

# A realistic view on heat reuse from direct free air-cooled data centres

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## ABSTRACT

This paper examines the opportunities to reuse excess heat from direct free air-cooled data centres without incorporating heat pumps to upgrade the heat. The operation of a data centre in northern Sweden, Luleå, was simulated for a year. It was established that heat losses through the thermal envelope and from the humidification of the cooling airflow influenced the momentary energy reuse factor, iERF, with up to 7%. However, for the annual energy reuse factor, ERF, the heat losses could be neglected since they annually contributed to an error of less than 1%.

It was shown that the ideal heat reuse temperature in Luleå was 13, 17, and 18 °C with an exhaust temperature of 30, 40 and 50 °C. The resulting ERF was 0.50, 0.59 and 0.66, meaning that a higher exhaust temperature resulted in potentially higher heat reuse. It could also be seen that raising the exhaust temperature lowered the power usage effectiveness, PUE, due to more efficient cooling.

Using heat reuse applications with different heat reuse temperatures closer to the monthly average instead of an ideal heat reuse temperature for the whole year improved the ERF further. The improvement was 11–31% where a lower exhaust temperature meant a higher relative improvement.

## Introduction

The data centre industry is electricity intensive and is responsible for around 1 % of the global electricity consumption [1]. Electricity is used to power the IT equipment, the cooling system, the uninterruptible power supply (UPS), and building infrastructure such as lights, ventilation and office areas. The interest in the data centres' electricity consumption emerged around the end of the 1990 s when the industry started to expand [2]. This naturally led to an increased interest in research concerning the excess heat rejected from the data centres and more specifically how it could be recovered and reused. The topic is now more relevant than ever since the EU, in February 2019, presented its strategy "Shaping Europe's digital future" [3] which states that data centres should become climate neutral by 2030 implementing, amongst other things, the reuse of waste energy.

Furthermore, the EU's 2030 climate target plan [4] states that the EU should reduce its greenhouse gas emissions by 55 % by 2030 on its way to becoming climate neutral by 2050. To provide a framework for the transition the EU proposed a package called "Fit for 55" [5] in July 2021. The package contains a set of proposals to revise and update EU

legislation to fit the EU's 2030 greenhouse emissions target. One part of the package is the recast of the energy efficiency directive [6] first established in 2012. At the time of writing, the recast procedure is ongoing. Still, some of the amendments have been adopted during the first reading [7], most interesting for this study is article 11a addressing data centres. The article states that data centres with an installed IT power above 100 kW should monitor and publish key performance indicators, KPI, from the CENELEC EN 50600-4 standard [8]. The Energy Reuse Factor metric (ERF) is defined in parts 4–6 which shows how much of the excess heat produced by the data centre is reused. Currently, few actors reports that they are reusing heat, either directly within the building or upgrading the heat with heat pumps and supplying it to the district heating network [9]. Mandatory ERF reporting will bring heat reuse into the spotlight making it easier to compare different data centres heat reuse and audit their heat reuse claims.

### Key performance indicators

The ERF quantifies the reuse ratio of the energy used within the data centre. The ideal and unachievable scenario is an ERF of 1, meaning that

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100 % of the energy used by the data centre is reused. It is calculated as,

$$ERF = \frac{E_{Reuse}}{E_{DC}} \quad (1)$$

where  $E_{DC}$  is the sum of the energy used by the IT equipment, the cooling system and all other infrastructure needed to run the data centre.

$$E_{DC} = E_{IT} + E_{cooling} + E_{humidification} + E_{powerdistribution} \quad (2)$$

And  $E_{IT}$  is the energy used by the IT equipment uses alone.

The standard states that  $E_{reuse}$  should be measured at the handoff point of the heat reuse application meaning that heat lost during the transfer to the heat reuse application is not counted as reused. It is also stated that for most cases the reused energy may be calculated from the temperature and flow of the heat reuse. This gives,

$$E_{Reuse} = \dot{m}_{reuse} * C_p * (T_{reuse,in} - T_{reuse,f}) \quad (3)$$

where  $\dot{m}_{reuse}$  is the mass flow of air that is reused,  $C_p$  is the specific heat capacity of the air and  $T_{reuse}$  is the initial and final temperature from the heat reuse. Note that the value of  $C_p$  changes with the air's absolute humidity of the air so the conditions of the heat reuse need to be considered. For example, the specific heat capacity of ambient air in Luleå ranges from 1.006 kJ/Kg,K in really cold weather to 1.016 kJ/Kg, K on warm and humid days.

Another important KPI for data centres is Power Usage Effectiveness (PUE) which describes how efficiently the data centres operate. It is calculated as,

$$PUE = \frac{E_{DC}}{E_{IT}} \quad (4)$$

The best scenario is a PUE of 1 which happens if the only energy user within the facility is the IT equipment e.g., no cooling or other infrastructure needed. The metric gives an indication of how efficiently the data centre runs as a facility. Still, there is no consideration of how efficient the actual IT operates, for example FLOPS per watt.

According to the standards [8,10], both the PUE and the ERF are annual figures so when they are calculated for smaller intervals or even real-time figures the prefix "i", interim, is used as iPUE and iERF which will be applied in this study.

#### Data centre heat reuse

Most data centres today are air-cooled, which makes heat reuse a challenge. The excess heat temperature ranges from 15 to 45 °C [11], depending on where it is captured and is bound to air, which results in a low specific heat capacity and energy density. This means that heat reuse applications must operate at low temperatures handling large volume flows of air and that transportation and storage of the heat is difficult.

The objectives for data centre energy research have in the past mainly been to optimize thermal management by finding more efficient cooling strategies, resulting in an increased power usage efficiency by reducing the demand for chiller work and facility electricity [12–16]. In general terms as [14] who investigated challenges and thermal management techniques in general for both air- and liquid-cooled data centres and [15], who studied how climate conditions and cooling systems affected the data centres energy use. But also with a focus on specific technologies, [12,13] investigated the use of economizers, and [16] the use of heat-pipe based heat exchangers to improve the cooling efficiency.

Several papers can be found in the field of data centre excess heat reuse e.g., absorption refrigeration, organic Rankine cycles, desalination-, clean water production, piezoelectric, thermoelectric, space heating, swimming pools, biomass-, power plant co-location, district heating alt. hot water production. For example, [17] showed that reusing otherwise rejected heat from the data centre to heat buildings in

Beijing would not only reduce the use of coal-based heating but also improve the energy efficiency of the data centre. Another example of synergy effects was studied by [18] where a swimming pool operator could reduce its operational expenses at the same time as the data centres cooling systems energy demand were reduced. Data centre excess heat driven cooling was studied by [19,20] showing payback periods below a year for absorption refrigeration cooling and adsorption chiller, respectively.

