Aleksi Ålander

Energy efficiency and waste heat utilization in data centers

School of Technology and Innovations
Master’s thesis in Energy Technology
Master’s Programme in Smart Energy

Vaasa 2025

UNIVERSITY OF VAASA
School of Technology and Innovations

Author:	Aleksi Ålander
Title of the thesis:	Energy efficiency and waste heat utilization in data centers
Degree:	Master of Sciences
Degree Programme:	Energy engineering
Supervisor:	Xiaoshu Lü
Instructor:	Anne Mäkiranta
Year:	2025 **Pages:** 89

ABSTRACT:

The growing demand for digital services has significantly increased the number of data centers and their energy consumption. This has led to greater environmental impacts and costs caused by data centers. Managing these impacts requires new technological solutions.
Data center components produce a large amount of heat, which requires efficient cooling methods to remove. This low-grade heat is often released into the environment unused. The development of efficient cooling solutions and waste energy recovery are therefore the key to sustainable development in the industry. The aim of this master's thesis was to map and study cooling solutions that promote energy efficiency in data centers and technologies for utilizing waste energy. The work was carried out as a narrative literature review, examing academic articles on the subject. The work examined different forms of cooling in data centers and the possibilities for utilizing waste heat.

Based on the study, air cooling is still the most common cooling method in data centers, due to its simplicity and low investment costs. The efficiency of air cooling can be improved, for example, by free cooling, but the future prospects of air cooling are limited due to the poor heat transfer capacity of air and the increasing heat loads.

Liquid cooling offers better potential for reducing energy consumption and utilizing higher-quality waste heat. However, liquid cooling methods require larger initial investments and more complex infrastructure, as well as careful risk management to address potential problems.

The work also investigated possible applications of waste heat. Waste heat can be utilized in many different ways. According to the study, connecting to a district heating network is the most efficient way of utilizing it in areas where the infrastructure is sufficiently developed. Waste heat can also be used to produce electricity using the organic Rankine Cycle (ORC) process. Waste heat can also be utilized in various industrial and agricultural processes, such as seawater desalination and greenhouse heating. These waste heat applications offer a low-emission alternative to traditional fossil-based energy sources.

In summary, improving the energy efficiency of a data center requires a focus on both efficient cooling solutions and waste heat utilization. Development should move towards more comprehensive assessment methods and technologies that reduce energy consumption while providing environmental benefits.

KEYWORDS: data centres, energy efficiency, heat recovery, cooling, heat energy, energy management, energy saving

VAASAN YLIOPISTO			
School of Technology and Innovations			
Tekijä:	Aleksi Ålander		
Tutkielman nimi:	Energy efficiency and waste heat utilization in data centers		
Tutkinto:	Diplomi-insinööri		
Koulutusohjelma:	Energiatekniikka		
Työn valvoja:	Xiaoshu Lü		
Työn ohjaaja:	Anne Mäkiranta		
Valmistumisvuosi:	2025	**Sivumäärä:**	89

TIIVISTELMÄ:

Digitaalisten palveluiden kasvava kysyntä on merkittävästi lisännyt datakeskusten määrää ja niiden energian kulutusta. Tämä lisää datakeskusten aiheuttamia ympäristövaikutuksia ja kustannuksia. Näiden hallinta edellyttää uusia teknologisia ratkaisuja.
Datakeskusten komponentit tuottavat suuren määrän lämpöä, jonka poistamiseen tarvitaan tehokkaita jäähdytysmenetelmiä. Tämä poistettava matala-asteinen lämpö vapautuu usein käyttämättömänä ympäristöön. Tehokkaiden jäähdytysratkaisujen ja hukkaenergian talteenoton kehittäminen on siis avain kestävään kehitykseen alalla. Tämän diplomityön tavoitteena oli kartoittaa ja tutkia datakeskusten energiatehokkuutta edistäviä jäähdytysratkaisuja sekä hukkaenergian hyödyntämisen teknologioita. Työ toteutettiin narratiivisena kirjallisuuskatsauksena, jossa tutkittiin akateemisia artikkeleita aiheesta. Työssä tarkasteltiin datakeskusten eri jäähdytysmuotoja sekä hukkalämmön hyödyntämismahdollisuuksia.

Tutkimuksen perusteella ilmajäähdytys on edelleen yleisin jäähdytysmenetelmä datakeskuksissa, johtuen sen yksinkertaisuudesta ja alhaisista investointikustannuksista. Ilmajäähdytyksen tehokkuutta voidaan parantaa esimerkiksi vapaajäähdytyksellä, mutta ilmajäähdytyksen tulevaisuuden näkymät ovat rajalliset ilman heikon lämmönsiirtokyvyn vuoksi ja jatkuvasti kasvavien lämpökuormien vuoksi.

Nestejäähdytys tarjoaa paremman potentiaalin energiankulutuksen pienentämiseen ja korkeampilaatuisen hukkalämmön hyödyntämiseen. Nestejäähdytysmenetelmät vaativat kuitenkin suurempia alkuinvestointeja ja monimutkaisempaa infrastruktuuria, sekä huolellista riskienhallintaa mahdollisten ongelmien ratkaisemiseksi.

Työssä tutkittiin myös hukkalämmön mahdollisia sovelluksia. Hukkalämpöä voidaan hyödyntää monin eri tavoin. Tutkimuksen mukaan kaukolämpöverkkoon liittäminen on tehokkain hyödyntämistapa alueilla, joissa infrastruktuuri on tarpeeksi kehittynyttä. Hukkalämpöä voidaan käyttää myös sähkön tuotantoon ORC-prosessilla. Hukkalämpö voidaan hyödyntää myös teollisuuden ja maatalouden erilaisiin prosesseihin, kuten meriveden suolanpoistoon ja kasvihuoneiden lämmitykseen. Nämä hukkalämmön sovellukset tarjoavat vähäpäästöisen vaihtoehdon perinteisille fossiilipohjaisille energialähteille.

Yhteenvetona voidaan todeta, että datakeskuksen energiatehokkuuden parantaminen edellyttää keskittymistä sekä tehokkaisiin jäähdytysratkaisuihin että hukkalämmön hyödyntämiseen. Kehityksen tulisi siirtyä kohti kattavampia arviointimenetelmiä ja teknologioita, jotka vähentävät energiankulutusta sekä tarjoavat ympäristöhyötyjä.

AVAINSANAT: palvelinkeskukset, energiatehokkuus, jäähtyminen, lämpö, energianhallinta, energiansäästö

Contents

Figures

1 Introduction

With the continuous growth of information technology, the number of data centers is continuously increasing at an accelerating pace. One of the biggest reasons for the increasing growth of data centers is the rapid expansion of 5G networks. In addition, the increasing growth of the use of artificial intelligence is one of the major reasons for the increase in the number of data centers. By 2026, the energy consumption of the use of artificial intelligence is estimated to increase tenfold compared to 2023. (IEA 2024, p. 35) With this growth, energy consumption and greenhouse gas emissions will increase at an accelerating rate. In 2022, data centers consumed an estimated 460 TWh of electricity, equivalent to about 2% of the world's total electricity consumption (Wang, F. et al. 2022, p. 1). The amount of electricity used by data centers is expected to increase to 620-1050 TWh in 2026 (IEA 2024, p.31). In 2014, data centers were estimated to produce 200 million tons of CO2 emissions, which would be equivalent to 2% of the world's total CO2 emissions. (Wang, F. et al. 2022, p. 1).

Most of the CO2 emissions from data centers are caused by the use of fossil energy sources in electricity generation. Data center emissions can be reduced by switching to renewable energy sources or nuclear power. Data center emissions can also be reduced by improving the energy efficiency of data centers. (Wang, F. et al. 2022, p. 1)
Data centers are experiencing significant growth in energy consumption, and their carbon footprint has become a key part of global energy policy and corporate sustainability goals. Improving energy efficiency offers a way to reduce environmental impacts and reduce energy costs. Although numerous individual studies and technical reports have been published on the topic, a comprehensive picture of the effects and suitability of different solutions requires a systematic review.

The aim of this master's thesis, based on a literature review, is to answer the following research questions:
" What are the key factors driving data center energy consumption?”

