CO_2 and operating cost saving potentials through the coupling of digital infrastructures with district heating networks

White Paper 2

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Content

List of abbreviations

dep.	-	dependent
resp.	-	respectively
elec.	-	electric
ERF	-	Energy Reuse Factor
DH	-	District Heating
p.a.	-	annually / per annum
const.	-	constant
max.	-	maximum / maximal
DC	-	Data Center
s.	-	see
spec.	-	specific
p.	-	page
cf.	-	compare
L.	-	Loss

1 Executive Summary

Advancing digitization combined with the realization of the energy transition is creating a growing need for sustainable IT infrastructures. Energy suppliers have discovered the resulting opportunity.

With its many years of experience in data center operation as well as in the development of cloud infrastructures, the company Cloud&Heat supports energy suppliers in entering this new market and helps them to contribute to climate neutrality. Based on the principle "Power to Data - Data to Heat", the direct hot water cooling used by Cloud&Heat enables data center waste heat to be used in local and district heating networks, as well as for an enterprise's own needs. The energy-saving technology reduces operating costs and provides CO_2-neutral heat for subsequent use.

With the help of model calculations, this white paper illustrates the CO_2 and cost-savings potential of data centers coupled with district heating networks. For the Frankfurt am Main site, the operating energy costs and CO_2 emissions were compared between a data center coupled with a district heating network and separated stand-alone systems.

The combined use of the data center (rated power: 550 kW, utilization: 50%) and the district heating network (heat source: natural gas-based hot water generator, peak heat output: 1 MW) can reduce the annual CO_2 emissions by 39.2% to 367 t and the operating energy costs by 9.8% to 543.7 T€. The calculated results achieve savings of 59.1 T€ and 237 t of carbon dioxide per year. To compensate for the same amount of CO_2, more than 18,900 deciduous trees would have to be planted, which corresponds to an area of 21 hectares or 30 soccer fields of forest.

2 Introduction

Having a high annual growth rate of 17.5% worldwide, the cloud market[1] is one of the most promising industries for many businesses. Data center energy consumption is increasing drastically, not least as a result of computationally intensive applications in the areas of artificial intelligence and machine learning and their high demands on data processing and storage. By 2030, digital infrastructures will account for 4 to 6% of the total global electricity consumption.[2] IT enterprises whose applications cause high resource consumption are becoming increasingly aware of their ecological responsibility and therefore have an increased interest in operating their applications on sustainable digital infrastructures.

This has also been recognized by energy suppliers, whose business areas, such as energy generation based on fossil fuels, are becoming increasingly less important in the wake of the energy transition. In their search for new business areas, they bring with them suitable prerequisites for establishing themselves on the market as providers of digital infrastructures: numerous locations, extensive infrastructures, network flexibility, direct access to energy, millions of existing customers, and a wealth of experience in the power and heating market.

Cloud&Heat provides the technology and know-how to connect the data center and cloud market to the energy industry, as well as the possibility to reuse CO_2-neutral waste heat. In comparison to conventional air cooling, the advantages of Cloud&Heat direct hot water cooling, such as achievable CO_2 and cost saving potential, have already been proven with the example of the company's own data center in Frankfurt am Main[3].

The aim of this white paper is to demonstrate the savings potential of coupling a data center (Frankfurt site) with a district heating network in an understandable and transparent manner using a concrete model calculation.

[1] Source: Research and Markets, Cloud Computing Market Report 2020
[2] Source: SDIA, The Utility of the Future 2020
[3] Source: White Paper 1, Cloud&Heat

3 Direct hot water cooling and waste heat recovery with Cloud&Heat

Data centers convert 100% of IT electricity into heat. A server with 500 W of electrical power consumption thus produces 500 W of thermal power. Cooling is therefore a basic requirement for reliable data center operation. Various solutions can be used to minimize energy consumption in the data center or to make its operation sustainable.

Cloud&Heat pursues the approach of minimizing the energy expenditure for cooling and making the waste heat available for subsequent use with the aid of direct hot water cooling. This involves water flowing through heat sinks that are in direct contact with the components to be cooled, such as processors. Accordingly, the thermal power of the IT components is dissipated directly at the point of origin. Figure 1 shows the implementation of Cloud&Heat direct hot water cooling on the Super Micro SuperServer 9029 as an example.

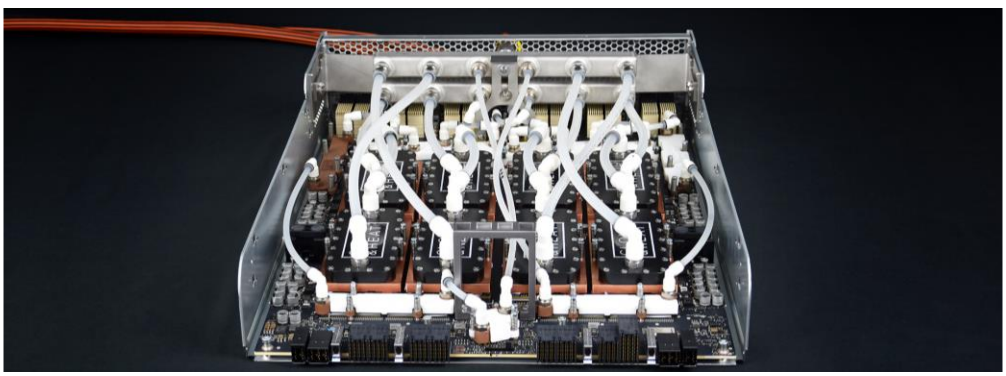

Figure 1: Super Micro SuperServer 9029 with Nvidia HGX-2 slot and Cloud&Heat Cooling Kit

In conventional, air-cooled data centers, the economic use of waste heat with air outlet temperatures of up to 40 °C is only possible to an extremely limited extent. With water cooling and the usage of suitable IT hardware a significantly higher temperature level of up to 63 °C is achieved due to precise control of the volume flows. This means that waste heat can be harnessed in typical hot water applications, such as heating buildings. Since the CO_2 emissions are allocated as data center use, its waste heat is assessed with a primary energy factor of 0.0[4]. This means that the data center waste heat is CO_2-free per definition.

[4] according to AGFW worksheet FW 309 part 1

4 Model calculation of a district heating network

The reuse of waste heat from data centers with direct hot water cooling in district heating networks reduces the primary energy requirement for providing district heating. The resulting economic and ecological benefits are evaluated by way of example using the model of a district heating network described below.

4.1 Methodology

A district heating network consists of three main components shown schematically in Figure 2:

- at least one heat source that provides the heat (e.g., a thermal power plant),
- at least one heat sink to which the heat is to be supplied (e.g., a residential area) and
- a heat distribution network, which is responsible for transporting heat from the heat source to the heat sink.

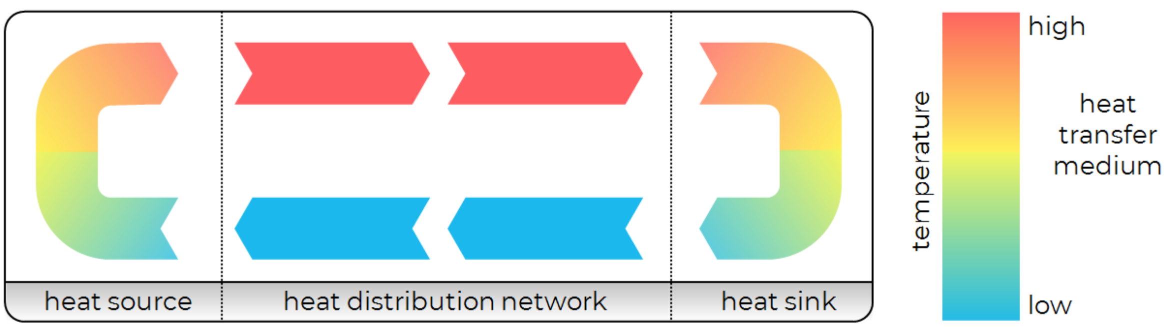

Figure 2: General schematic representation of a heat network based on the mass flow and local temperature profile of the heat transport medium.