The most researched heat reuse application as of today is district heating. This normally requires the excess heat to be upgraded with the use of heat pumps. One study [21] compared the heating demand for London boroughs with the excess heat output from nearby data centre and showed that up to 55,4% of the boroughs heating demands could be met with data centre excess heat. The amount of excess heat available to reuse as district heating was shown to be stable over the day by [22] and synergy effects where the data centre become more energy efficient with heat reuse were also observed here. Another study [23] showed that the data centre could adapt the excess heat generation to the demand of the grid by actively optimizing the cooling system making the data centre a more on the demand heat source.

Since heat pumps add even more electricity to the load of an already electricity-intensive industry, to provide a more comprehensive picture this study focuses on heat reuse without incorporating heat pumps to upgrade the heat. Besides no need for additional energy, the main advantage is that the heat reuse will not be part of the cooling system making it a solution easier to retrofit.

There is a great variety of applications, shown in Fig. 1, that could reuse the excess heat from data centres besides district heating. Areas highlighted with red rings are explored and evaluated by the data centre research team at the Research Institutes of Sweden (RISE) [24]. Their aim is to provide knowledge and understanding about how to reuse excess heat from data centres and, in the long run, support the industry to become more sustainable.

Ebrahimi et al. [11] conducted one of the most comprehensive reviews to date on the opportunities to recover and reuse data centre excess heat. They clearly explain the conditions for heat reuse and the difficulties that might ensue. Furthermore, they explore several applications, which could reuse the excess heat. However, a crucial element is missing: the seasonal perspective, changing ambient conditions will impact heat reuse. Neither the shape of the available excess heat nor the

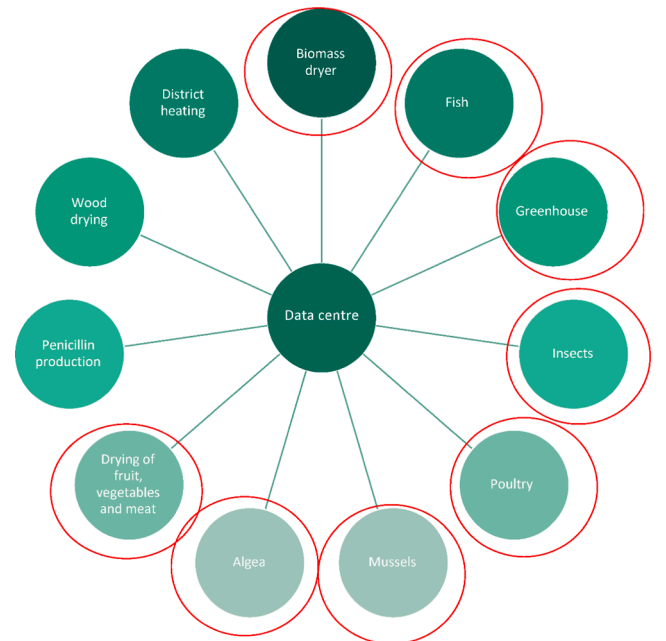


Fig. 1. Heat reuse applications.

heat demand of most applications is constant over the year, and this will affect how well the excess heat can be reused.

For example, the authors of [22] argue, justifiably, that excess heat will be available at a constant load because the IT equipment's electrical consumption is constant. Moreover, [25] showed that 97 % of the data centre electric consumption is available as excess heat throughout the year. The problem is that even if all the electrical consumption of a data centre is exhausted as excess heat it doesn't mean that the heat reuse application can absorb all heat. Depending on the cooling system, ambient conditions may severely impact the possibility of reusing the heat by altering the volume flow of excess heat. This study's authors have previously [26] concluded that the lowest volume of excess heat output in northern Sweden for a direct free air-cooled data centre was only 10 % of the peak output. This means that the heat reuse application must operate at a larger temperature interval, e.g., a lower final temperature, to reuse the same amount of heat, to compensate for the reduced volume flow of excess heat.

This study aims to give a realistic view on the opportunities to reuse excess heat from direct air-cooled data centres. The objective is to analyse how heat reuse temperatures, and the seasonal changes of the ambient conditions affect the heat reuse potential of the data centre by quantifying the maximum achievable ERF at different ambient and heat reuse temperatures. The focus is on data centres with direct-free air-cooling systems since this is the most energy-efficient cooling technology for data centres. Finding an upper limit on the heat reuse of data centres is important for future legislature and data centre owners to be able to set reasonable demands and expectations. The cooling method explored in this paper is used by several hyperscale data centres in the sub-arctic region, for example by Meta (formerly known as Facebook) [27,28] which makes it important to investigate, both for future establishments and improvement of already existing facilities.

## Methodology

To fulfil the aim and achieve the objectives the workflow described in Fig. 2 was followed.

At first, the energy flows in a data centre operating for a full year were simulated to check if the heat losses in a direct free air-cooled data centre could be neglected when calculating the ERF. Then, three different exhaust temperatures were analysed to determine the highest achievable ERF at a constant heat reuse temperature. This was followed up by investigating how using various heat reuse temperatures could improve the ERF.

## Simulation

The dynamic building energy simulation software IDA ICE 4.8 (IDA Indoor Climate and Energy) was used to compute hourly values for the energy balance of the data centre operating at 1 MW. The energy balance calculates values for all sources of energy loss, for example transmission and ventilation losses, and energy supply, for example internal loads and solar radiation. Both researchers and engineers use the software and it has been validated several times [29,30]. The model used in the software is a refined version of previous work [26] by the authors. The main update to the model was implementing variable cooling supply temperature. The previous model could only operate with a constant supply temperature on the cooling airflow which does not result in optimal cooling. It is favourable to use a supply temperature as low as possible. This reduces the airflow needed to supply the same amount of cooling, due to a larger temperature difference. Resulting in a reduced energy demand from the cooling fans and therefore more efficient cooling.