“What are the most common cooling solutions in data centers and how do they affect energy efficiency?”
“What technologies have been developed to utilize waste energy?”

The thesis does not contain an experimental part but is based on the analysis and comparison of existing scientific and technical literature.

2 Literature review methods

This master's thesis has utilized a narrative literature review. The purpose of this approach is to form a comprehensive overview and synthesis of existing knowledge regarding data center cooling solutions and waste energy utilization.

The source material for this literature review has been collected from a variety of sources. Academic search engines and databases, such as Google Scholar, ScienceDirect and IEEE Xplore, have been used as search tools. The searches were targeted with related keywords, such as "data center cooling", "liquid cooling", "free cooling", "immersion cooling" and "waste heat recovery data center".

The following principles have been followed in the selection of source material:
The material has been selected mainly from scientific articles and conference proceedings, which represent the latest and most reliable information in the field.
The selection of sources has been based on their direct relevance to the research questions of the work. The main focus has been on the description of technical solutions and their energy efficiency analyses.
The focus has been on mainly articles published in the last ten years, so that the information is as up-to-date as possible.
The collected information has been analyzed thematically. Information was extracted and classified from the sources, which covered:

1. The principles, advantages and disadvantages of different cooling methods, such as air cooling, free cooling, liquid cooling.
2. Waste heat recovery technologies and utilization targets.
3. The energy efficiency of these different solutions.

Based on the analysis, the main chapters of the work were created, in which different solutions are presented and compared. This approach allowed to form a comprehensive picture of the topic and identify its most important trends and challenges.

3 Data centers and energy efficiency meters

To understand the energy consumption of data centers, it is important to understand how data center energy consumption is distributed. However, knowing the distribution alone is not enough to assess performance or compare different facilities. For this purpose, energy efficiency metrics have been developed that provide standardized ways to measure, compare, and guide improvements in data center operations. The following sections first examine the distribution of data center energy consumption and then examine data center energy efficiency metrics.

3.1 Data center

A data center is a physical location that contains mainly electronic equipment that processes information. This information processing includes data processing, data storage, and communication. This information processing requires a lot of energy, which is why data centers can use electricity from 1 MW to over 500 MW. The IT equipment in data centers converts almost all of this input power into heat. 1 watt used for data processing produces almost 1 watt of heat. (Geng, H. 2015, p. 50-51) A lot of energy is needed to remove this heat, and cooling data centers can in some cases account for up to 38% of total electricity consumption, as shown in Figure 1, when air conditioning systems, humidifiers and chillers are taken into account (Ahmed, K. et al 2021, p. 152541).

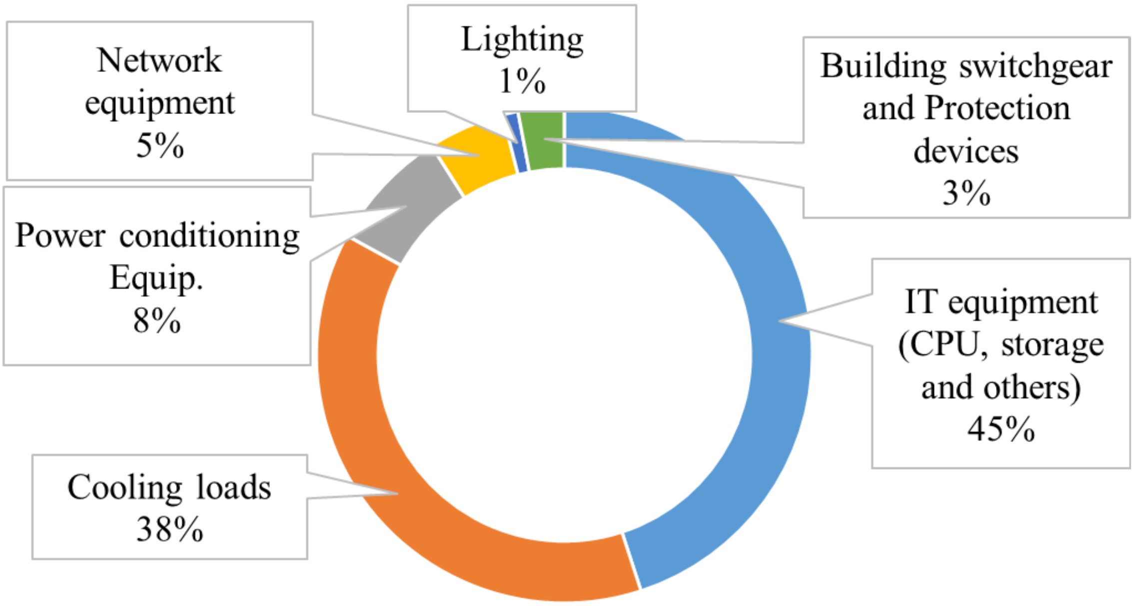


Figure 1. Power consumption proportionality in data center (Ahmed et al., 2021)

Data center hardware can be divided into 4 categories. These categories are power equipment, cooling equipment, IT equipment, and other miscellaneous components, such as lighting and fire protection systems. (Dai, J. et al. 2014 p. 9)

3.1.1 Power equipment

Power equipment includes UPS, switchgears, generators, PDUs and batteries (Dai et al. 2014 p. 11). Data center power first enters a substation, where the high voltage is converted to medium voltage. From there, the power is distributed to primary distribution centers, where the voltage is converted to low voltage by a medium voltage transformer. From there, the power is transferred to the data center UPS systems. UPS systems can also be powered by diesel generators if utility power is not available, for example during a power outage. Instead of diesel generators, a flywheel or AC generator can also be used. These data center UPS systems have 3 functions:

1. The function is to switch the active input source between two input sources. These input sources are usually utility and generator power.

2. The 2nd function is to store energy, for example for an electric roof. Storage can be electrical, chemical or mechanical.
3. 3. The function of a UPS is to regulate the incoming power supply, eliminate voltage spikes and dips, and eliminate harmonic distortion in the AC power supply. These can be achieved through AC-DC-AC double conversion.

PDUs are the last layer of power systems in data centers. The PDU unit's job is to receive power from the UPS, convert it to the correct voltage, and then distribute it to many smaller circuits that distribute power to the servers. These smaller circuits contain their own circuit breakers that protect the circuit and the rest of the data center in the event of a short circuit, for example. (Barroso L. et al. 2019, p. 75-80)

3.1.2 Cooling equipment

The main function of data center cooling equipment is to remove the heat generated by the equipment. The main components of data center cooling equipment are Computer room air conditioners (CRAC) or Computer room air handler (CRAH) , Chillers and cooling towers. (Barroso L. et al. 2019, p. 86-90)

CRAC and CRAH are used for the same purpose, which is to maintain and control the temperature, air distribution, and humidity of a data center. The difference between these devices is in which applications they are best suited for and how the air is cooled. CRAC units are best suited for small and low-density data centers, while CRAH units are better suited for medium and large data centers. CRAC units use compressor cooling to cool the air, i.e. they have an internal refrigerant circuit, like regular air conditioners. CRAH units, on the other hand, cool the air with water, usually from a separate chiller or chilled water plant. (von Hesler, A. 2021)

Data center cooling systems include an evaporator and condenser, as well as a compressor, expansion valves and piping. Data center cooling systems can be divided into a cold and hot section. In the cold section, the hot water from the computer room is cooled in the evaporator and then returned to the process chilled water supply (PCWS). The hot section heats the cold water in the condenser water loop with a condenser coil and uses this to transport the heat away to the cooling tower. In cooling towers, the water stream coming from a chiller or another heat exchanger connected to the PWCS loop is cooled. Cooling occurs by evaporating part of the water stream into the atmosphere. (Barroso L. et al. 2019 p. 89)

3.1.3 IT Equipment

IT equipment accounts for the largest portion of energy consumption in data centers. These components can consume up to50% of the total energy used by a data center This category includes servers, storage systems, and networking devices, which together form the core infrastructure of the data center. (Liu, Y., et al. 2020, p. 273).
Server racks are a central part of the data center's physical structure. They house servers, switches, storage devices, and other components, and are designed to optimize airflow and cooling. In addition, they enable efficient cabling and easy access for maintenance and upgrades.