The chronological sequencing of the heat-sink heat demand is of decisive importance both for the dimensioning of a district heating network and for the selection of the operating parameters. A residential area connected to the district heating network via a substation was selected as the heat sink for the model calculation. Heat is supplied to this area for both heating and hot water production. To ensure the scalability of the model calculation to different district heating network sizes, the residential area was selected to result in a maximum heat demand capacity of 1 MW.

With a share of approx. 42%[5], gaseous energy sources (such as natural gas) are still the predominant, primary energy sources for district heating networks. The model, therefore uses a hot water generator operated with natural gas (cf. Figure 3, left) to serve as the heat source of the district heating network. The heat distribution network is assumed to be simplified as one supply and one return line, each of identical length.

The model calculation refers to the location Frankfurt am Main in 2019 with hourly increments. Figure 3 (right) shows the temperature data used in this context (air temperature at a height of 2.0 m, ground temperature at a depth of 0.5 m).

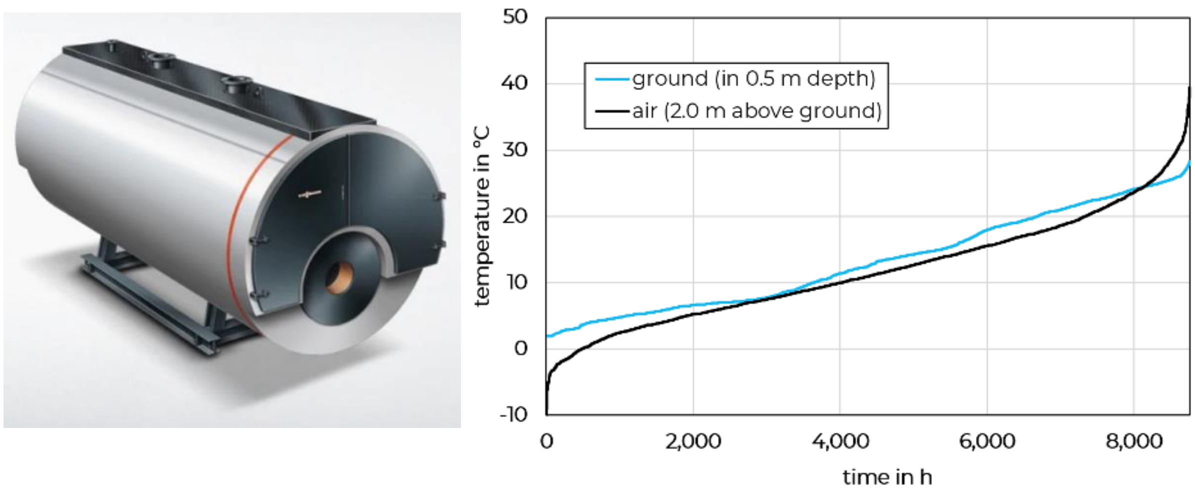

Figure 3: left - low pressure hot water boiler operated with natural gas (example)[6];
right - hourly data of air temperature (2.0 m height) and ground temperature (at 0.5 m depth) each as annual duration curves at the Frankfurt am Main site for the year 2019[7]

[5] Source: Working Group on Energy Balances, Energy Balance for Germany, as of 08/2018
[6] Source: Low-pressure hot water generator Vitomax LW, Fa. Viessmann
[7] Source: DWD, weather station 1420

4.2 Heat demand calculation

In the following, the determination of the area-specific thermal energy and thermal power demand of the hot water and building heating heat sinks are explained in each case. The assumptions used and the resulting key figures are summarized in Table 1.

4.2.1 Hot water

A typical daily hot water demand of 40 liters per person for Germany forms the starting point for determining the associated heat demand. Assuming that cold water is heated by an average of 37 K[8] when providing hot water, this results in a heat demand of 1.7 kWh per person per day or 619.6 kWh per person per year. In combination with an average living space of 47 m² per person, this results in an area-specific heat demand of 13.2 kWh/(m² a) for the provision of hot water. Assuming the supply on the consumer side takes place via a hot water tank system, the hot water heating power $\dot{q}_{\text{Warm water}}$ is considered constant over the year at 1.5 W/m².

4.2.2 Building heating

Residential buildings built in 2000 have an area-specific heat requirement q_{Heating} of 50 kWh/m². The corresponding heating threshold temperature $T_{\text{Heat threshhold}}$ i.e., the ambient temperature below which heating must be supplied to the living space, was assumed to be 15 °C. For time periods in the calculation model with ambient temperatures above the heating threshold temperature, the area-specific heating demand $\dot{q}_{\text{Heating}}$ is zero. For time periods with ambient temperatures below the heating threshold temperature, the area-specific heating power was determined using equation (1).

$$\dot{q}_{Heating} = U \cdot a \cdot \Delta T = U \cdot a \cdot (T_{\text{Heat threshhold}} - T_{\text{ambient}}) \quad (1)$$

The product of the heat transfer coefficient U and the enveloping surface area associated with one square meter of living space a was determined iteratively, resulting in an annual heat demand of 50 kWh/m² for the site. In summary, this product corresponds to a temperature- and area-specific heating power requirement of 1.087439 W/(m² K) for the example given. The maximum value for the area-specific heat output $\dot{q}_{\text{Heating,max}}$ occurs at the coldest ambient temperature of -10.0 °C and is 27.2 W/m².

[8] Heating of 8 °C cold water to average hot water temperature of 45 °C.

4.2.3 Heat sink scaling

To ensure the comparability of the calculation model for district heating networks of different sizes, the required maximum heat power demand $\dot{Q}_{\text{total}}$ is normalized to 1 MW. According to equation (2), the combination with the maximum heating and hot water demand results in a living space of 34,855 m² for 742 persons.

$$A = \frac{\dot{Q}_{total}}{\dot{q}_{Heating,max} + \dot{q}_{Warm\,water}} = 34.855\ m^2 \quad (2)$$

The resulting annual heat demand for hot water and heating, including the maximum heat outputs, can be taken from Table 1

Table 1: Heat sinks - assumptions and characteristic values

Designation	Formula symbol	Value	Unit	Source
Heat sink 1: Building heating				
Heating threshold temperature	$T_{\text{Heat threshhold}}$	15	°C	www.effizienzhaus-online.de
Annual area-specific heat demand (residential building, year of construction 2000)	q_{Heating}	50	kWh/(m² a)	ASUE, 2017
Temperature and area spec. heating power demand	$U \cdot a$	1.087439	W/(m² K)	Calculated value (iterative)
Max. area-spec. heat output requirement	$\dot{q}_{\text{Heating,max}}$	27.2	W/m²	Calculated value
Total living space	A	34.855	m²	Calculated value (iterative)
Annual heat demand	Q_{Heating}	1.743	MWh/a	Calculated value
Max. thermal power requirement	$\dot{Q}_{\text{Heating,max}}$	948	kW	Calculated value
Heat sink 2: Hot water				
Person-specific hot water demand		40	l/(person d)	www.energie-lexikon.info
Effective temperature difference to cold water		37	K	Acceptance
Annual person-specific heat demand		619.6	kWh/(person a)	Calculated value
Living space per capita		47	m²/person	Federal Statistical Office, 2019
Annual area-specific heat demand	$q_{\text{Warm water}}$	13.2	kWh/(m²*a)	Calculated value
Area-spec. thermal power requirement	$\dot{q}_{\text{Warm water}}$	1.5	W/m²	Calculated value
Annual heat demand	$Q_{\text{Warm water}}$	460	MWh/a	Calculated value
Average thermal power requirement (const.)	$\dot{Q}_{\text{Warm water}}$	52	kW	Calculated value

