waste heat fraction f_{WH}, which describes the fraction of the overall heat demand $Q_{building}$ that is supplied by the waste heat source:

$$f_{WH} = \frac{Q_{WH,utilized}}{Q_{buildings}}$$

The waste heat fraction is defined analogously to the solar fraction, which correspondingly characterizes the fraction of the overall heat demand that is covered by solar thermal collectors. The second indicator is defined analogously to the seasonal performance factor *SPF* of conventional heat pump systems and thus characterizes the energy efficiency of the heating system:

$$SPF_{WH} = \frac{Q_{buildings}}{E_{HP,DES} + E_{HP,buildings} + E_{Pumps,DHN}}$$

Effect of quantity: influence of available waste heat power $\dot{Q}_{WH,availble}$

The nominal power of the waste heat source $\dot{Q}_{WH,available}$ affects the available waste heat and thus the energetic and economic performance of the district. The influence of the quantity of $\dot{Q}_{WH,available}$ on the energy balance and the corresponding key performance indicators (KPIs) is investigated in the following case study. We use the previous waste heat profile of a water-cooled data center and vary its annually available waste heat as a percentage of the overall heating demand of the buildings $Q_{WH,available}/Q_{buildings}$ from 0% - 200%. The baseline case without integrated waste heat is given by the case "0%", while "100%" corresponds to the case described in the previous section. Figure 5 shows the energy balance of the district with the contributions of the different energy sources for each case.

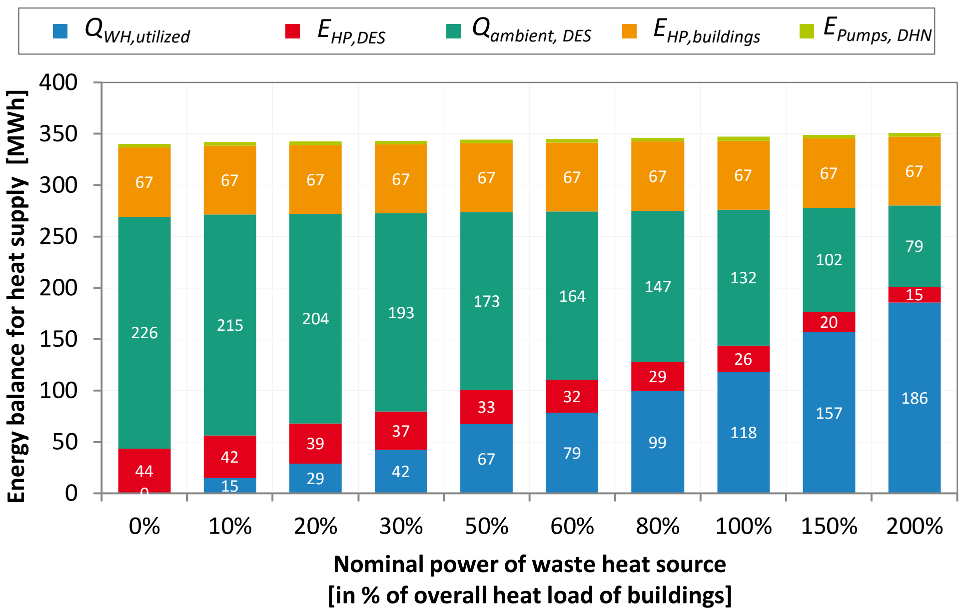

Figure 5: Energy balance of 5DHC network with varying power of waste heat source.

With increasing power of the waste heat source, the share of utilized waste heat increases $Q_{WH,available}$, and as a consequence the heat supplied by the DES and the electricity for the central heat pump $E_{HP,DES}$ decrease continuously.

The integration of waste heat affects the performance of the decentral heat pumps in the individual buildings only marginally. As the grid temperatures only differ minimally compared to the case without waste heat, the coefficient of performance of the decentral heat pumps and thus $E_{HP,buildings}$ is affected only marginally.[2]

[2] The influence on the performance of the cooling system is not shown in detail in this analysis, although it is considered in the simulation model. As the adapted control of the waste heat integration does not change the operating temperatures of the 5GDHCN significantly, also the effect of waste heat on the energy efficiency for cooling is insignificant.

Note that a doubling of available waste heat does not result in a doubling of the utilized waste heat: due to the specified heat demand and waste heat profile, which must coincide temporally, the potential to utilize the available waste heat is limited. As a result, the ratio of utilized waste heat decreases with an increasing available waste heat power.