Servers are the most critical components in data centers, as they are responsible for a variety of tasks including data processing, storage, and network management.
Storage systems are designed to store and manage large volumes of data securely and efficiently. The most commonly used storage solutions include Network Attached Storage (NAS), Storage Area Network (SAN), and Direct Attached Storage (DAS), which differ in interface type, performance, and scalability.
Networking devices enable data transfer between servers, storage systems, and external networks. These typically include switches, routers, firewalls, load balancers, and cabling infrastructure. Together, these IT components form the technological foundation of a data center, enabling data processing, storage, and communication. (Wilson, M., 2023)

3.2 Data center sustainability metrics

Improving energy efficiency is important when trying to reduce carbon dioxide emissions and energy consumption. Improving energy efficiency also helps to reduce all energy-related costs. For this reason, energy efficiency has long been one of the most important development targets in various technological fields. (Barroso L. et al. 2019, p. 99)

However, measuring the energy efficiency and environmental impact of data centers is complicated by the different indicators, interpretations, and measurement methods. The choice of indicators and calculation methods affect comparability, and there is no objective universal metric. However, there are some indicators used internationally, for example, the international standard ISO/IEC 30134 and the European standard EN 50600-4, both of which provide the following indicators for the energy efficiency of data centers: Power usage effectiveness (PUE), Renewable energy factor (REF/RES), Energy Reuse Factor (ERF), Cooling Efficiency Ratio (CER), Carbon Usage Effectiveness (CUE), and Water Usage Effectiveness (WUE). (Gynther L. et al. 2022, p. 12-13)

In addition to these, other energy efficiency indicators have also been developed, for example Data Center infrastructure Efficiency (DCiE), Power to Performance Effectiveness (PPE), Data Center Energy Productivity (DCeP), Data Center Performance Per Energy (DPPE).

3.2.1 PUE

Perhaps the most widely used energy efficiency indicator is PUE. PUE tells you how much energy is used to run data center IT equipment compared to the energy consumption of the entire data center. PUE can be defined as follows (Gynther L. et al. 2022, p. 13-14):

$$PUE = \frac{Total\ facility\ power}{IT\ equipment\ power}. \tag{1}$$

The theoretical minimum PUE value is 1.00 and the maximum is infinity. PUE then measures how much useful work is produced per unit of energy.
During the introduction of PUE, the industry average PUE values have dropped significantly. When PUE was introduced in 2007, the industry average PUE values were 2.5-3, while the 2016 average was already 1.7. (Van De Voort T. et al 2017, p. 6-7) Today, new data centers can have PUE values as low as 1.1, which is already very close to the theoretical minimum, meaning that it is increasingly difficult to find savings opportunities to improve PUE.

PUE is not the most reliable measure of energy efficiency, as it does not measure the energy efficiency of ICT equipment, but only the energy efficiency of the surrounding building and infrastructure. Another problem is that companies do not calculate PUE in a completely consistent way. (Gynther L. et al 2022, p. 13-14) PUE reporting parameters are not regulated at all, which means that data centers can choose the best possible parameters to achieve the best possible PUE for comparison and marketing purposes. PUE is limited to energy consumption only, does not take into account, for example, on-site energy production, waste heat recovery. (Barroso L. et al 2019, p. 102).

According to Barroso, L. et al. (2019, p. 102), temperature variations during different times of the day and season can clearly affect PUE values. The current reading may not necessarily correspond to the actual average level. For example, PUE values can be clearly lower on cold days, while they can rise higher on warm days. This means that individual measurements do not provide a reliable picture of energy efficiency. According to Van De Voort, T. et al. (2017, p. 6-8) PUE also does not monitor the energy source used, and the ecological impacts of the energy source, so it does not take into account whether renewable energy or fossil fuels are used as an energy source. PUE also does not take into account other resource consumption, such as water consumption.

Van De Voort, T. et al. (2017, p. 6-8) also mention that one of the biggest problems with using PUE is that it does not measure the efficiency of IT equipment at all. For example, if the computational power of IT equipment improves, i.e. more performance per watt, the overall efficiency can improve significantly even if the PUE value does not change. This means that replacing old equipment with newer equipment can be one of the most effective ways to reduce energy consumption, but the PUE does not necessarily reflect this improvement. In addition, the PUE depends a lot on how heavy the IT load is. When servers are heavily loaded, the PUE is often better. However, the introduction of new, more energy-efficient equipment can reduce the average load on the center, which can make the PUE appear lower, even though the overall efficiency is actually improving.

3.2.2 DCiE

DCiE is a slightly less common way to measure energy efficiency than PUE. Like PUE, DCiE measures the overall efficiency of a data center. DCiE shows the amount of energy used by IT equipment out of the total energy in the facility. The unit of DCiE is a percentage. Its formula is(Gynther L. et al 2022, p. 15):

$$DCiE = \frac{IT\ equipment\ power}{Total\ facility\ power} \times 100\%. \tag{2}$$

3.2.3 REF

REF is an energy efficiency metric that describes the share of renewable energy in a data center’s total energy consumption. REF values range between 0 and 1. 0 means that all energy comes from non-renewable sources and 1 means that all energy comes from renewable sources. REF is therefore defined as follows (Gynther L. et al 2022, p. 15):

$$REF = \frac{Renewable\ energy\ used\ by\ the\ data\ center}{Total\ energy\ consumbtion\ by\ the\ data\ center}. \tag{3}$$

3.2.4 ERF

ERF describes how much of the energy consumed by a data center can be reused for other purposes. The ERF value can be between 0 and 1, where 0 means that no energy is reused at all and 1 means that all energy is reused. ERF is defined as follows (Gynther L. et al 2022, p.16):

$$ERF = \frac{Reuse\ energy\ ouside\ of\ data\ center}{Total\ energy\ consumbtion\ by\ the\ data\ center}. \tag{4}$$

3.2.5 ERE

Energy Reuse Effectiveness or ERE is an energy efficiency metric that takes into account reused energy. ERE was created to complement the traditional energy efficiency metric PUE. The theoretical minimum value of ERE is 0, which would mean that all energy brought into the data center has been reused elsewhere. ERE has no theoretical maximum value. ERE can be defined as follows (Patterson, M. 2010, p. 9):

$$ERE = (1 - ERF) \times PUE = \frac{Cooling + Power + Lightning + IT - Reuse}{IT}. \tag{5}$$

3.2.6 CUE

CUE measures how much carbon dioxide emissions a data center produces in relation to the energy consumption of IT equipment. The lower the CUE value, the less carbon dioxide emissions the data center produces in relation to energy consumption. CUE provides important information about the ecological footprint of a data center. The widespread use of the CUE metric could help the industry move towards renewable energy sources. CUE is defined as follows (Belady, C. et al 2010, p. 4-5):

$$CUE = \frac{CEF \times Total\ energy}{IT\ energy} \left[\frac{kgCO_2}{kWh}\right], \tag{6}$$

Where CEF, or carbon emission factor, is:

$$CEF = \frac{CO_2\ emitted}{unit\ of\ energy} \left[\frac{kg}{kWh}\right]. \tag{7}$$

3.2.7 WUE

Data center cooling requires large amounts of water. Even a relatively small 1 MW data center using traditional cooling methods can consume up to 26 million liters of water per year. In addition, the production of electricity used by data centers also consumes a lot of water. (Ashtine m. & Mytton d. 2021)

Measuring the water use of data centers over the entire life cycle would be very complicated, but it is possible to calculate the end-of-life phase and WUE has been developed for this purpose. WUE is therefore a sustainability indicator that describes how much water data centers use to cool IT equipment. The unit of WUE is m^3/kWh. The lowest theoretical WUE value is 0, which means that no water is consumed in the data center at all. There is no highest theoretical value for WUE. The definition of WUE is as follows (Gynther L. et al 2022, p. 7):

$$WUE = \frac{Annual\ water\ usage}{IT\ equipment\ energy} \left[\frac{m^3}{kWh}\right]. \tag{8}$$

3.2.8 CER

Cooling effectiveness ratio or CER is a metric that describes the energy efficiency of data center cooling systems. CER calculates the ratio between the amount of heat removed from a data center and the energy consumption of the cooling system. The definition of CER is therefore(Gynther L. et al 2022, p. 16):

$$CER = \frac{Q}{E} \left[\frac{kWh}{kWh}\right], \tag{9}$$

where Q is amount of heat removed from the system and E is cooling systems energy consumption.