4.3 Flow temperature and volume flow control

In the calculation model, the flow temperature results as a function of the ambient temperature in conjunction with a power-dependent volume flow control. This so-called combined mode is shown as an example in Figure 4

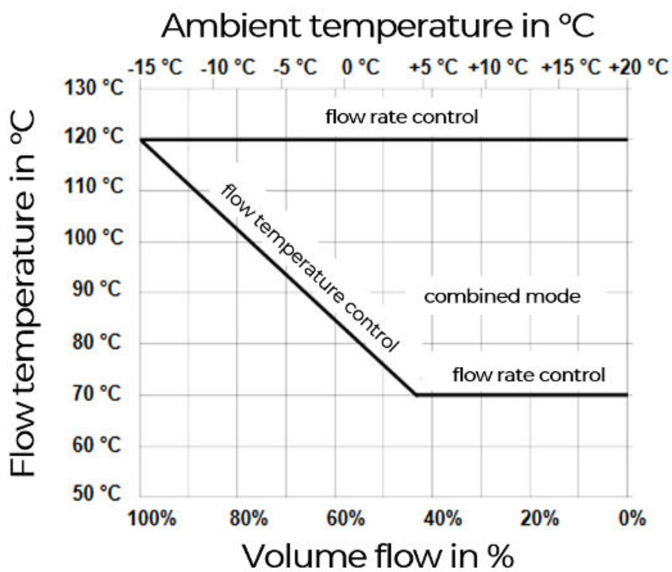

Figure 4: Typical flow temperature and flow rate control of a district heating network[9]

To reflect the trend[10] towards more energy-efficient heating networks with lower network temperatures and thus reduced heat losses, a range of 70 °C to 100 °C was selected instead of the flow temperature range of 70 °C to 120 °C as shown. For ambient temperatures above 3 °C, the flow temperature is thus 70 °C, and 100 °C for ambient temperatures below -15 °C. For the ambient temperature range between 3 °C and -15 °C, the flow temperature is interpolated linearly accordingly (see Table 2).

The volume flow is controlled as a function of the total heat output required for heating and hot water. Assuming a spread of 20 K between the flow and return temperatures, the output-specific volume flow is $\dot{v}_{\mathrm{DH}}$ 40 m^3/(h MW). Outside the heating period, the heat demand is reduced only to the hot water supply. To prevent the formation of legionella, heating the hot water to a temperature above 60 °C at the substation must be ensured. This is done by providing a minimum volume flow through the district heating network. The calculations are based on the assumption, that the district heating temperature entering the substation is still

[9] Source: Fraunhofer Study, 1998

[10] Source: Sustainable requirements for heat grids of the future, Agora Energiewende, 2019

at least 66 °C[11] and that after the transfer $\dot{Q}_{\text{Warm water}}$ (52 kW), the hot water has cooled down to 60 °C. According to equation (3), this results in a minimum flow rate $\dot{V}_{\text{DH,MIN}}$ of 7.7 m³/h.

$$\dot{V}_{DH,MIN} = \frac{\dot{Q}_{Warm\ water}}{c_{p,H_2O} \cdot \varrho_{H_2O} \cdot \Delta T} = 7{,}7\ \frac{m^3}{h} \tag{3}$$

Table 2: Heat source - assumptions and characteristic values

Designation	Formula symbol	Value	Unit	Source
Heat source 1: natural gas-fired hot water generator				
Efficiency	$\eta_{\text{Hot water generator}}$	0.95		Viessmann
Flow temperature district heating	$T_{\text{DH,flow}}$			
for $\text{T}_{\text{ambient}} > 3\ °C$		70	°C	Acceptance
for $3\ °C > \text{T}_{\text{ambient}} > -15\ °C$		70...100	°C	linear interpolated
for $-15\ °C >\ \text{T}_{\text{ambient}}$		100	°C	Acceptance
Volume flow district heating	$\dot{V}_{\text{DH}}$			
Minimum volume flow	$\dot{V}_{\text{DH,MIN}}$	7,7	m³/h	Calculated value
Power-specific volume flow for a spread of 20 K	$\dot{v}_{\text{DH}}$	40.0	m³/(h MW)	Planning Manual District Heating, p.12
Maximum volume flow	$\dot{V}_{\text{DH,MAX}}$	40.0	m³/h	Calculated value

4.4 Heat losses

The heat losses from underground district heating pipelines to the surrounding ground can be calculated using equation (4). Here $\dot{q}_{\text{v}}$ is the specific heat loss per meter of pipe run, L the pipe length of the pipeline, and ΔT is the temperature difference between the temperature in the pipeline T_{DH} and the temperature of the ground T_{ground}. Moreover, the equation is valid only under the assumption that both T_{DH} as well as T_{ground} are constant over the considered pipeline section. Accordingly, heating of the ground in the vicinity of the pipeline is not considered in the present calculation.

$$\dot{Q}_V = \dot{q}_v \cdot L \cdot \Delta T = \dot{q}_v \cdot L \cdot (T_{DH} - T_{ground}) \tag{4}$$

The specific heat loss per linear meter of pipeline $\dot{q}_{\text{v}}$ depends on the pipeline material, its thermal insulation, and the pipeline diameter d_{DH}. The required minimum pipe diameter $d_{\text{DH,MIN}}$ is 84.1 mm. It is calculated based on a typical maximum flow velocity for district heating networks $v_{\text{DH,MAX}}$ of 2.0 m/s and the maximum total volume flow $\dot{V}_{\text{DH,MAX}}$ determined in section 3.4. of 40 m³/h. Consequently, the next largest common pipe diameter of 100 mm (DN100) is chosen for the district heating pipes. The piping material is assumed to be a plastic jacket

[11] Assumption was confirmed in the further course (cf. T_2 in Figure 11 and Figure 11)

composite pipe of insulation class DS3 (see Figure 5). Under these boundary conditions, the specific heat loss per linear meter of pipe $\dot{q}_{\mathrm{V}}$ results in 0.43 W/(m K) (see Table 3).

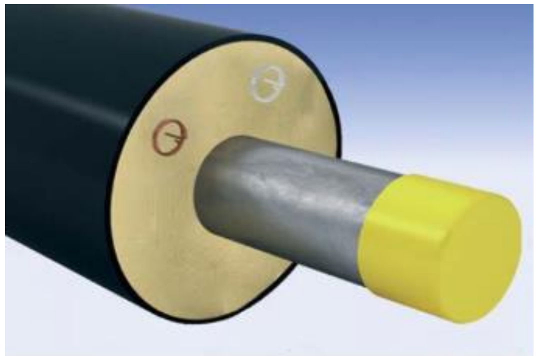

Figure 5: Example of a plastic jacket pipe (KMR) with insulation class DS3[12]

Table 3: Heat distribution network - assumptions and characteristic values

Designation	Formula symbol	Value	Unit	Source
Heat distribution network				
Design parameters				
Default typ. flow velocity	$v_{\mathrm{DH,MAX}}$	2,0	m/s	Planning Manual District Heating, p. 13
Minimum pipeline diameter	$d_{DH,\mathrm{MIN}}$	84.1	mm	Calculated value
Selected pipeline diameter	d_{DH}	100	mm	Acceptance
Flow velocity range for DN100		0.3...1.4	m/s	Calculated value
Flow line length	$L_{\mathrm{DH,flow\ line}}$	1.000	m	Acceptance
Return line length	$L_{\mathrm{DH,return\ line}}$	1.000	m	Acceptance
Heat losses				
Specific heat loss per linear meter of pipeline (KMR, DS3 plastic jacket pipe)	$\dot{q}_{\mathrm{V}}$	0.43	W/(m K)	Planning Manual District Heating, p. 206
Line section length for loss calculation	$L_{\mathrm{DH,line\ section}}$	100	m	Acceptance
Heat loss per pipe section	$\dot{Q}_{\mathrm{V,pipe\ section}}$	1.8...3.8	kW	Calculated value
Max. temperature drop in DH line section	$\Delta T_{\mathrm{V,DH,MAX}}$	0.33	K	Calculated value

Within the scope of the calculation example, only the losses of the supply and return lines with an assumed length of 1,000 m each are considered in a simplified manner ($L_{\mathrm{DH,Flow}}, L_{\mathrm{DH,Return}}$). Assuming a constant ground temperature per time period and dividing the supply and return pipes into 100 m long pipe sections for which the following assumption $T_{\mathrm{DH}} = constant$ applies, the power loss of the individual pipe sections can be determined for each time period of the calculation example.