## Reference data centre

Boden Type DC One (BTDC [31]) was chosen as a reference data centre for this study's data centre model. It is a data centre funded by the EU grant No 768,875 with the objective becoming the world's most energy-efficient data centre. BTDC has released a public raw data collection on one year's operation, 2019–2020 [32]. The PUE during that year was 1.014 which will be used to validate the resulting PUE of the model. BTDC consists of an entrée, a tech room (mainly power distribution) and three pods for up to 250 kW of IT equipment each. The only additional load for BTDC is the cooling system since it lacks permanent staff and power redundancy e.g., uninterruptible power sources. An extra pod of 250 kW was added to the model to bring the IT load to 1 MW for easier reference. The building is ambitiously constructed (blueprint is shown in Fig. 3) compared to data centre standards, featuring an insulated roof and walls with a U-value of 0.23 W/m<sup>2</sup>K and a concrete floor with a U-value of 0.17 W/m<sup>2</sup>K.

BTDC is located in the municipality of Boden in the north of Sweden. Still, due to a lack of local weather data, Luleå (40 km away) was used as the location, and the corresponding climate [33], for the model.

BTDC practices direct free air cooling. This means outdoor air is used directly to cool the data centre without involving heat exchangers or refrigeration cycles. A schematic overview is shown in Fig. 4.

Outdoor air (1) is mixed with warm air (8) recirculated from the server room to regulate the supply temperature (2). The air stream can also be humidified (3) if the ambient conditions require it before being

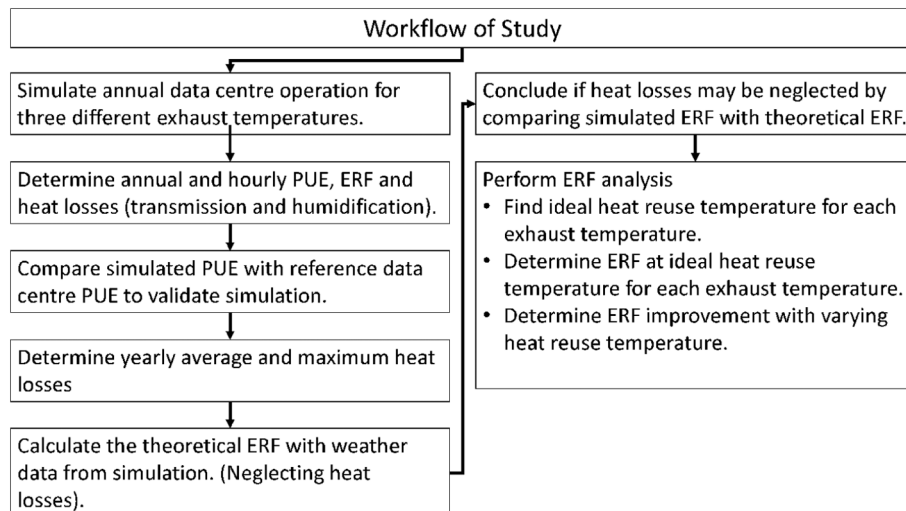


Fig. 2. Workflow of the study.

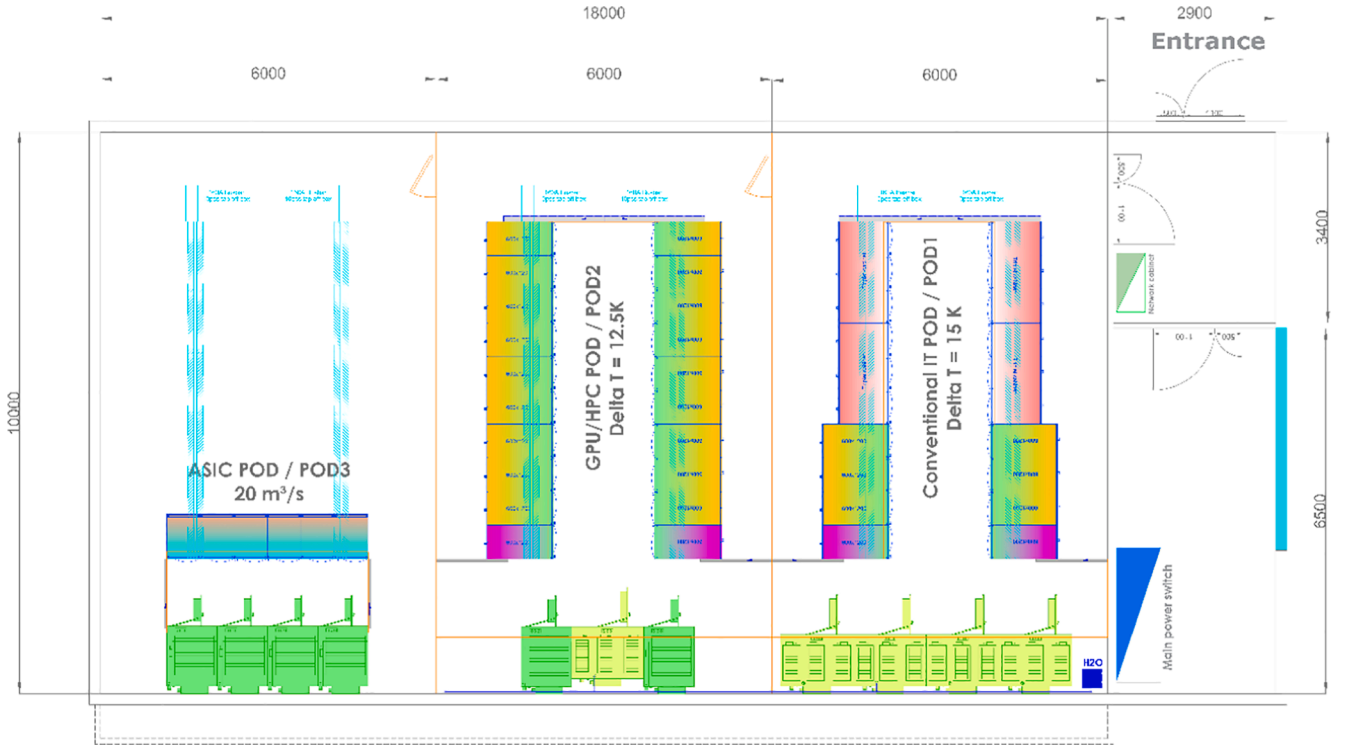


Fig. 3. Blueprint of data centre facility BTDC.