3.2.9 DCeP

Data Center Energy Productivity (DCeP) is a metric that describes the efficiency of a data center in producing useful computing work relative to the total energy consumption of the data center. Unlike PUE or DCiE, which describe the distribution of energy consumption, DCeP describes the productivity of work relative to the energy used. DCeP can be used for comparison or to examine the productivity of just one data center. Useful work can be difficult to define, and DCeP allows each user to define useful work that is appropriate for their own business class. DCeP is not very widely used. DCeP is therefore defined as follows (Shao, X. et al. 2022, p. 13):

$$DCeP = \frac{Useful\ work\ produced}{Total\ data\ center\ energy\ consumed\ producing\ this\ work}\ , \qquad (10)$$

where useful work may be defined by the equation (Maagøe, V. 2022) :

$$\sum_{i=1}^{m} V_i \times U_i(t,T) \times T_i\ , \qquad (11)$$

Where M is the number of tasks started during the evaluation window,
V_i is a normalization factor that allows tasks to be summed,
T_i is 1 if a task was completed during the evaluation window, otherwise it is 0
$U_i(t,T)$ is a time-based auxiliary function for each task
t is the elapsed time from task start to task completion, and
T is the absolute completion time of the task.

3.2.10 GEC

GEC or Green energy Coefficient tells you what percentage of the energy used by a data center comes from renewable energy sources. The maximum value of CEG is 1.0, which means that 100% of the data center's energy comes from green energy sources. A problem with using CEG is the regional and local differences in the definitions of green energy. The definition of GEC is (Maagøe, V. 2022, p. 24):

$$GEC = \frac{Green\ energy\ consumed}{Total\ energy\ consumed}\ . \qquad (12)$$

3.2.11 ITEE & ITEU

ITEE or IT equipment Efficiency describes how energy-efficiently IT equipment uses energy to do useful work. Its definition is (Maagøe, V. 2022, p. 23):

$$ITEE = \frac{Total\ rated\ capacity\ of\ IT\ equipment}{Total\ rated\ power\ of\ IT\ equipment}\ . \tag{13}$$

Capacity is divided into three categories: Servers [GTOP], Storage [Gbyte] and Network [Gbps]. (Van De Voort T. et al. 2017 p.10)

ITEU, or IT Equipment Utilization, describes how efficiently the capacity of IT equipment is used in data centers. In other words, ITEU describes the utilization rate of IT equipment. Its formula is defined as follows (Maagøe, V. 2022, p. 23):

$$ITEU = \frac{Total\ energy\ consumption\ of\ IT\ equipment}{Total\ rated\ energy\ consumption\ of\ IT\ equipment}\ . \tag{14}$$

3.2.12 DPPE

DPPE, or Data Center Performance Per Energy, is a metric that measures the overall energy efficiency and green energy use of a data center. DDPE calculates how much business benefit a data center generates per unit of energy consumed, taking into account the share of green energy used. DPPE consists of the four sub-indicators mentioned earlier. These are ITEU, ITEE, PUE and GEC. DPPE can therefore be calculated using the formula (Gynther L. et al 2022, p. 18):

$$DPPE = ITEU \times ITEE \times \frac{1}{PUE} \times \frac{1}{1-GEC}\ . \tag{15}$$

3.2.13 OEF & OEM

On-site Energy Fraction (OEF) and On-site Energy Matching metrics can also be used to measure the energy efficiency of data centers. These metrics are designed to complement the CUE metric. They help assess how efficiently a data center uses on-site renewable energy. OEF indicates how much of the energy is generated on-site. OEM estimates how much of this on-site energy is actually used on-site and not, for example, transferred to the grid or stored for later use. Both have a maximum value of 1.00, which means that an ideal situation is achieved where 100% of the energy is generated and consumed on-site, without loss or external energy dependency. The definitions of OEF and OEM are (Cao, S. et al. 2013, p. 425):

$$OEF = \frac{\int_{t_2}^{t_1} Min[G(t);L(t)]dt}{\int_{t_2}^{t_1} L(t)dt};\ 0 \leq OEF \leq 1\ , \tag{16}$$

$$OEM = \frac{\int_{t_2}^{t_1} Min[G(t);L(t)]dt}{\int_{t_2}^{t_1} G(t)dt};\ 0 \leq OEM \leq 1\ , \tag{17}$$

where G(t) is the on-site renewable energy produced and L(t) is the load power at time t and dt is the calculation time step. (Cao, et al. 2013)

3.2.14 Other useful indicators

EER, COP or ESR are often used to measure the energy efficiency of data center cooling equipment. EER measures the cooling capacity in relation to the electricity consumption. EER is usually used to measure the energy efficiency of refrigeration equipment and heat pumps. EER is defined as follows (Dincer, et al. 2015):

$$EER = \frac{Cooling\ capacity\ (\frac{Btu}{h})}{Electrical\ energy\ input\ (W)}\ . \tag{18}$$

The coefficient of performance (COP) is the ratio of the heat transferred to the work input to the device. COP can be defined as follows (Abdullah, S. et al. 2023, p. 8):

$$COP = \frac{Cooling\ capacity}{total\ energy\ consumption}. \tag{19}$$

ESR, or energy saving rate, is a fairly common way to assess the energy efficiency of a data center. ESR indicates how much energy has been saved relative to a reference situation. ESR is defined as follows Li, M. et al. 2016, p. 245):

$$ESR = \frac{E_{baseline} - E_{new}}{E_{baseline}}, \tag{20}$$

Where $E_{baseline}$ is the energy consumption before the change and E_{new} is the energy consumption after the change.

4 Data center cooling

Data center cooling is one of the largest single sources of energy consumption in the entire infrastructure. Cooling can currently account for almost 50% of the total energy consumption of a data center. (Dei, J. et al. 2014. p. 47) The high thermal load of servers requires continuous and efficient thermal management to maintain equipment reliability and temperatures within acceptable limits. For example, most servers are designed to operate at temperatures below 45 °C and the recommended temperature range for data centers is typically around 18-27 °C (Azarifar, M. et al. 2024, p. 3-5). The task of the data center cooling system is to maintain temperatures at these temperatures. Without cooling, data center temperatures can rise too high, which would damage equipment, cause data loss and reduce energy efficiency (Alkrush, A. et al. 2024, p. 247). Traditionally, data centers have used mechanical air cooling systems, but as the power of IT equipment continues to increase, traditional air cooling methods are no longer able to keep IT equipment temperatures within recommended limits. (Azarifar, M., et al. 2024, p. 5)

In today's data centers, the power consumption of devices has increased significantly: CPUs often exceed 300 watts and advanced graphics cards can consume up to 1000 watts. At the same time, rack-level power density has increased significantly, according to a 2024 study, 17 % of data centers had rack-level power exceeding 30 kilowatts. This development has made efficient cooling essential, as high heat loads in chips and high-power server racks pose a risk of overheating. (Zheng, S. et al 2025, p.1-2) For these reasons, traditional air cooling may no longer be sufficient to cool heat sources efficiently enough, which is why the use of various alternative cooling solutions, such as liquid cooling or free cooling, is becoming more common. This chapter examines how heat is managed in data centers and what solutions modern data centers utilize. It also examines how cooling solutions affect energy efficiency.