[12] Source: Fact sheet FW lines, Basler & Hofmann AG

4.5 Time period calculation

Using the variables described and derived in the previous sections, the heat flows and individual temperatures of the district heating network are now determined for one year in hourly intervals and the calculation sequence for a single time period n, shown in Figure 6.

First, the parameters of the hot water generator (flow temperature and water mass flow) are determined based on the input values. Then, for the 1,000 m long supply line, the heat losses to the ground and the remaining temperature in the district heating network are calculated for each 100 m section of pipe. The temperature at the outlet of the district heating network is determined by the heat output at the substation, which in turn is based on the heating and hot water demand. This is followed by the calculation of the losses and the resulting district heating temperatures for the return pipe in the same way as for the supply pipe. The temperature at the end of the return line again corresponds to the inlet temperature at the hot water generator.

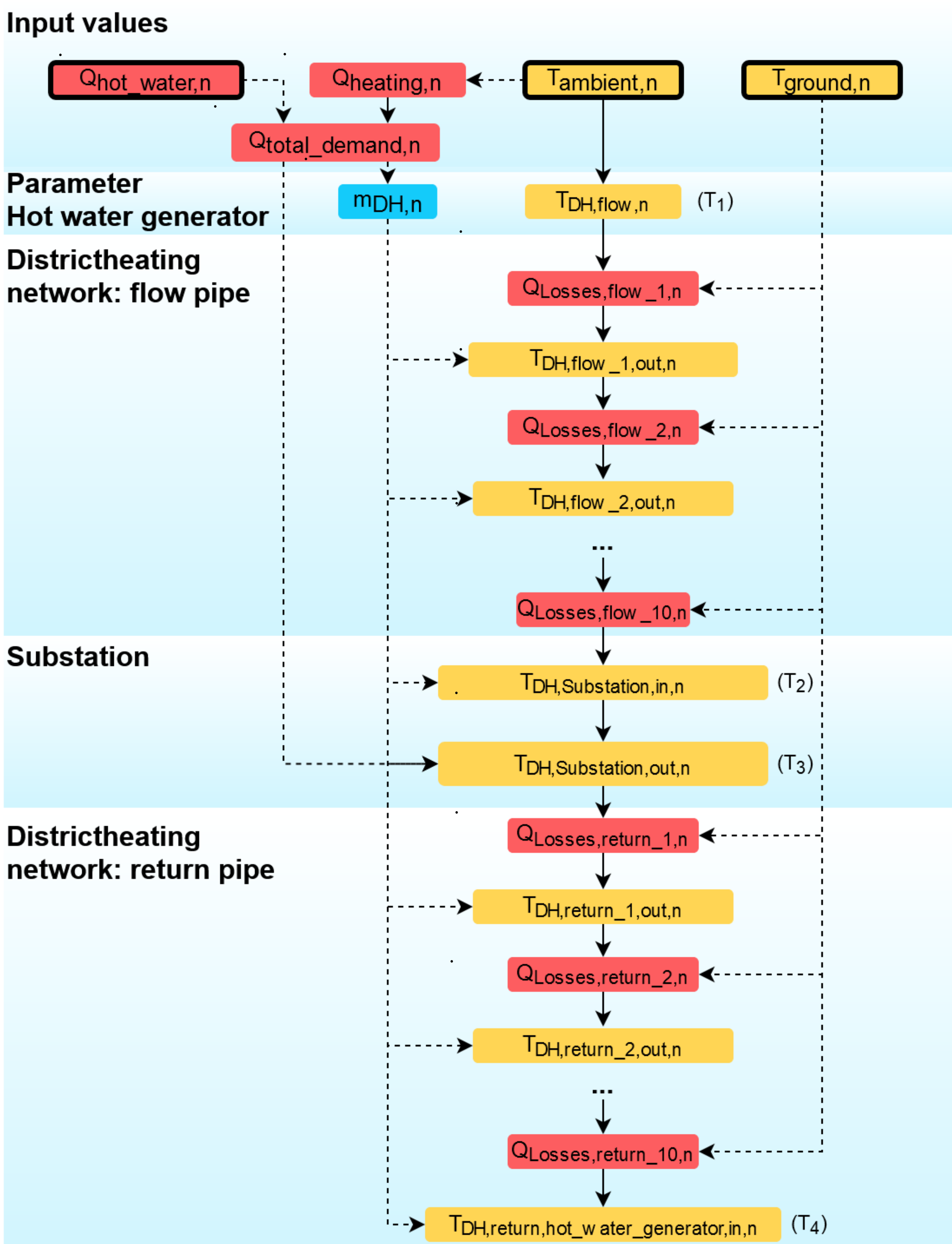

Figure 6: Calculation procedure for determining the heat flows and temperatures in the district heating network for the time n

4.6 Results

The district heating model results are illustrated in the heat output curves of Figure 7. Here, the losses of the hot water generator as well as the losses via the heating network pipelines to the surrounding ground can be seen. In addition, the figure illustrates the division of the heating requirements between heating and hot water. Another result of the calculation model are the temperature curves over time at the different positions in the district heating network. These form the calculation basis for evaluating the utilization potential of data center waste heat in district heating networks (see Figure 11). The annual primary energy demand of the district heating network considered here[13] with a peak heat demand of 1 MW is 2.69 GWh/a. With an assumed specific natural gas price of 4.5 ct/kWh, this results in annual energy costs of 121,040 €/a. The associated CO_2 emissions amount to 543 t per year[14].

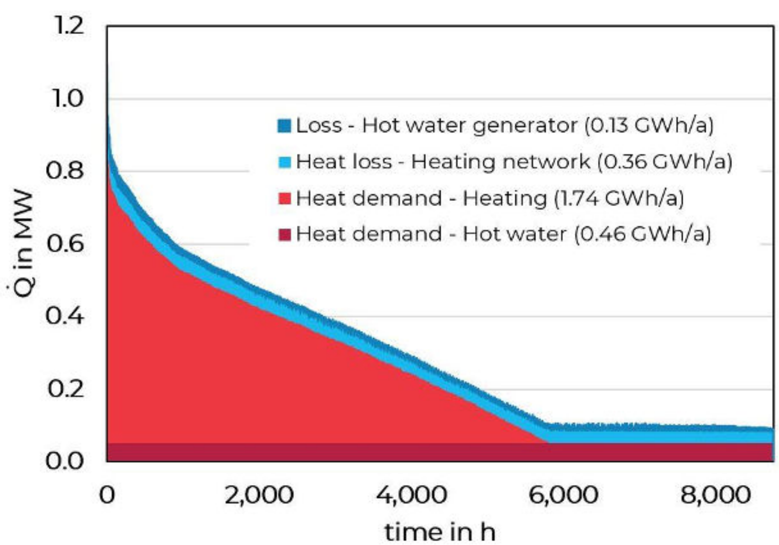

Figure 7: Heat outputs of the district heating network as annual duration curves

[13] Required fuel energy of the hot water generator without considering additional auxiliary energy such as pumps, etc.
[14] Emission factor for natural gas: 202 g CO_2/kWh, source: leaflet on CO_2 factors, BAFA 2019.