Figure 6 shows the resulting indicators of the waste heat fraction f_{WH} and seasonal performance factor *SPF*. The integration of waste heat increases the seasonal performance factor from 2.8 to 3.4, in the 100% case. A further doubling of the available waste heat increases the *SPF* to 3.9. This corresponds to an overall reduction of the electricity consumption of 32%, and 51% respectively. Increasing the waste heat power further would effectuate a further improvement of energy efficiency, but the waste heat utilization ratio would continue to decrease.

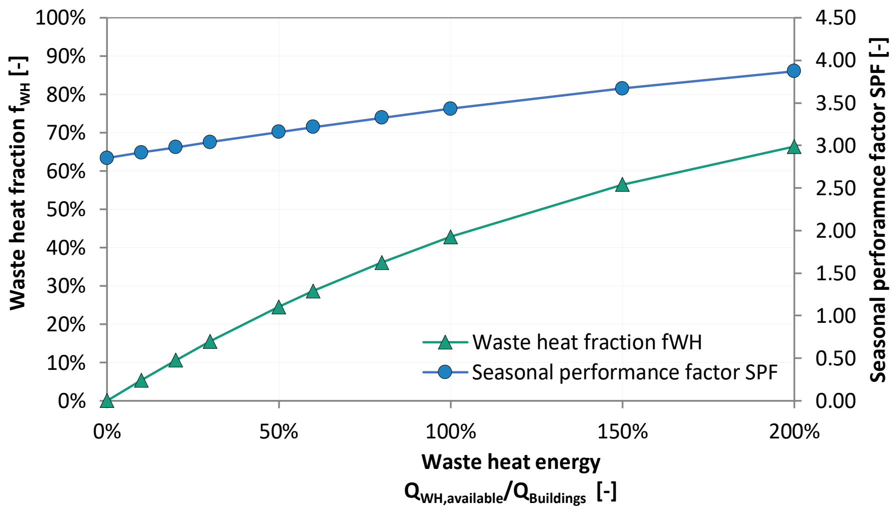

Figure 6: Waste heat fraction and seasonal performance factor with a varying quantity of available waste heat energy $Q_{WH,available}$.

Effect of quality: influence of the supply temperature $T_{sup,mean}$

The utilizable amount of waste heat also depends on the quality, i.e. the temperature levels of supply and return flow. The floating temperature levels in the 5GDHC network vary in a range of 16°C - 26°C depending on the current heating or cooling demand. The control of the central heat pump in the DES maintains temperatures above 16°C during the heating period to ensure sufficient power and supply temperatures for operating the decentral heat pumps in each building. Therefore, only waste heat temperatures above 16°C can be injected into the heating grid while heat below this temperature threshold is not utilized.

To analyze the effect of temperature levels on the the waste heat fraction and seasonal performance factor, the supply temperature levels of the waste heat profile of the water-cooled data center is varied within a range of 15°C and 50°C. The corresponding return temperature is set to $\Delta T = 10\ K$ below the supply temperature. Aside from these temperature modifications, the measured waste heat profile is used. Figure 7 shows the corresponding results.

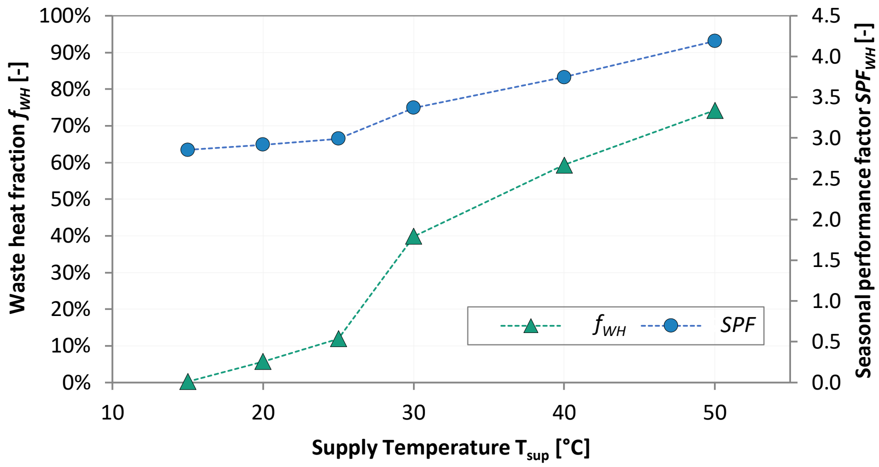

Figure 7: Waste heat fraction and seasonal performance factor with varying quality the waste heat in terms of supply temperature T_{sup} [°C] for an open waste heat process.