4.1 Air cooling

In modern air-cooled data centers, the most common way to handle cooling is to use a Hot/Cold Aisle configuration. The configuration is shown in Figure 2. This configuration has hot and cold channels that prevent air mixing and improve the cooling efficiency of the air-cooled system. The function of the cold aisle is to remove air from the operating air conditioner and transfer it to the rack. The function of the hot aisle is to remove hot air from the rack out of the room and back to the operating air conditioner, which cools the air for reuse. In this configuration, it is important to maintain maximum insulation of these aisles to prevent air mixing (Alkrush, A. et al. 2024, p. 249). These configurations can be divided into three different configurations: Room level, Row-level and rack-level. (Zhang, Q. et al. 2021, p.3)

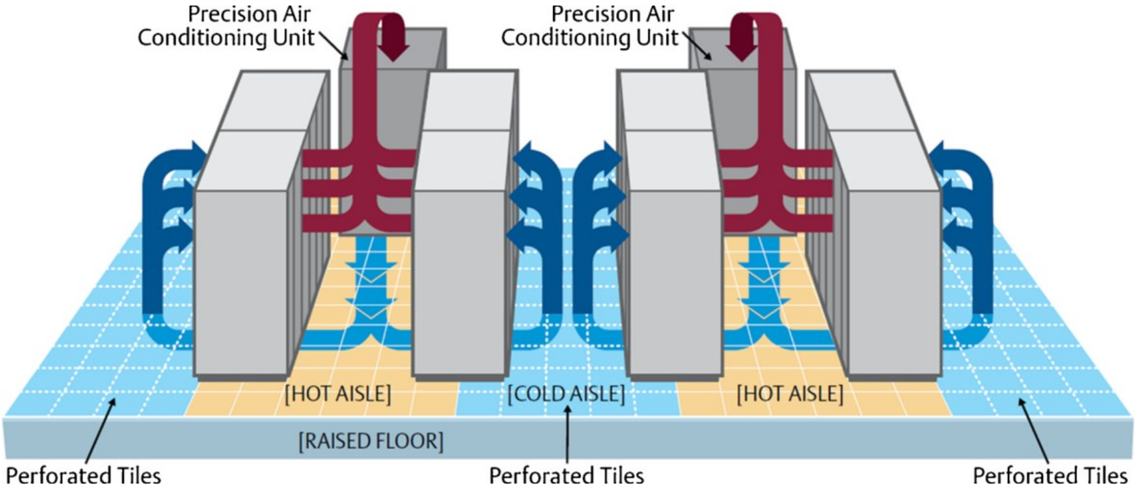


Figure 2. Hot/Cold Aisle configuration (Nadjahi et al., 2018)

4.1.1 Room-level cooling

Room-level air cooling using a raised floor structure is one of the most traditional solutions for managing the heat load in data centers. The system utilizes the air space created under the floor to distribute cold air and exhaust vents located at the top of the ceiling to remove warm air. The cold air is produced by a CRAC or CRAH unit and is led into the server room through perforated floor tiles.

The server rows are arranged in such a way that alternating cold and hot aisles are formed, as seen in Figure 2. Cold air is supplied to each cold aisle by means of a pressure difference between the subfloor and the hall space. The air passes through the server equipment, absorbs the heat generated by the components and moves behind the server rows to the hot aisle, from where it rises up to the exhaust vents in the ceiling. The warm air then returns to the cooling unit, where it is cooled and the cycle starts over. One significant problem with this air circulation model is the mixing of heated return air and cold supply air. The phenomenon is known as the concepts of harmful air circulation: Hot Air Recirculation (HAR) and Cold Air Bypass (CAB). In HAR, hot air is re-mixed with cold air supply, which increases the air intake temperature of the servers and reduces their performance. In CAB, on the other hand, cold air does not flow to the equipment but is directed directly to the upper part of the room, which leads to energy inefficiency. Both phenomena require a larger cooling capacity, which significantly increases energy consumption. Airflow management can be improved by using various insulation solutions, such as Aisle Containment Systems (ACS), Hot Aisle Containment (HACS) and Cold Aisle Containment (CACS), which reduce air mixing and improve cooling efficiency. The advantage of the system is its flexibility: cooling can be easily adjusted by changing the position of the perforated floor tiles. For this reason, the solution is particularly suitable for low-density data centers. In addition, CRAC/CRAH units are usually located outside the hall, which facilitates maintenance without affecting the operation of ICT equipment. (Zhang, Q. et al. 2021, p. 3-4)

According to Dunlap K. and Rasmussen N. (2012) Room-level cooling is very sensitive to the physical characteristics of the room space, such as ceiling height, room shape, and floor and ceiling obstructions, which can limit the effective circulation of cooling air. Because the supply and return paths of cooling air are distributed and disconnected, airflow control can be difficult, which can lead to air mixing, uneven temperatures, and hot spots in different parts of the room. In addition, even small changes in the placement or amount of IT equipment can significantly change the airflow behavior, often requiring redesign or additional testing to ensure system functionality. Retrofitting air spaces is also often expensive and structurally challenging. (Dunlap K. and Rasmussen N. 2012, p.3-4)

4.1.2 Row-level Cooling

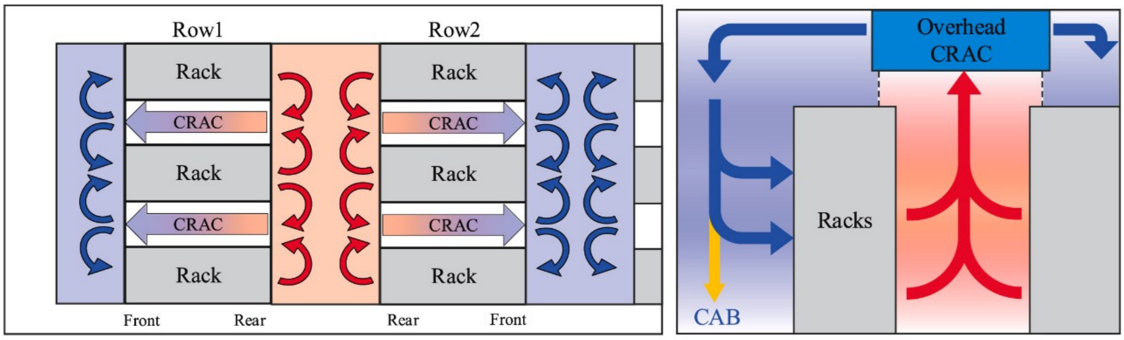
Producing large volumes of air throughout a room is very inefficient in most data centers. Although room-level cooling reduces the amount of air that needs to be moved, this method of cooling the entire room is often inefficient because much of the cold air is spread to areas where it is not needed. Although raised floors and hot-cold aisle separation improve air control and reduce the need for air, cold air is still wasted because it is not directed directly at hot components, but is distributed imprecisely throughout the open space. Traditional room-specific cooling solutions are also starting to become insufficient in many modern data centers, as hot spots can develop in certain areas of the server room, compromising the reliability and energy efficiency of the equipment. (Zhang, Q. 2021, p. 4)

Row-level cooling could be the solution to this. In row-level cooling, air conditioners can be placed between or above the rows, as seen in figure 3. The advantage of this cooling method is that air conditioners can be placed close to the equipment that needs cooling. Airflows can also be predicted better. In addition, the nominal capacity of the cooling unit can be utilized in its entirety. This also allows for higher power density (Dunlap K & Rasmussen N. 2012, p. 4-5).

In a row-level cooling configuration, the air path is short and focused, which makes cooling more efficient than in traditional room-level cooling, where air circulates through the entire room. In addition, the cooling devices can be adjusted per row, allowing more efficient cooling near the servers that produce more heat. (Zhang, Q et al.2021, p.4)

However, row-level cooling devices are as large as server racks, so they take up a lot of space and can make it difficult to place the devices, especially in small data centers. Therefore, to save space, overhead cooling devices can also be used, where CRAC units are installed in the middle of the top of two rows, which turns the hot aisle into an upward-facing structure. However, the problem here is the CAB effect, as cold air is most likely to accumulate in the lower parts of the room and is therefore not effectively directed to the equipment. (Zhang, Q et al.2021, p.4)

Row-level cooling is more energy efficient than room-level cooling, as it utilizes shorter airflow paths and allows for more precise cooling control. It also facilitates system scalability, as new cooling units can be added as needed. However, the disadvantages are higher installation costs in larger data centers, and maintenance of cooling equipment can disrupt server operations because it is carried out in the same room as ICT equipment. (Zhang, Q et al.2021, p.4)



Inter-row cooling (top view)

Overhead Cooling

Figure 3. Row-level cooling methods (Zhang et al. 2021)

4.1.3 Rack-level cooling

In rack-level cooling, rack coolers are installed directly inside individual racks, as seen in the figure 4. This makes the airflow path shorter and more efficient than in room or row-level cooling. (Cai S. & Gou, Z. 2024, p. 8-9)