5 Potential of waste heat utilization in water-cooled data centers

5.1 Waste heat utilization potential

This analysis of the potential for waste heat recovery from data centers focuses on data centers with direct hot water cooling, as currently offered by Cloud&Heat Technologies - e.g., in the form of container data centers (see DCC20F in Figure 8).

Figure 8: DCC20F - water-cooled 20 ft. Data Center Container, max. total power: 275 kW, max. IT power: 240 kW (Cloud&Heat Technologies)

Figure 9 provides an overview of the basic cooling structure. The electrical energy supplied to the IT hardware is completely converted into heat. Depending on the water-cooled IT hardware used, typically a share of 83% of this heat can be cooled by means of a hot water circuit with a spread of 63/53 °C.[15] Due to the high temperature level of up to 63 °C, this energy is directly available as usable waste heat. The remaining waste heat (17%) first dissipates into the air and is then fed to a cold-water circuit by means of air/water heat exchangers (e.g., InRow/Side cooler, Door Cooler).

A compression chiller then raises this low-temperature waste heat to the temperature level of the hot water circuit, thus ensuring that this proportion of the waste heat can also be used. The thermal energy of the auxiliary electrical energy required to operate the ancillary units (pumps, heat pumps, side coolers, etc.) is transferred to air or water

[15] The temperature of the hot water circuit with the IT hardware is 53 °C in the flow and 63 °C in the return.

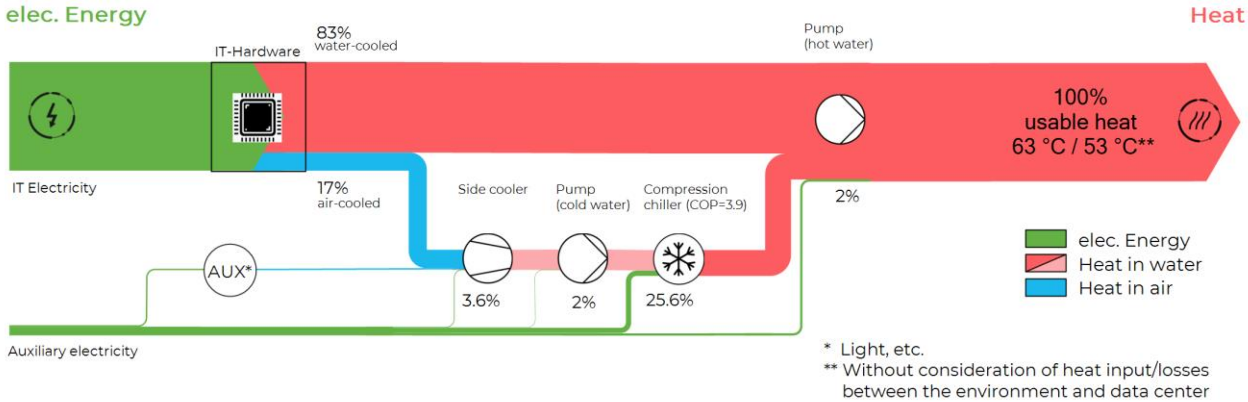

Figure 9: Energy flow diagram of a water-cooled C&H data center (without recirculating chiller) using the DCC20F as an example.

within the data center, so that finally this heat is also added to the waste heat stream at 63 °C. Experience shows that the heat input and heat loss of a DCC20F data center to the environment is ± 3 kW. These are neglected in the further considerations. Therefore, according to Figure 9 it is initially assumed that 100% of the invested electrical energy can be used in the form of heat for potential further use in downstream processes. The decoupling of the data center waste heat is realized by means of a heat exchanger. Depending on the operating conditions, design, and construction, this has a temperature difference between the hot medium (here the hot water circuit of the data center) and the cold medium (for example a district heating network). For the present simplified calculation, a counterflow heat exchanger with a constant temperature difference of 3 K is assumed. As a result, the heat dissipation is limited by two boundary conditions:

1. The cold medium can be heated to a maximum of 60 °C (63 °C - 3 K).
2. To cool the IT hardware, the hot water circuit must be cooled down to 53 °C. If the temperature of the cold medium at the heat exchanger is above 50 °C (53 °C - 3 K), their waste heat cannot be completely transferred to the district heating network, so a second heat sink (e.g., a dry cooler) is required.

In both cases, the data center waste heat cannot be transferred to the connected heat sink, or only partially. However, the cooling of the data center must always be ensured regardless of the further use of its waste heat. The remaining heat must therefore dissipate to the environment via a heat sink downstream of the heat exchanger, such as a dry cooler. In this process, the electrical energy supplied to the dry cooler is also converted into heat. However, since this is discharged directly to the environment, it cannot be put to any subsequent use. The specific electrical energy requirement of a dry cooler in relation to the amount of heat it transports is assumed to be 3%. Accordingly, 2.9% of the total rated power of the data center must be reserved for the dry cooler, so that a maximum of 97.1% of the total rated power of the data center is supplied for subsequent use in the form of waste heat. Table 4 summarizes the performance data of a water-cooled DCC20F data center container.

Table 4: Water-cooled DCC20F data center container - performance data and assumptions

Designation	Formula symbol	Value	Unit	Source
Total rated power	$P_{\mathrm{DC,total,100\%}}$	275	kW	C&H
IT rating	$P_{\mathrm{DC,IT,100\%}}$	240	kW	C&H
Rated power auxiliary units	$P_{\mathrm{DC,aux.energy,100\%}}$	35	kW	C&H
...of which dry cooler	$P_{\mathrm{DC,recooler,100\%}}$	8	kW	Acceptance
Average capacity		50	%	Acceptance
Max. useful waste heat	$\dot{Q}_{\mathrm{DC,useful\ heat,100\%}}$	267	kW	Calculated value
		(97.1	%)	Ref. to $P_{\mathrm{RZ,Gesamt,100\%}}$

5.2 District heating & data center - separate and coupled use in comparison

The energy coupling of district heating networks and data centers with hot water cooling makes it possible to reduce the primary energy demand of the district heating network as well as the auxiliary energy required for cooling the data center. This relationship is demonstrated by the comparison of the annual energy and mass flows for the separate and coupled use of both systems as illustrated in Figure 10. The scenario shown is based on two DCC20F data center containers (cf. Figure 8) with a total rated power of 550 kW (IT power: 480 kW) and an assumed constant utilization of 50%, as well as the district heating network described in Chapter 4 with a maximum heat demand of 1 MW.

When used separately, the district heating network requires 2.69 GWh/a of primary energy in the form of natural gas to operate the hot water generator. In Figure 10 this energy quantity always corresponds 100% in relation to the district heating network. After the conversion of the chemical energy of the natural gas into thermal energy, 95% of the original energy is available for the district heating network at the output of the hot water generator at the temperature level of T_1 (see Figure 11). After deducting the thermal losses of the supply pipeline to the ground (8%), 87% of the output energy reaches the district heating transfer station at the temperature level of T_2. After meeting the heat demand (hot water 17%, heating 65%), the temperature in the district heating network at the output of the district heating transfer station drops to the temperature level of T_3. The remaining energy (5%) dissipates into the ground as heat loss from the return flow, and the water in the district heating network cools down to T_4.