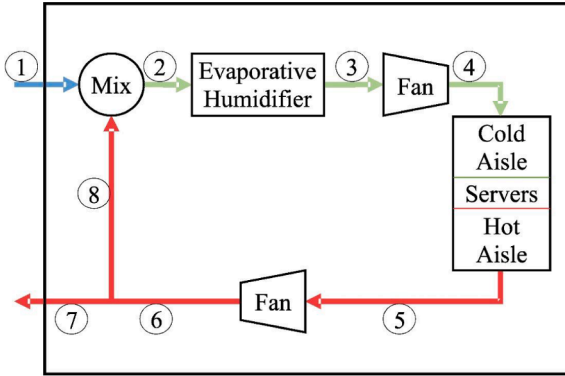


Fig. 4. Schematic of direct free air cooling. The ambient is the outside of the large rectangle.

supplied to the server room (4). The tempered air is then forced through the servers, raising the temperature to around 35–45 °C by absorbing the heat generated by the IT equipment (5). The air's ability to keep the IT equipment below harmful operating temperatures limits the maximum outlet temperature from the servers. For example, most processors require the temperature to be kept below 85 °C. The now warm air is transported out of the hot aisle (6) and either exhausted (7) to the surroundings or recirculated to be mixed with ambient air (1). The heat reuse application should be connected directly to the exhaust to avoid heat losses during the transport.

ASHRAE has published guidelines [34] for the condition of the supply of air in air-cooled data centres. It states that it is recommended to be between 18 °C and a dew point of −9 °C to 27 °C with a dew point of 15 °C and 60 % relative humidity. The recommended envelope is drawn in a psychrometric chart in Fig. 5.

Data centres are allowed to operate with air conditions outside of the recommended envelope within a suitable envelope based on which conditions the IT equipment is designed for. Data centres typically fall

into the A1 envelope. However, a data centre should be designed to operate within the recommended range, therefore, those are the conditions used in this study.

#### Theoretical ERF

The energy balance of a direct air-cooled data centre with heat reuse was outlined (Fig. 6) with the aim of finding an expression that describes the highest iERF at certain exhaust, final heat reuse and ambient temperatures. The highest in this regard means that there are no heat losses and only thermodynamic laws limit heat reuse.

The energy supplied to the data centre equals the energy leaving the data centre.

$$\dot{E}_{DC,in} = \dot{E}_{DC,out} \quad (5)$$

This means that the sum of the electricity supplied to the data centre (IT equipment, cooling system and power distribution) and recirculated heat for humidification is equal to the amount of heat that leaves the data centre. All the electricity for cooling and IT is assumed to be transformed to heat where most of it may be exhausted and either reused or rejected. The rest will be heat losses.

$$\dot{Q}_{IT} + \dot{Q}_{cooling} + \dot{Q}_{PD} + \dot{Q}_{humidification} = \dot{Q}_{exhaust} + \dot{Q}_{heatloss} \quad (6)$$

As the reference data centre lacks an uninterruptible power source, UPS, and relies on a robust electrical grid instead, the heat from the power distribution will be negligible. The heat generated by the IT and cooling equipment will raise the temperature of the cooling airflow as,

$$\dot{Q}_{IT} + \dot{Q}_{cooling} = \dot{m}_{cooling} * C_p * (T_{exhaust} - T_{supply}) \quad (7)$$

The air absorbs all the heat generated by the cooling fans, increasing the exhaust temperature.

The heat losses consist of,

$$\dot{Q}_{heatloss} = \dot{Q}_{humidification} + \dot{Q}_{transmission} \quad (8)$$

All the heat supplied in the humidification process will become latent heat that is not deemed recoverable and therefore lost. Humidification

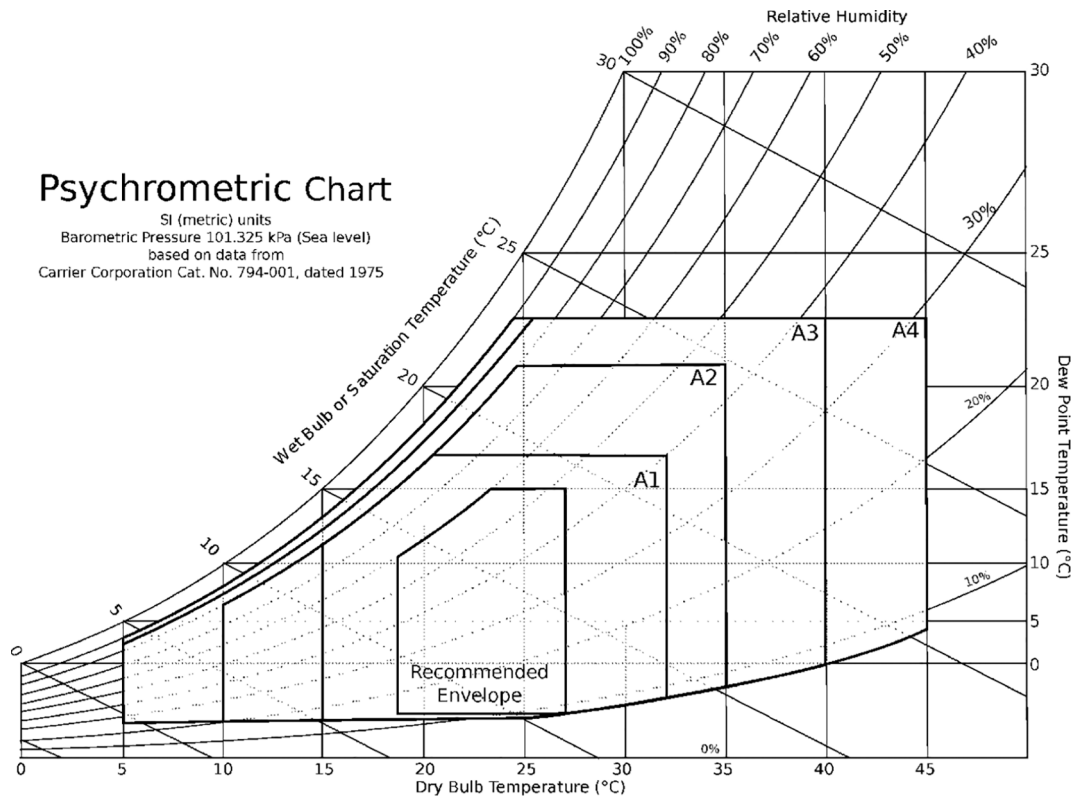


Fig. 5. A psychrometric chart [35] with the recommended and allowable supply air conditions for air-cooled equipment according to ASHRAE Thermal Guidelines [36] overlaid.