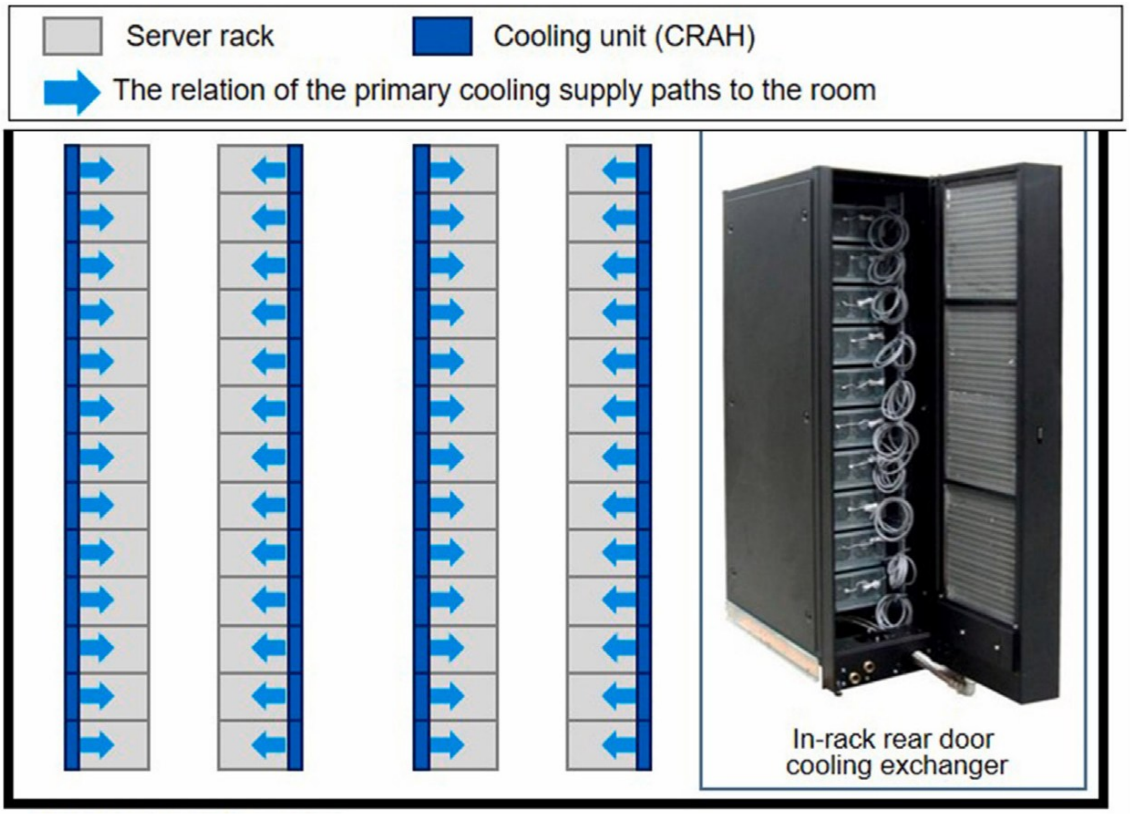


Figure 4. Rack-level cooling (Cai, S. & Gou, Z. 2024)

Inside the rack, the interior space is divided into cold and hot aisles by means of a partition wall. This allows cold air to be directed directly to the equipment, and warm air is collected without mixing with each other. This significantly reduces the energy consumed in moving the air needed for cooling. The biggest advantage of rack-level cooling is its precision and flexibility: cooling can be adjusted rack-by-rack according to the actual load of IT equipment. The closed air circulation inside the rack prevents the mixing of cold and warm air and improves cooling control. In addition, modular coolers can be installed in different racks as needed, which enables efficient cooling even when the server load is dynamically shifted in real time. However, this form of cooling also has disadvantages. Installation costs can be high because each rack needs its own cooling unit, and capacity can be over-provisioned. In addition, the system requires more effort to maintain because the coolers are numerous and located directly in the ICT equipment. (Zhang, Q et al.2021, p. 4-5)

The cooling efficiency of an air-cooled data center is affected by negative pressure, bypass and high recirculation ratio. Significant energy savings can be achieved in data centers by improving ventilation. In addition, significant energy savings can be achieved by increasing the supply air temperature and reducing the airflow. The problem with increasing the supply air is that it can increase the heat load during rapid peaks in usage. (Chethana G.D. & Sadashive Gowda B. 2020, p.146)

According to a study by Moazamigoodarzi H. et al. (2019), when switching from room-level cooling to row-level or rack-level cooling, cooling energy consumption can be reduced by up to 29%. In addition, the study found that by isolating the hot air exhaust of IT equipment from the cold air intake with a separate shelter building, energy savings of up to 18% can be achieved. These shelter buildings can be used for room-level, row-level and rack-level cooling solutions. Using these enclosures reduces the required airflow by up to 46% in a room-based, 24% in a row-based and 8% in a rack-based solution. These solutions reduce air recirculation and bypassing. According to the study, in all cooling solutions, the compressor in the chiller cooling cycle is responsible for the majority of the power consumption. (p. 526-533) As the thermal loads in data centers continue to increase and due to the tightening of energy efficiency requirements, it would be necessary to move from air cooling to other more energy-efficient cooling solutions.

4.2 Free Cooling

Free cooling, also known as an economizer cycle, refers to a cooling method that utilizes natural environmental conditions—such as cool outside air or water—as the cooling medium instead of relying solely on mechanical refrigeration. For free cooling to function effectively, the surrounding environment must provide sufficiently low temperatures. Therefore, the performance of a free cooling system depends heavily on ambient temperature and humidity levels. Due to these requirements, free cooling is particularly well-suited for data centers with low power density, where the cooling load is moderate. Free cooling systems are commonly classified into two main categories: airside free cooling and waterside free cooling. These can be further divided into direct and indirect configurations. (Cai S. & Gou Z. 2024, p. 9-11)

4.2.1 Air-side free cooling

Air-side free cooling utilizes the coolness of the outdoor air to cool data centers either directly or indirectly. In direct free cooling, outdoor air is directly introduced into the central processing unit and cooling system, effectively removing heat from the equipment without mechanical cooling. If necessary, warm exhaust air can be recirculated back through a mixing chamber to control temperature and humidity (Zhang Y. et al., 2021, P.4-6). Figure 5 illustrates the operating principle of such a system.

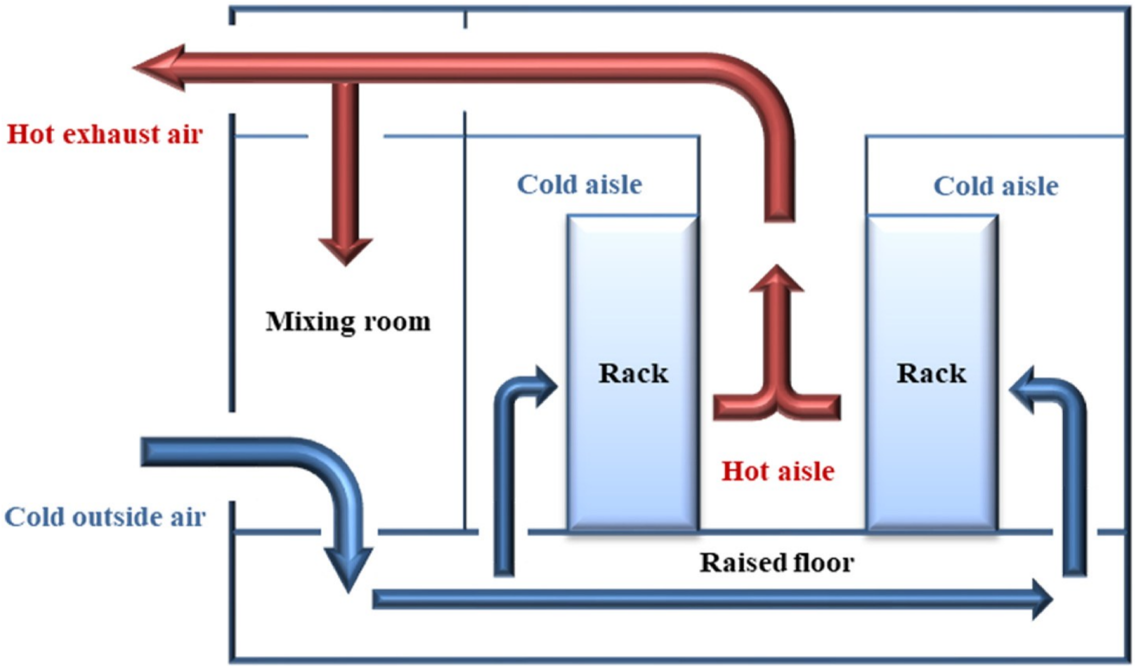


Figure 5. Air-side direct free Cooling (Nadjahi, C. et al., 2018)