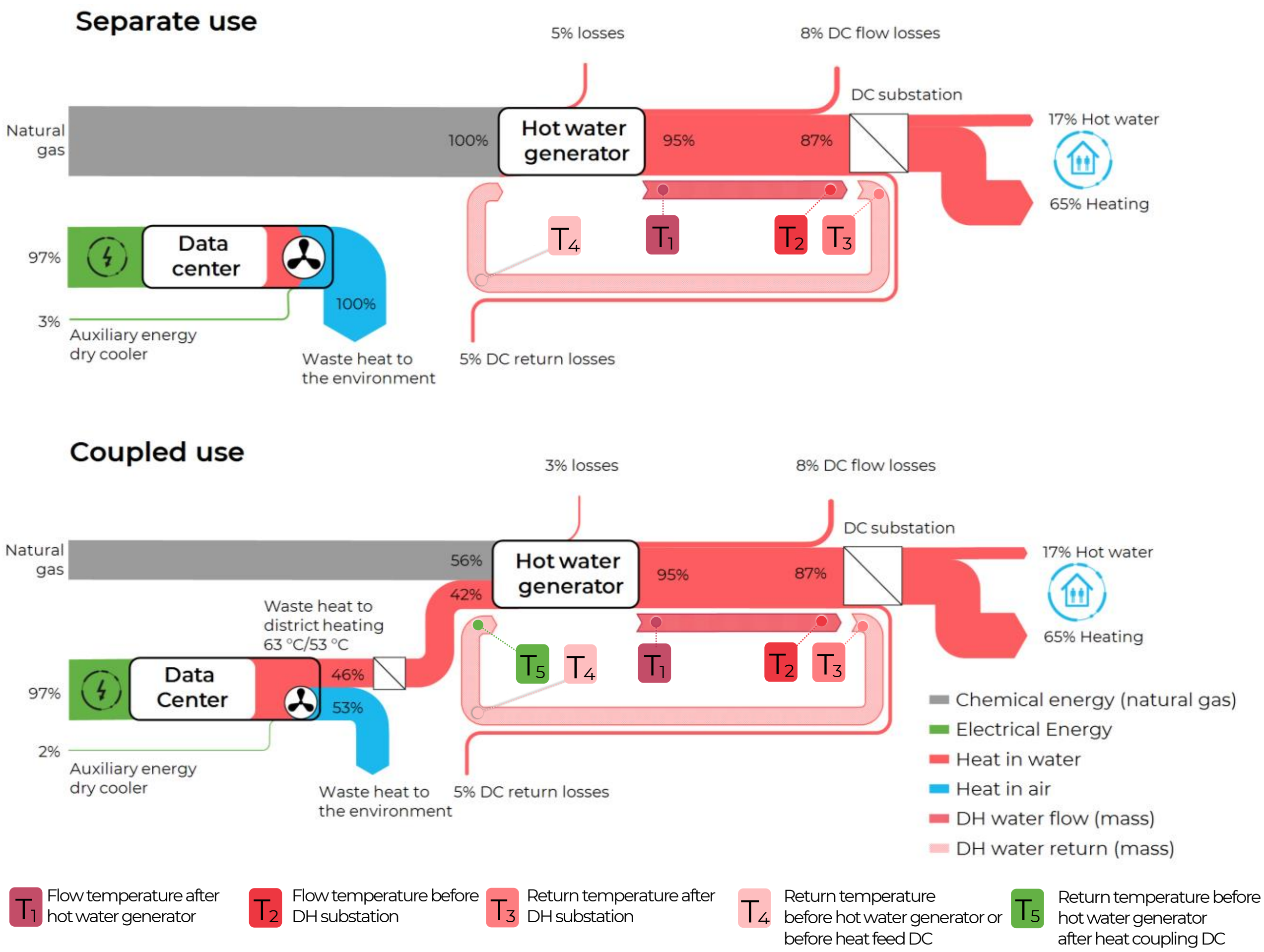

Figure 10: Annual energy and mass flows of district heating network and data center with separate and coupled use

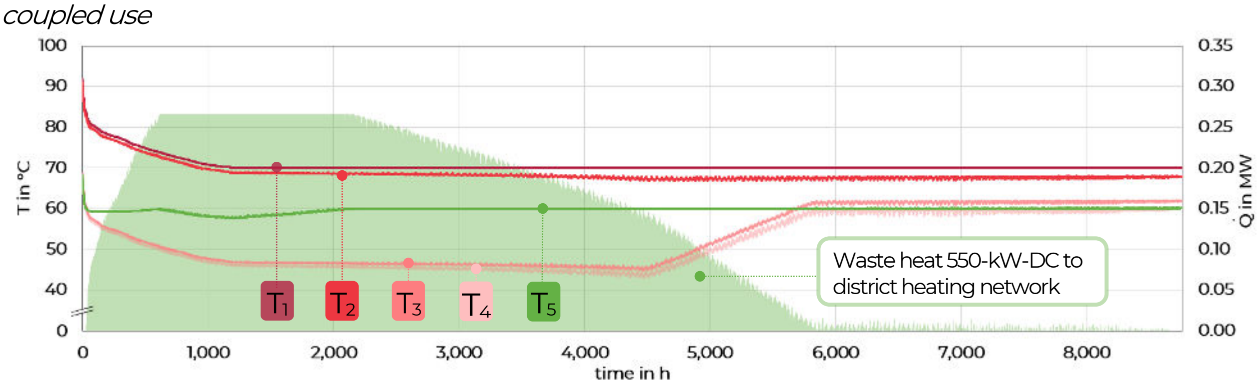

Figure 11: Temperature curves in the district heating network and power curve of the waste heat from the data center that can be used in the district heating network

With a utilization of 50%, the operation of the 550-kW data center has an electrical energy demand of 2.41 GWh per year. This represents the reference value of 100% for the data center in Figure 10. 97.1% is used to operate the data center while 2.9% is used to operate the dry cooler. As described in Section 5.1, this energy is completely converted into thermal energy and then released to the environment. The data center and district heating network are coupled by feeding data center waste heat via a heat exchanger into the return flow of the district heating network, hereby raising its temperature level from $T_{4,\mathrm{n}}$ to $T_{5,\mathrm{n}}$. Here, the transmittable heat flow is limited by the two boundary conditions described in section 5.1

The first condition states that the return flow of the district heating network can be heated to a maximum of 60 °C using data center waste heat. Equation (5) is therefore used to determine the time-dependent maximum heat flow that can be applied to the district heating network. $\dot{Q}_{\mathrm{DC,waste\ heat,max,n}}$ which is necessary to raise the temperature $T_{4,\mathrm{n}}$ to $T_{4,\mathrm{target}} = 60\ °\mathrm{C}$.

$$\dot{Q}_{DC,waste\ heat,max,n} = c_{p,H_2O}(T)\ \dot{m}_{DC,n}(T_{4,target} - T_{4,n}) \tag{5}$$

The second condition specifies that the data center can only deliver as much heat to the district heating network as the inlet temperature of the cold medium at the heat exchanger allows (district heating return temperature $T_{4,\mathrm{n}}$). Equation (6) demonstrates how to determine the corresponding heat flow $\dot{Q}_{\mathrm{DC,waste\ heat,n}}$. The temperature difference $\Delta T_{\mathrm{DC,n}}$ between flow and return temperature in the hot water circuit (see Table 5) is set in relation to the maximum temperature difference $\Delta T_{\mathrm{DCmax}} = 10\ \mathrm{K}$ and multiplied by the useful heat flow available at 50% utilization $\dot{Q}_{\mathrm{DC,useful\ heat,50\%}}$.