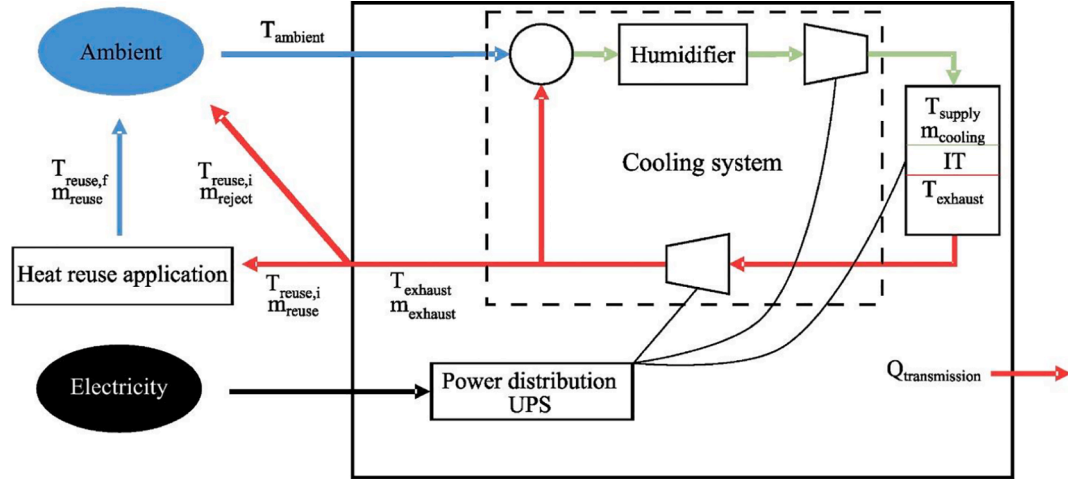


Fig. 6. The system boundary of the data centre shows energy entering and leaving the system to be reused and/or rejected.

losses are due to the heat needed to evaporate the water added. The heat is extracted from the air, thus lowering the temperature. This only happens during a short period of the year, since it is only necessary during very low ambient temperatures. It may be significant momentary but negligible over a whole year. The transmission losses are heat losses through the thermal envelope. They normally make up for a considerably large amount of heat leaving the building but will be negligible for data centres due to their energy-intensive nature,  $\dot{Q}_{exhaust} \gg \dot{Q}_{transmission}$ . This means that all the energy entering the data centre may be assumed to leave with the exhaust,

$$\dot{E}_{DC} = \dot{Q}_{exhaust} \quad (9)$$

The amount of exhausted heat can be written as,

$$\dot{Q}_{exhaust} = \dot{m}_{exhaust} * C_p * (T_{exhaust} - T_{ambient}) \quad (10)$$

and may be either rejected or reused,

$$\dot{Q}_{exhaust} = \dot{Q}_{reject} + \dot{Q}_{reuse} \quad (11)$$

The rejected heat contains three parts. It is either directly rejected, lost during transport from the data centre to the heat reuse application or heat still left when the air is released to the ambient after the heat reuse application.



$$\dot{Q}_{reject} = \dot{m}_{reject} * C_p * (T_{exhaust} - T_{ambient}) + \dot{m}_{reuse} * C_p * (T_{exhaust} - T_{reuse,i}) + \dot{m}_{reuse} * C_p * (T_{reuse,f} - T_{ambient}) \quad (12)$$

where  $\dot{m}$  is the mass flow of the air stream directly rejected or going to the heat reuse application. The reused heat is written as,

$$\dot{Q}_{reuse} = \dot{m}_{reuse} * C_p * (T_{reuse,i} - T_{reuse,f}) \quad (13)$$

Applying this to the equation for the iERF gives,

$$iERF = \frac{\dot{Q}_{reuse}}{\dot{E}_{DC}} = \frac{\dot{Q}_{reuse}}{\dot{Q}_{exhaust}} = \frac{\dot{m}_{reuse} * C_p * (T_{reuse,i} - T_{reuse,f})}{\dot{m}_{exhaust} * C_p * (T_{exhaust} - T_{ambient})} \quad (14)$$

The ideal heat reuse for a heat reuse application means that the whole air stream goes to the application, and nothing is directly rejected.

$$\dot{m}_{reuse} = \dot{m}_{exhaust} \quad (15)$$

and

$$\dot{m}_{reject} = 0 \quad (16)$$

The initial heat reuse temperature will be the same as the exhaust temperature, meaning there is no heat loss during the heat transport from the data centre to the heat reuse application,

$$T_{reuse,i} = T_{exhaust} \quad (17)$$

This results in,

$$iERF = \frac{\dot{m}_{exhaust} * C_p * (T_{exhaust} - T_{reuse,f})}{\dot{m}_{exhaust} * C_p * (T_{exhaust} - T_{amb})} = \frac{T_{exhaust} - T_{reuse,f}}{T_{exhaust} - T_{amb}} \quad (18)$$

As shown, the iERF can be calculated using only the exhaust-, final heat reuse- and ambient temperature. Since the iERF also may be written as,

$$iERF = \frac{T_{exhaust} - T_{reuse,f}}{T_{exhaust} - T_{amb}} = \frac{1 - \frac{T_{reuse,f}}{T_{exhaust}}}{1 - \frac{T_{amb}}{T_{exhaust}}} \quad (19)$$

it is also clear that  $iERF \rightarrow 1$  when  $T_{exhaust} \rightarrow \infty$ , meaning that raising the exhaust temperature raises the maximum iERF for the same heat reuse application in the same ambient conditions.

## Results

### Simulation

The results from the simulations with the data centre model (shown in Fig. 7) will be presented in this section.