A typical direct air-side free cooling system consists of ductwork and fans, grilles, filters, air intakes, and control dampers. These enable the system to utilize outdoor air for cooling, either fully or partially. By bringing cool outdoor air directly into the data center, heat from the equipment can be effectively removed without mechanical cooling. This approach is common, and it is estimated that in 2016, approximately 40% of all free cooling economizers in use operated with direct ventilation. (Daraghmeh H. & Wang C., 2016, p.1227)

Lee K. & Chen H. (2013) analyzed the energy saving potential of direct free cooling in 17 climate zones using numerical models. According to this study, every 2 degrees decrease in the internal temperature of a data center reduces the energy savings of free cooling technology by 2.8-8.5%, depending on the climate zone. However, direct free cooling is not an optimal solution in all climate zones – especially in dry or humid conditions, the system benefit may be limited due to the high fan energy and the energy requirement for humidifying or dehumidifying the air. According to the study, data centers located in cool climate zones can achieve significant energy saving potential with air-side free cooling technology. (p. 111-112)

A significant challenge in a direct system is the entry of contaminants such as dust or smoke into the data center space, which can damage equipment and reduce system reliability. Therefore, it is important to invest in air pretreatment and filtration. On the other hand, the use of filters can restrict airflow, which can affect cooling efficiency. These problems can be partially mitigated by monitoring algorithms that help predict disturbances and improve system reliability (Daraghmeh H. & Wang C., 2016, p. 1228) However, in a direct system, the mixing of indoor and outdoor air challenges indoor air quality management, and requires additional equipment such as dehumidifiers and filters. This increases both investment and operating costs. For these reasons, indirect free cooling may be a more attractive option in many cases. (Zhang, Y. et al 2021, p. 4-6)

In indirect free cooling, the outdoor and indoor air are not in direct contact with each other, but heat is transferred between these air flows using separate heat exchangers. There are various types of heat exchangers, the most classic of which are wheel heat exchangers, plate heat exchangers, evaporative heat exchangers and heat pipe exchangers. (Zhan, Q. et al 2021, p. 7). These allows the coolness of the outdoor air to be utilized without pollutants or high humidity directly affecting the indoor air quality of the data center. Figure 6 shows a typical indirect solution (Nadjahi, C. et al., 2018, p.18).

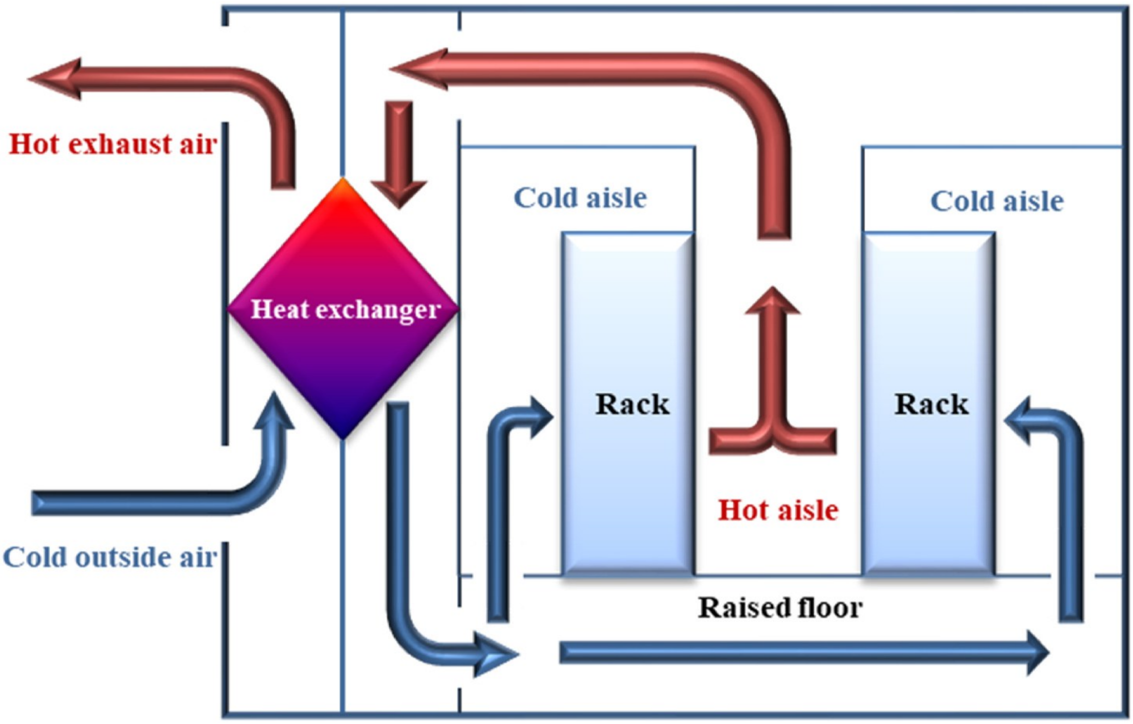


Figure 6. Air-side indirect free cooling system (Nadjahi, C. et al., 2018).

The most common implementation of indirect free cooling is an air-to-air heat exchanger, which allows the transfer of thermal energy between two separate air flows without mixing. This achieves efficient heat transfer but prevents pollutants from entering the data center space. Such a system can also be supplemented with evaporative cooling, which allows it to operate efficiently even in warm conditions. In this case, an indirect evaporative cooler, pumps, fans, water jet nozzles, sensors and, if necessary, direct expansion cooling as a supplementary cooling method are added to the system. (Daraghmeh H. & Wang C., 2017, p.1228)

4.2.2 Water-side free cooling

Water-side economizers are based on the idea of utilizing the natural cold of the environment – for example, outdoor air or water – to cool the data center. The goal is to reduce the need for mechanical cooling by cooling the circulating water, for example, using a cooling tower or dry cooler, when the outdoor air temperature is low enough.

This allows the desired indoor temperature to be maintained without additional energy consumption. (Daraghmeh, H. M & Wang C. 2017, p. 1229-1232)

A direct water-cooled system uses naturally cold water, such as seawater, to transfer heat away from the data center equipment. The water circulates in a closed cooling system and transfers heat to the seawater through a heat exchanger. (Khalaj, A. & Halgamugeb S. 2017, p.1183) The system can utilize the kinetic energy generated by ocean currents to drive pumps, which improves energy efficiency. Direct water-cooled systems keep the cooling water temperature constant all year round, but their implementation requires a large body of water nearby. Weather conditions and sea waves can also cause problems in systems, which can be harmful to the systems. (Daraghmeh, H. M & Wang C. 2017. p. 1232-1233) In addition, salt water can cause challenges to structures and systems.