Table 5: Attainable temperature difference in the data center hot water circuit $\Delta T_{DC,n}$ between flow and return as a function of the district heating return temperature $T_{4,n}$

	$T_{4,n}$ < 50 °C	50 °C < $T_{4,n}$ < 60 °C	$T_{4,n}$ > 60 °C
$\Delta T_{\mathrm{DC,n}}$ in K	10	60 °C – $T_{4,\mathrm{n}}$	0

$$\dot{Q}_{DC,waste\ heat,n} = \frac{\Delta T_{DC,n}}{\Delta T_{DC,Max}} \dot{Q}_{DC,utilized\ heat,50\%} \tag{6}$$

The heat flow transferred to the district heating network $\dot{Q}_{\mathrm{DC,waste\ heat,real,n}}$ can be determined using the case distinction in equation (7). After this, the DC return temperature $T_{5,\mathrm{n}}$, following the heat-feed by the data center is calculated using equation (8).

$$\dot{Q}_{DC,waste\ heat,real,n} = \begin{cases} \dot{Q}_{DC,waste\ heat,n}, & \text{für } \dot{Q}_{DC,waste\ heat,n} \leq \dot{Q}_{DC,waste\ heat,max,n} \\ \dot{Q}_{DC,waste\ heat,max,n}, & \text{für } \dot{Q}_{DC,waste\ heat,n} > \dot{Q}_{DC,waste\ heat,max,n} \end{cases} \tag{7}$$

$$T_{5,n} = \frac{\dot{Q}_{DC,waste\ heat,real,n}}{c_{p,H_2O}(T) \cdot \dot{m}_{DC,n}} + T_{4,n} \tag{8}$$

The electrical power required to meet the remaining data center cooling demand via a dry cooler is shown in equation (9).

$$P_{el.,recooler,n} = 0.03 \cdot (\dot{Q}_{DE,useful\ heat,50\%} - \dot{Q}_{DC,waste\ heat,real,n}) \tag{9}$$

Due to the lower use of the dry cooler in coupled use, the energy demand of the data center is reduced by 0.03 GWh/a to 2.38 GWh/a. Figure 11 shows the power curve of the energy supplied to the district heating network in the form of heat. This adds up to 1.11 GWh/a, which corresponds to an energy reuse factor (ERF) of 46.7% for the energy invested in the data center.

This amount of heat is consequently no longer provided by the hot water generator of the district heating network. The annual primary energy demand of the hot water generator in the form of natural gas is thus reduced to 1.52 GWh/a, which corresponds to a saving of 1.17 GWh/a, or 43.4%. Table 6 provides an overview of the annual energy quantities for separate and coupled use of the data center and district heating network and the resulting potential savings.

Table 6: Annual energy quantities for separate and coupled use of a 550-kW data center and a 1 MW district heating network.

	separate use		coupled use		Savings	
Designation	Value	Unit	Value	Unit	Value	Unit
Hot water generator						
Primary energy (natural gas)	2.69	GWh/a	1.52	GWh/a	1.17	GWh/a
Losses	0.13	GWh/a	0.08	GWh/a		
Generated heat	2.19	GWh/a	1.45	GWh/a		
Data center						
Elec. energy demand	2.41	GWh/a	2.38	GWh/a	0.03	GWh/a
...of which dry cooler	*0.07*	*GWh/a*	*0.04*	*GWh/a*		
Heat to environment	2.41	GWh/a	1.27	GWh/a		
Heat to DC network	-	GWh/a	1.11	GWh/a		
District heating network						
Heat into the district heating network	2.56	GWh/a	2.56	GWh/a		
Heat losses DH flow	0.21	GWh/a	0.21	GWh/a		
Heat to hot water	0.46	GWh/a	0.46	GWh/a		
Heat to heating	1.74	GWh/a	1.74	GWh/a		
Heat losses DH return	0.15	GWh/a	0.15	GWh/a		

5.3 Savings potential

5.3.1 Carbon dioxide emissions

The energy savings potential shown in Table 6 results in a reduction of carbon dioxide (CO_2) emissions caused by the operation of the data center and district heating network. Figure 12 illustrates the corresponding CO_2 emissions and the achievable savings. Emissions are calculated using the associated emission factors of 0.202 kg/kWh[16] for natural gas and 0.025kg/kWh[17] for green electrical energy.

With annual CO_2 emissions of 367 t, the coupled use of the data center and district heating network can thus save 39.2% (237 t) of CO_2 per year compared to separate use.

To compensate for the same amount of CO_2, more than 18,900 deciduous trees would have to be planted[18]. Since the German forest absorbs an average of about 11 tons of CO_2 per hectare and year[19], this would require 21 hectares or 30 soccer fields of forest.

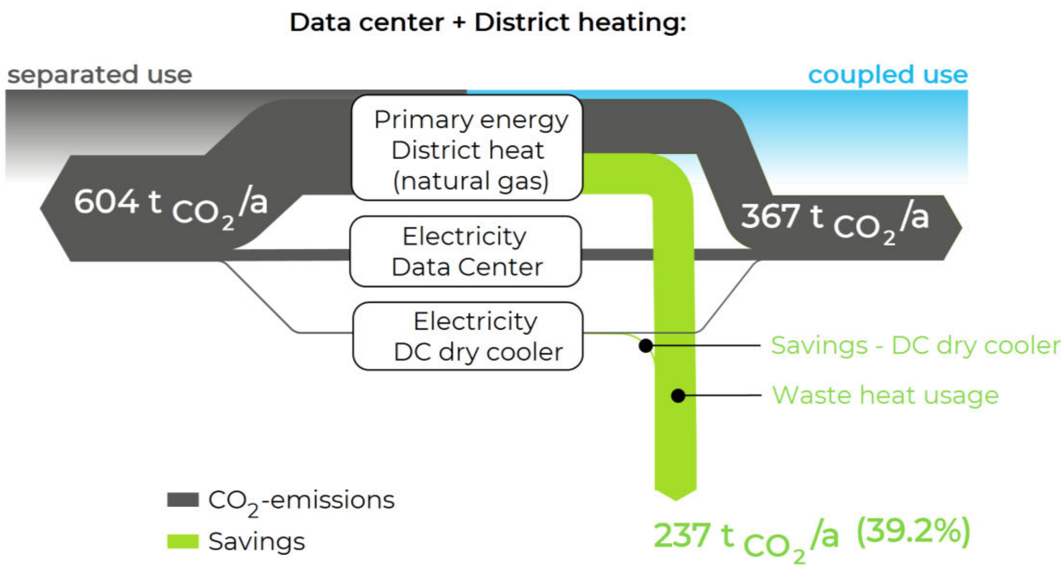

Figure 12: CO_2 emissions for separate and coupled use of a 550-kW data center and a 1 MW district heating network and possible savings for coupled use.

[16] Leaflet on CO_2 factors, Bafa 2019
[17] Green electricity mix with equivalent shares of photovoltaics, wind and hydropower Source: Emissionsbilanz erneuerbarer Energieträger, Umweltbundesamt 2018
[18] Source: co2online.de
[19] Source: Bayrische Staatsforsten AöR

5.3.2 Operating energy costs

In addition to reducing the CO_2 emissions, the coupled use also reduces the operating energy costs. The savings are largely dependent on the specific energy prices. For industrial customers in Germany, a specific energy price of 4.5 ct/kWh is assumed for natural gas and a price of 20.0 ct/kWh for electrical energy. Figure 13 compares the cost flows and savings for separate and coupled use of a 550-kW data center and a 1 MW district heating network under the defined boundary conditions. Compared to separate use with annual operating energy costs of 602.8 T€, coupled use has costs of 543.7 T€ per year. The resulting saving of 59.1 T€/a amounts to 9.8% of the annual operating energy costs. Of this, 89% (52.5 T€/a) is due to the 43.4% reduction in natural gas demand and 11% (6.6 T€/a) is due to the reduction in the electrical energy demand of the dry cooler.