Three cases with different exhaust temperatures: 30, 40 and 50 °C

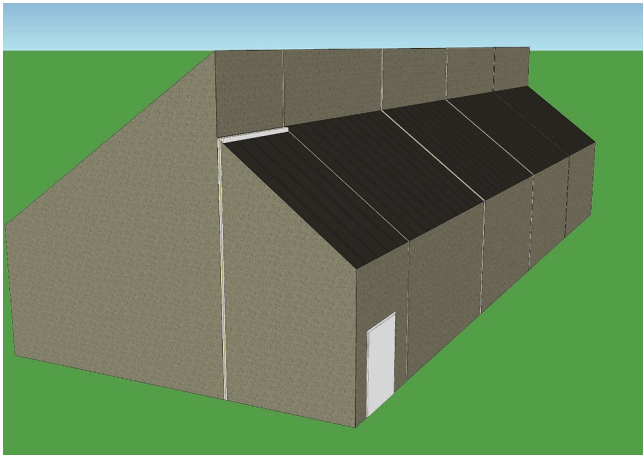


Fig. 7. The IDA-ICE model used in this study.

were simulated. The result was analysed to understand how the heat reuse potential changes with ambient conditions and how the temperature needs of different heat reuse applications affect the iERF and ERF.

The amount of warm air exhausted from a 1 MW data centre operating with 30, 40 and 50 °C exhaust air temperatures in the north of Sweden, for one year on an hourly basis is shown in Fig. 8.

The mass flow of air from the data centre varies due to ambient temperature and exhaust temperature changes. The simulated ambient temperature ranges from −27.5 °C to 26.2 °C. Minimum exhaust flow is 17, 14 and 12 kg/s and maximum is 252, 73 and 42 kg/s resulting in a min/max flow ratio of 7, 19 and 29 %. A lower exhaust temperature resulted in higher flows and a lower min/max ratio meaning that a heat reuse application would need to be able to absorb heat from a larger volume and handle larger variations in the flow.

To verify that the model works as intended the PUE was calculated and the iPUE over the year is shown in Fig. 9. The resulting PUEs for the model were from 1.012 to 1.048 depending on exhaust temperature, which means that the actual value for BTDC (1.014) fits within the range. This concludes that the model is in good agreement with measurements and represents a DC in the north of Sweden with direct free air cooling.

As can be seen, the iPUE rises during summertime when the ambient temperature exceeds the minimum supply temperature. This causes a raised supply temperature resulting in a need for larger airflow to achieve the same amount of cooling due to a reduced temperature difference over the servers.

The heat losses from the data centre with an exhaust temperature of 40 °C at different ambient temperatures are shown in Fig. 10. Both the losses due to humidification and transmission from the thermal envelope are shown.

The annual heat loss average was calculated to be 1.43 %, where 0.88 % was contributed by the thermal envelope and 0.55 % due to the humidification. Humidifying the air amounts to considerable heat losses during the coldest day (up to 5 %), significantly reducing the maximum iERF at cold ambient conditions. Since the annual heat losses are only 1.43 % of the total energy input, neglecting heat losses is valid for estimating the maximum annual ERF and iERF during warmer conditions. The only difference between the simulations is slightly higher/lower transmission losses since the humidification happens independently of the exhaust temperature. Heat losses during the warmer days are sometimes negative due to solar radiation and changes in air supply temperature.

The error from assuming no transmission and humidification heat losses when calculating the iERF is shown in Fig. 11.

The average error is around 1 % but an error margin of up to 6 % must be accounted for during cold days when humidification is needed.

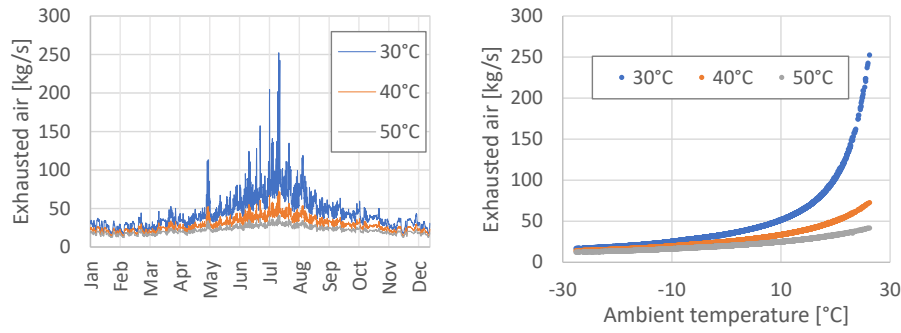
Since the simulation showed acceptable error margins when neglecting the heat losses, the study proceeded to analyse how heat reuse temperatures and ambient temperatures affect the ERF and iERF.

### ERF analysis

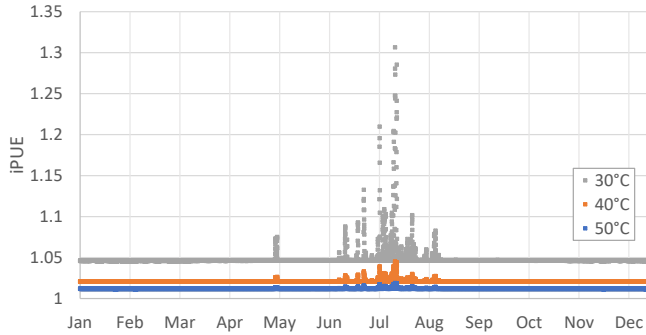
The upper limit for the iERF at different heat reuse temperatures with the weather conditions in Luleå and an exhaust temperature of 40 °C were calculated according to eq. (19) where the results are shown in Fig. 12.

To clarify, the iERF shown in the figure is the ideal iERF where the data centre has no heat losses, either from the thermal envelope, the cooling or during the transport of the excess heat from the data centre to the heat reuse application. For example, a heat reuse application with a final temperature of 20 °C would have a maximum iERF of 0.5 when there is 0 °C outside and iERF = 0 when it is 20 °C. If the heat reuse temperature is below the ambient temperature no heat reuse is possible since the application would instead need cooling.

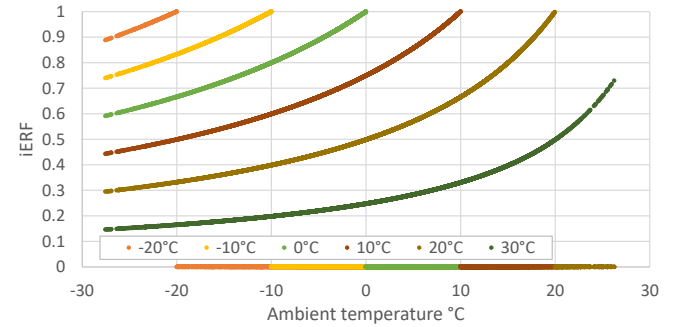
The iERF for each hour during a year was calculated according to eq. (19) and compiled to the resulting ERF for a whole year with different



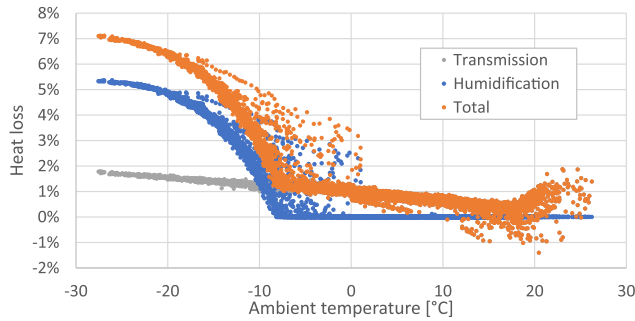
**Fig. 8.** The data centre exhaust mass flow for three different exhaust temperatures during a year and for different ambient temperatures.