Both the waste heat fraction and the seasonal performance factor increase with higher temperatures levels, reaching a *SPF* of 4.1 at $T_{sup} = 50°C$. Note the sharp increase above $T_{sup} = 25°C$ of the supply temperature: with higher temperature levels, the full potential of the return temperature can be utilized. Below $T_{sup} = 25°C$ (or T_{ret} = 15°C) only the fraction of heat above the return pipe temperature in the district, typically 16°C during the heating period, is utilized. Correspondingly, no heat is transferred to the district with waste heat temperatures below 15°C.

Effect of waste heat profile: influence of type of waste heat source

Finally, we assess the effect of integrating different types of waste heat sources in 5GDHC networks. For this purpose, the corresponding waste heat source is varied according to the previously described hourly profile. The waste heat sources differ in their seasonal, weekly, and daily profile regarding available waste heat power and supply/return temperatures. In combination with the seasonal waste heat demand and required supply temperatures, an effect on the utilization of waste heat and thus waste heat fraction f_{WH} and seasonal performance factor *SPF* is be expected.

With the scope of comparing the utilization of waste heat from different heat sources on a consistent basis, the annually available waste heat $Q_{WH,available}$ is identical for all five profiles and set equal to the required source energy of the district ($Q_{WH,available}/Q_{Buildings}$ = 100%). As all profiles have a different average heat power, the corresponding nominal heat power of the sources also varies.

Figure 8 shows the resulting waste heat fraction and seasonal performance factors.

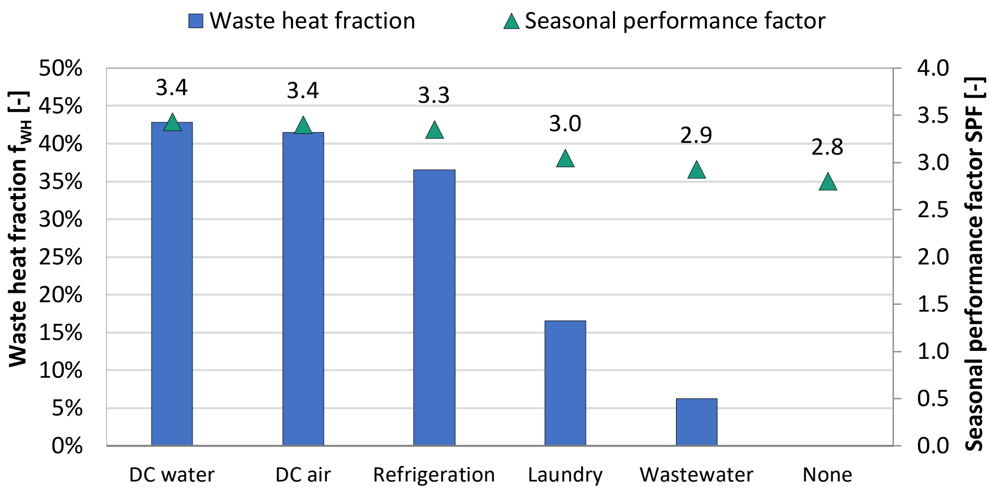

Figure 8: Waste heat fraction and seasonal performance factor for varying waste heat sources with equal annually available waste heat.

The results reveal interesting effects regarding the utilization of low temperature heat from different types of waste heat sources:

- Despite the higher mean supply temperature of the water-cooled DC racks of $T_{sup,DC\_water} = 38°C$ compared to air-cooled DC racks with $T_{sup,DC\_air} = 31°C$, the effect on waste heat fraction and seasonal performance factor is negligible ($SPF_{DC,water} = 3.4$ and $SPF_{DC,air} = 3.4$).
- Waste heat from refrigeration systems in supermarkets are characterized by relatively high supply temperatures and a heat load peak during summer. Despite the seasonality, a high waste heat utilization and seasonal performance factor of $SPF_{Refrigeration} = 3.3$ can be achieved.
- The industrial process in laundry is highly intermittent with a characteristic daily profile. A buffer heat storage could increase the utilizable waste heat and further improve the seasonal performance factor.
- Wastewater in sewage systems is subject to seasonal variations regarding waste heat profile and supply temperatures. In the given case study, the utilized waste heat is very low, as supply temperatures lie below the required heating grid temperature during most of the heating period. Therefore, the vast potential of the wastewater heat is not exploited. Lowering grid temperatures or integrating a booster heat pump have a high potential to strongly increase the level of utilized waste heat.