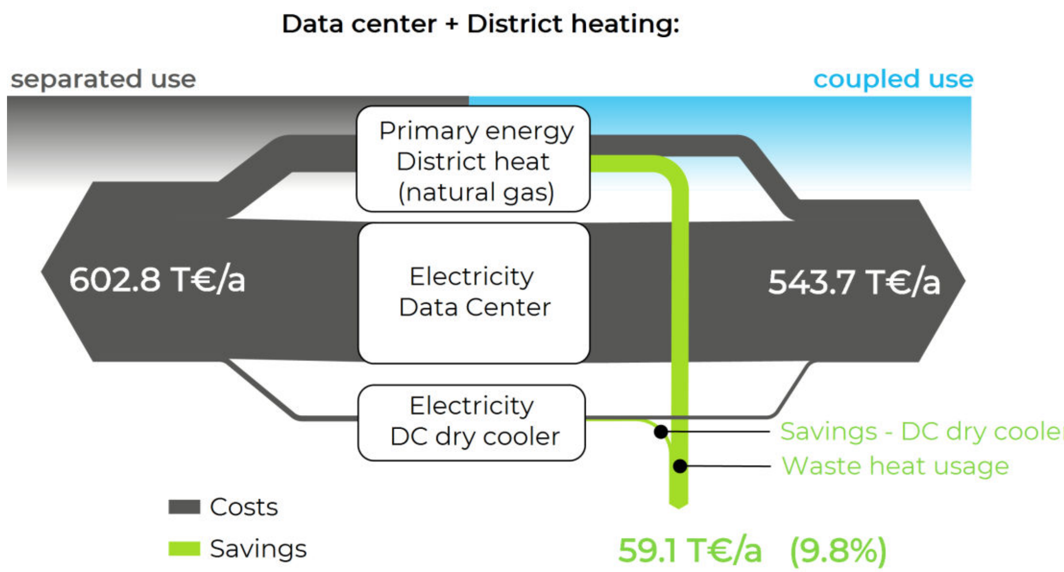

Figure 13: Energy costs for separate and coupled use of a 550-kW data center and a 1 MW district heating network and possible savings for coupled use.

5.3.3 Influence of the performance ratio of the data center to the district heating network

As the previous results (cf. Figure 11) suggest, there is a limit to the amount of waste heat that a data center can couple with a given district heating network. This is mainly due to the restrictions mentioned in section 4.1. For the district heating network described, the maximum potential of coupled heat can be realized by a data center with an electrical connected load of 758 kW and 50% constant utilization (cf. Figure 14, left). This increases the primary energy cost savings for natural gas to 45.5% and the total cost savings to 62 T€.

As Figure 14 (right) illustrates, the size ratio between the district heating network and the data center is thus a decisive factor for the achievable primary energy savings (natural gas) of the district heating network and the associated costs. In addition, the ratio also influences the heat efficiency of the data center (ERF).

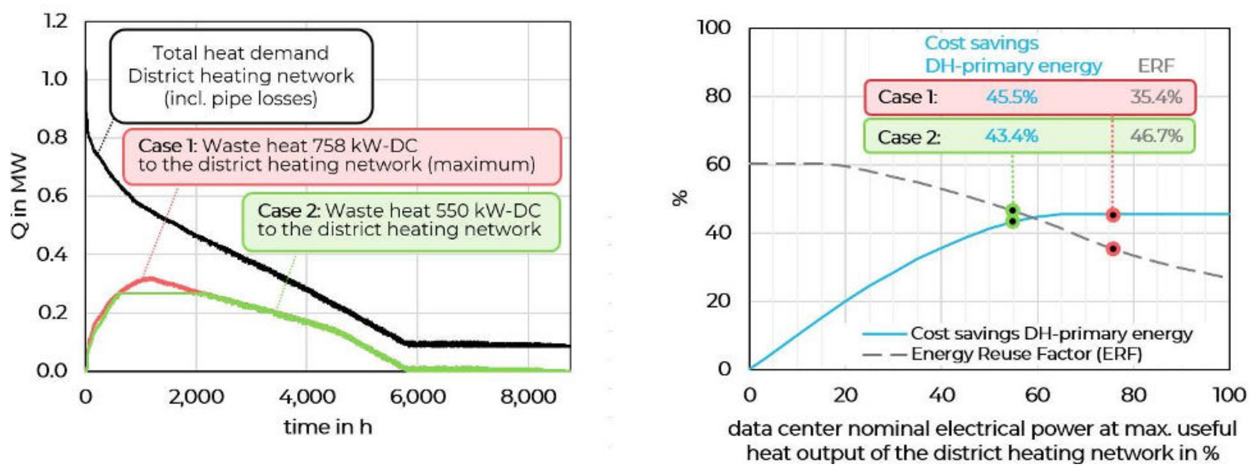

Figure 14: left – annual load duration curve of the district heating network total heat demand and the feed-in thermal power curve for a 758 kW and a 550 kW data center with an average utilization of 50%; right - cost savings of the district heating primary energy (natural gas) and heat utilization rate of the data center as a function of the ratio of the connected load of a data center to the max. useful heat output of the district heating network.

To ease the scalability of the results for comparison with other use cases, the maximum useful heat output was selected as the size indicator for the district heating network and the electrical connected load (constant utilization 50%) for the data center. An increase in the size ratio up to 60% is also accompanied by a significant increase in the cost savings percentage for the district heating primary energy. In contrast, the heat utilization rate of the data center shows its maximum value of 60% in the lower size ratio range at 0...20%.

If a data center is small in relation to the district heating network, a large part of its waste heat can be used. However, the cost savings percentage with respect to the primary energy of the district heating network are low. Up to a size ratio (data center to district heating network) of 65%, higher cost savings can be achieved by increasing the connected load of the data center.

The increasing relevance of waste heat utilization in the future raises the complexity of location decisions for new data center buildings. In this context the methodology presented in this white paper offers valuable assistance, e.g. by allowing the evaluation to which extent local heating networks can still absorb additional waste heat.

6 Conclusion and outlook

The success of energy suppliers in the energy-intensive cloud market depends not least on how strongly they can set themselves apart from existing suppliers in the areas of technical innovation, operating costs, and sustainability. Energy suppliers in particular can exploit existing synergies and thus make a significant contribution to climate neutrality, for example by feeding waste heat from data centers into existing heating networks.

This model calculation shows the savings potential of coupling a 550-kW data center (location: Frankfurt, average utilization: 50%) with a district heating network with a peak power heat demand of 1 MW.

The separate use of both infrastructures causes an energy demand of 2.69 GWh/for the district heating network (natural gas) and 2.41 GWh/a electrical energy for the data center. Coupled use reduces the energy demand of the district heating network by 1.17 GWh/a to 1.52 GWh/a and that of the data center by 0.03 GWh/a to 2.38 GWh/a.

CO_2 emissions are reduced accordingly from 604 t/a with separate use to 367 t/a with coupled use. The 237 t of carbon dioxide saved per year in this way correspond to an emission reduction of 39.2%. This is accompanied by a reduction of operating energy costs of 9.8% from 602.8 T€ to 543.7 T€ per year[20]. The absolute cost saving is therefore 59.1 T€/a. Apart from district heating networks, utilities have other infrastructures, such as renewable energy sources, whose coupling with data centers reveals significant synergy effects.

With the current energy transition, Germany is undergoing a change in terms of energy supply and use. Renewable energy sources (e.g., wind, solar), low-loss heating networks (e.g., low-temperature heating networks, local heating networks, neighborhood solutions) in combination with alternative hot water generators (biomass, hydrogen), and a decreasing specific heat demand of residential buildings[21] are elementary components. These factors influence the sustainability of the operation of data centers and their waste heat utilization, the investigation of which lends itself to further consideration.

[20] specific energy prices: Natural gas: 4.5 ct/kWh, electrical energy: 20.0 ct/kWh
[21] ASUE, 2017

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