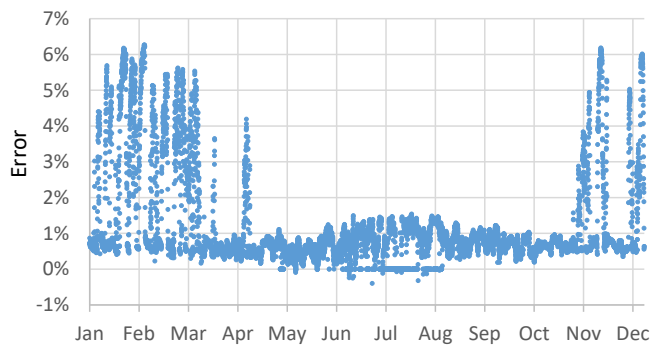
**Fig. 9.** iPUE during one year of operation for three different exhaust temperatures.



**Fig. 12.** iERF at different ambient and heat reuse temperatures with a constant 40 °C exhaust temperature.



**Fig. 10.** The heat losses from the data centre for one year of operation are sorted by ambient temperature.



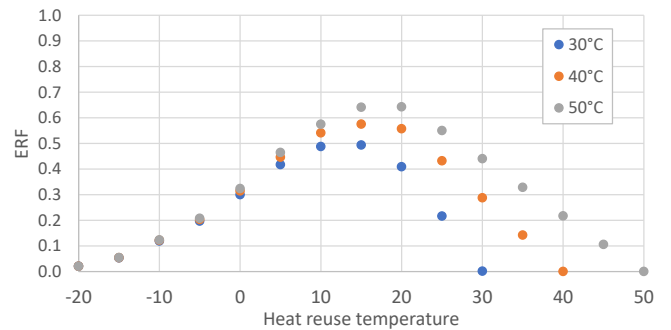
**Fig. 11.** The iERF error margin over the year when estimating the iERF using only exhaust, reuse and ambient temperature, compared to calculating the iERF from simulation data.

constant heat reuse temperatures,  $-20\text{ }^{\circ}\text{C}$  to  $+50\text{ }^{\circ}\text{C}$ . This was done for three exhaust temperatures, 30, 40 and  $50\text{ }^{\circ}\text{C}$ , to find the ideal heat reuse temperature in Luleå and the result is shown in Fig. 13.

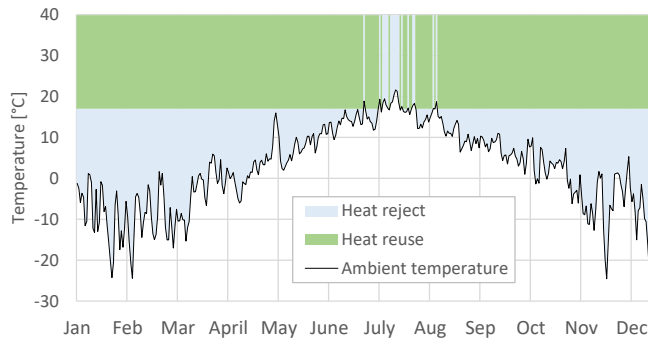
The ideal heat reuse temperature that would reuse most heat in Luleå is 13, 17 or  $18\text{ }^{\circ}\text{C}$  with an exhaust temperature of 30, 40 and  $50\text{ }^{\circ}\text{C}$  from the data centre. The resulting ERF was 0.50, 0.59 or 0.66 meaning 50–66 % of the energy input of the data centre could be reused if choosing the heat reuse temperature wisely. This can be compared with results from the author's previous study [20] that reused 30 % of the energy supplied to a data centre by heating a greenhouse operating at a temperature of  $18\text{--}24\text{ }^{\circ}\text{C}$ .

To illustrate further, the heat reuse at the ideal temperature ( $17^{\circ}$ ) for a data centre in Luleå with an exhaust temperature of  $40\text{ }^{\circ}\text{C}$  is shown in Fig. 14. Heat below the ideal temperature is rejected.

The data in the figure is a filtered 24-hour average representation of the raw simulation data. No heat reuse is possible when the ambient temperature is above the ideal temperature, and everything is rejected. As shown with eq. (19) the ratio between the amplitude of the vertical segment of heat reuse and the total amplitude of both vertical segments



**Fig. 13.** ERF at different heat reuse temperatures for three exhaust temperatures.



**Fig. 14.** The amount of reused and rejected degrees Celsius with the ideal heat reuse temperature.

gives the maximum iERF during that day.

#### Multiple heat reuse applications

To be able to reuse more of the heat it would be reasonable to choose applications with different heat reuse temperatures during different seasons to make the heat reuse temperatures as close to ambient temperature as possible. The heat reuse temperature in this study was chosen to be 5 °C above the average monthly temperature. The extra 5 °C was added to avoid extended periods of no heat reuse when the ambient temperature exceeded the average.

In Luleå, that results in heat reuse temperatures according to Table 1:

The heat reuse is illustrated by showing how it looked in the case with an exhaust temperature of 40 °C in Fig. 15.

The data in the figure is a filtered 24-hour average representation of the raw data. The resulting ERF was 0.66, 0.71 and 0.73 depending on exhaust temperature, with higher exhaust temperature resulting in higher ERF.