BUSINESS MODELS

As viable waste heat sources are identified and corresponding suitable 5GDHC networks are proposed, supportive development, ownership, and operations models will be needed to ensure such systems can be cost effectively offered to building owners. Based on lessons learned from leading district energy planning efforts (Zaleski 2018), the following challenges remain in implementing district waste heat recovery approaches:

- Financial, governance, and implementation challenges are limiting more widespread adoption of zero energy districts thermal systems.

- Suitable analysis tools for scaling district waste heat recovery systems are limited. This includes understanding how heat recovery technologies available in individual buildings can translate and perform in a 5GDHC network district as well as how to quantify zero energy district benefits.
- Non-technical barriers such as overcoming resistance to setting zero energy goals, engaging utilities, developing finance and governance structures, and ensuring performance over time.

As the potential energy savings and electrification of heating across a range of viable waste heat sources are documented, pairing the technical potential with emerging development and ownership models becomes important. To address many of the barriers related to high cost of infrastructure and district system first costs, developers and owners can look to emerging thermal utility business models. In these types of ownership models, a district thermal solution can be developed, designed, financed, and operated in a business model similar to electric utilities. Both public/private thermal utility and solely municipal thermal utility models could provide upfront design, modeling, and financing in return for a monthly thermal use bill over a long operational horizon. Successful waste heat recovery district thermal utilities have been implemented, such as an Amazon Datacenter cooling system that collects waste heat and distributes to local buildings in Seattle[3] and the National Western Center city wastewater heat recovery public/private agreement in Denver[4]. As additional 5GDHC district thermal utility pilots are implemented, such as the Massachusetts district ground source heat pump thermal utility micro district pilot program[5], there will be a broader opportunity to integrate waste heat recovery technologies into viable business models.

CONCLUSION

Dynamic simulations for a model district with residential and commercial buildings quantify the potential of utilizing low temperature waste heat sources in a fifth generation district heating and cooling (5GDHC) network. Waste heat can substitute a considerable fraction of heat, which would be otherwise supplied by the central heat pump or other fuel sources. Integration of low temperature waste heat therefore increases the energy efficiency by reducing the overall consumption of electricity required for space heating. However, the potential of waste heat is limited to covering a fraction of the overall heat demand, as additional compression steps are required, and available waste heat power often lies below the peak heat load of the district.

Depending on the quantity, quality, and type of process, waste heat has the potential to improve the overall energy efficiency in terms of the seasonal performance factor *SPF* from 2.8 to 3.9 and thus reduce the overall electricity consumption for heating in the model district by up to 51%. In this case, waste heat covers two thirds of the overall heat supplied to the heating network.

The individual waste heat processes with their corresponding seasonal and daily profiles of heat load $\dot{Q}$ and temperature T, significantly influence the quantity of usable waste heat Q_{WH}. A relatively constant waste heat and temperature profile, as found in data centers, facilitates the

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[3] https://www.aboutamazon.com/news/sustainability/the-super-efficient-heat-source-hidden-below-amazons-seattle-headquarters

[4] https://nationalwesterncenter.com/about/what-is-the-nwc/sustainability-regen/energy/

[5] https://www.greentechmedia.com/articles/read/can-gas-companies-evolve-to-protect-the-climate-and-save-their-workers

utilization of waste heat. Intermittent processes with a strong daily profile (laundry, for example) reduce the delivered waste heat. Thermal storage may be a suitable solution for intermittent waste heat sources. Moreover, low supply temperatures of the waste heat source reduce the utilizable waste heat substantially. During the heating period, wastewater temperatures frequently lie below the lower temperature limit of the network of 20°C. In this case, waste heat cannot be utilized directly, but an additional compression step is required, or network temperatures must be lowered.

As emerging thermal utility models and district developers look to scale these systems, the value of waste heat for integration in 5GDHC network must be always viewed in the context of seasonal matching of supply and demand, as well as quality in terms of supply temperatures. The moderate operating temperatures of 5GDHC networks facilitate the integration of a wider range of waste heat sources, and, when selected and controlled properly, waste heat sources have the potential to increase the energy efficiency of such systems and expand the potential savings for district thermal utility offerings.

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