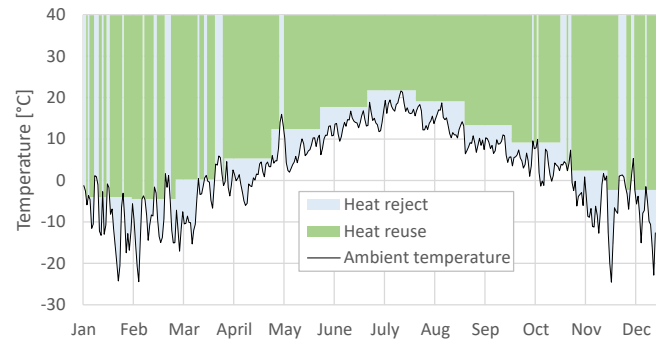
#### Discussion

The data centre model was proven to be sufficiently accurate to investigate the influence of ambient and heat reuse temperature on the ERF. The cooling method used by the reference data centre requires a climate that rarely, or ever, exceeds the maximum air supply conditions from ASHRAE which means that the model may only be used for such climates. However, letting the conditions of the supply air cross over to the allowable envelope, A1, would probably not be a problem considering that the equipment is rated for this.

In this study a constant IT power was assumed to simplify the calculations. As shown by [22] this is a valid assumption. However, if the operation of the heat recovery solution is critical it may need to be fitted with an alternative heat source as backup. For example, losing the heat source for a greenhouse in cold climate would destroy the harvest.

The main aim of this study has been to give reasonable expectations of the potential to reuse excess heat from data centres. This has been done by showing the best possible outcome of different heat reuse schemes. Therefore, the results of this study should not be considered a benchmark of what is achievable, but rather a guide to the theoretical thermodynamic restrictions of the process (in the same way as the Carnot efficiency). Maximising the heat reuse means the heat reuse should take place as close to the ambient temperature as possible.

The heating demand of an application usually increases with an increased temperature difference between its temperature need and the ambient. For example, the heating demand of a building approaches



**Fig. 15.** The amount of reused and rejected degrees Celsius with the multiple heat reuse temperatures.

zero when the ambient temperature approaches the indoor temperature. Accordingly, that building would need to be infinitely large to absorb all the heat from the data centre at that point.

There are of course exceptions to this. For example, one heat reuse application idea is to reuse the data centre excess heat to pre-heat black water. This would improve the efficiency of the nitrogen removal step by increasing the speed of nitrification. The black water adopts the ground temperature which may be both colder and warmer than the ambient temperature. This means that at an iERF above 1 could be achieved at certain conditions since the final heat reuse temperature would be lower than the ambient temperature.

Utilising multiple heat reuse applications is promising, increasing the ERF by 20–35 % where a lower exhaust temperature resulted in a higher relative increase of the ERF. It should be mentioned that adding a different number of degrees to the monthly average temperature when choosing the heat reuse temperature will influence the results. Also, finding heat reuse applications with suitable heat reuse temperatures may be tricky, especially in sub-zero temperatures. Another approach to reuse heat closer to the ambient temperature, improving the ERF, is with applications that require lower temperatures during the night when the ambient temperature also decreases. An example of this is greenhouses which employ this practice to improve the growing conditions for the crops and reduce the heating demand.

Raising the exhaust temperature will increase the ERF for the same heat reuse application. It will also reduce the variation in exhaust air's volume flow, making it easier to size the heat reuse application. However increased exhaust temperatures mean that the servers run at a higher temperature, which may result in higher power leakage of the processors [37,38] making them work efficiently. In other words, more electricity for the IT equipment is needed to maintain the same services. There will be a trade-off between increased powering of the equipment on one side and decreased costs for cooling (better PUE) and better heat reuse potential on the other side.

It would be interesting to study how the ERF would be affected by integrating a data centre directly with a heat reuse application as part of the cooling system. The heat reuse application would cool the warm air after the servers enough for it to be re-supplied to the servers again, avoiding the need to use ambient air for cooling. This means that the ambient temperature dependency would be removed when choosing a heat reuse application. Problems with air quality, humidity and pollution, could arise when the data centre and the heat reuse application share the same air. For example, a greenhouse would humidify the air above recommended server supply levels. This could be solved by

**Table 1**

The heat reuse temperatures used for multiple heat reuse applications.

Jan	Feb	Mar	April	May	June	July	Aug	Sep	Oct	Nov	Dec
−4.0	−4.5	0.2	5.3	12.4	17.7	21.8	19.1	13.4	9.2	2.4	−2.3



separating them with a heat exchanger, or a heat pump or choosing a heat reuse application with the same air quality needs.

## Conclusions

This study aimed to give a realistic view on the opportunities to reuse excess heat from data centres. This was done by showing how the maximum achievable interim ERF, iERF, varied with ambient conditions, heat reuse temperature and exhaust temperature in the climate of Luleå, a subarctic region. The ideal heat reuse temperature in Luleå, 13; 17 and 18 °C, and the corresponding ERF, 0.50; 0.59 and 0.66, was determined at an exhaust temperature of 30, 40 or 50 °C. A higher exhaust temperature meant a higher ideal heat reuse temperature and a higher ERF.

It was also shown that using different heat reuse applications at heat reuse temperatures closer to the monthly average improved the ERF compared to using the ideal heat reuse temperature throughout the year. The improvement was 11–31 % depending on the exhaust temperature. A lower exhaust temperature meant a higher relative improvement. Additionally, raising the exhaust temperature improved the cooling efficiency and in turn improved the PUE from 1.045 to 1.012 and reduced the min/max ratio of the exhaust flow. A lower min/max ratio makes it easier to size the heat reuse application since it does not have to accommodate as significant a variation of volume flow.

Finally, it was shown that the ideal iERF at a certain ambient and heat reuse temperature may be estimated with eq. (19)

$$iERF = \frac{T_{exhaust} - T_{reusef}}{T_{exhaust} - T_{amb}}$$

But the error margin will increase with colder temperatures and low absolute humidity particularly due to the humidification of the air supplied to the servers but also to the increased thermal envelope heat losses.

In summary, this paper concludes that raising the exhaust temperature, and therefore the excess heat temperature, improves the prerequisites to reuse heat from data centres by allowing higher heat reuse temperatures and increases the maximum ERF. The heat reuse application must be chosen wisely, and a multi-heat reuse application approach should be considered.

## CRediT authorship contribution statement

**Hampus Markeby Ljungqvist:** Writing – original draft, Writing – review & editing, Methodology, Conceptualization, Visualization. **Mikael Risberg:** Conceptualization, Writing – review & editing, Supervision, Funding acquisition. **Andrea Toffolo:** Conceptualization, Writing – review & editing. **Mattias Vesterlund:** Conceptualization, Writing – review & editing, Supervision, Funding acquisition.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will be made available on request.

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