Free cooling of the water side can also be implemented using air cooling. This system utilizes a dry cooler, which cools the temperature of the water circulating in the cooling system when the outside air is cool enough. The dry cooler can be connected to a CRAC unit or air-cooled chillers. (Khalaj, A. H. & Halgamugeb S. K. 2017, p. 1183) The advantages of these systems are their simplicity and integrability. The disadvantages of the systems are that when the outside air is not cold enough, the systems must switch back to mechanical cooling, which significantly reduces efficiency. In addition, additional components in the systems can increase energy consumption. (Daraghmeh, H. M & Wang C. 2017, p. 1234)

Water-side free cooling can also be implemented as a cooling tower system. In these systems, the water circulating in the system is cooled by cooling towers, as shown in Figure 7. A traditional CRAC unit can be modified by adding a plate heat exchanger, which allows the chiller to be bypassed when external conditions allow free cooling. In this case, pumps circulate the cooling water directly through the heat exchanger, eliminating the need for mechanical cooling. The system can be further expanded to utilize solar cooling using absorption chillers, solar collectors, and data center waste heat. (Khala, A. H. & Halgamugeb S. K. 2017, p.1183)

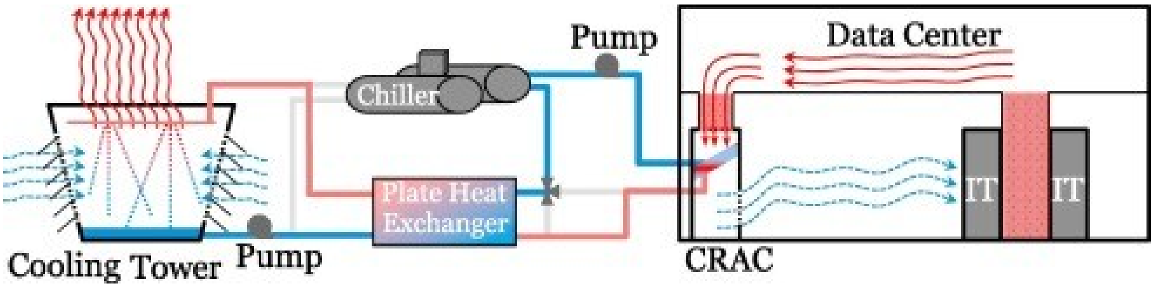


Figure 7. Cooling tower system (Khajala, A. H. & Halgamugeb S. K. 2017)

Water-side free cooling method is efficient, reliable, and generally easier to control than air-side free cooling because it is less dependent on outdoor air quality. According to studies, water-side free cooling can save up to 21% energy, and it works especially well in areas with abundant water resources and cool climates (Cai S. & Gou Z. 2024, p. 11).

Fan, c et al. (2024) study found that water-side free cooling can reduce cooling energy consumption by up to 62.6% in cold climates. The study showed that the system performance is climate sensitive. In warm climates, large energy savings are not achieved with this method. The study also found that water consumption increases significantly in warm climates. The study concluded that water-side free cooling is not suitable for hot and humid climates. (p.15)

4.3 Liquid cooling

The power of server components has been continuously increasing – for example, the power of chips can exceed 300 watts, and special chips up to 700 watts. (Kong R. et al. 2024, p.1) The development of artificial intelligence and the Internet of Things has increased power density even further, and the heat fluxes of modern processors are already 52–112 W/cm², while for example a household hob produces only about 10 W/cm². In some places, such as hot spots, the heat output can increase up to six times compared to the average, and in the future heat fluxes are predicted to increase up to 4500 W/cm². (Sarkar, S. et al 2023, p. 19) This makes efficient cooling vital, as high temperatures increase the risk of equipment failure. Therefore, one of the biggest challenges is to combine reliable operation and energy efficiency alongside the increasing amount of data. Air cooling methods have long been the most widely used cooling method in data center infrastructures due to their low cost and easy availability. However, the low density and poor heat transfer capacity of air can lead to insufficient cooling and local hot spots in data centers. (Kong, R. et al. 2024, p. 1-2).

As can be seen in Figure 8, air cooling can be considered the weakest cooling solution from a purely heat transfer perspective. The poor thermophysical properties of air significantly limit heat transfer, and in addition, the required airflows and higher cooling temperatures make it difficult to control the heat load and increase energy consumption. One promising and more energy-efficient alternative to air cooling is liquid cooling. Liquid cooling achieves significantly better heat transfer and lower cooling temperatures due to the better physical properties of liquids. Especially when energy efficiency, better performance or waste heat recovery are sought, liquid cooling offers significant advantages. (Kheirabadi & Groulx 2016, p. 626-627)

The significantly improved heat transfer capability of liquid cooling systems makes them a better option, especially for high-power systems. Liquid cooling solutions are being developed rapidly and can increase the maximum power of a single rack by up to five times compared to air cooling. This improves server performance and enables more compact equipment configurations. In addition, noise levels are reduced and heat can be reused, improving both energy efficiency and economic profitability. (Kong R. et al.

2024, p.2). Liquid cooling can be divided into two different parts: Direct and indirect cooling.

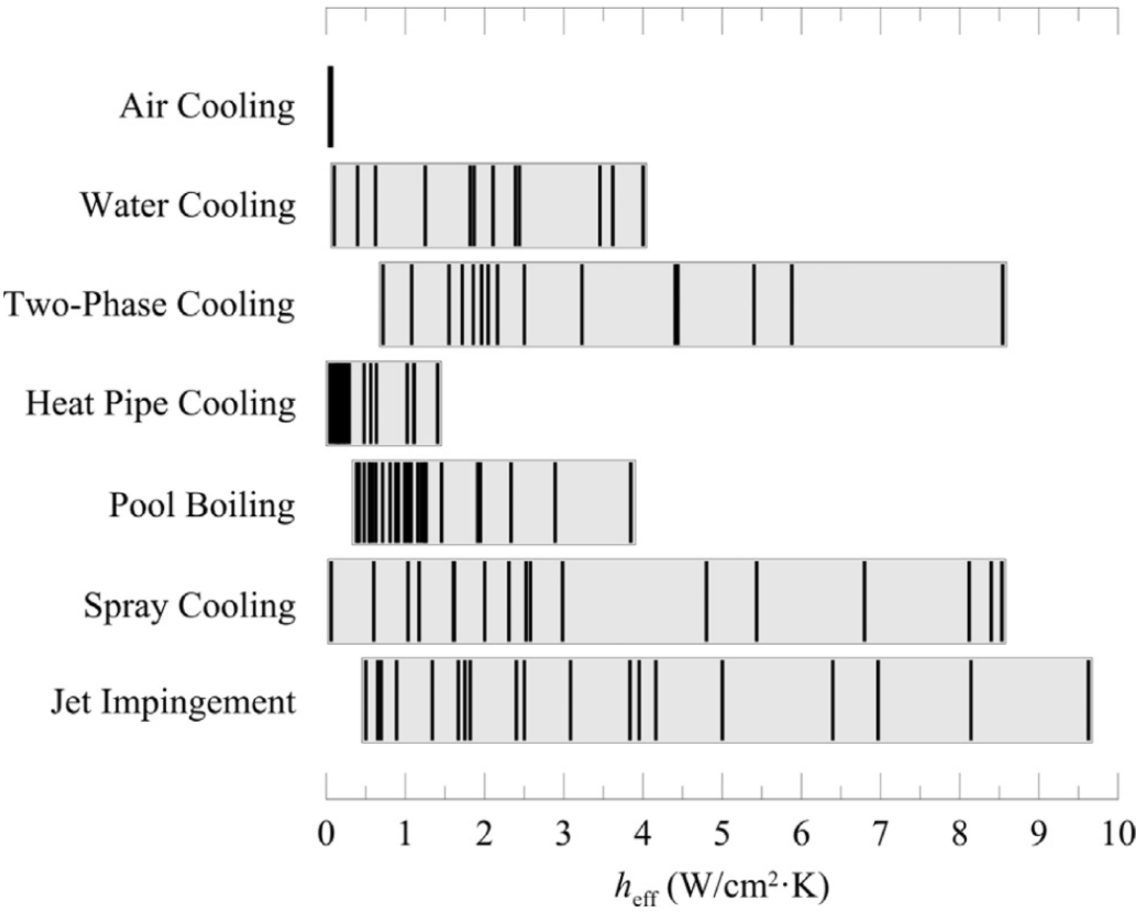


Figure 8. Ranges of heat transfer coefficients for different types of cooling methods (Kheirabadi, A.C. & Groulx, D. 2016)

4.3.1 Indirect liquid cooling

Indirect liquid cooling transfers heat without the coolant coming into direct contact with heat sources such as processors. Evaporators or other liquid-cooled heat sinks are used instead of traditional air coolers. Indirect liquid cooling methods traditionally use cold plates and water blocks, but recent research has focused on microchannel heat sinks, which have better heat transfer performance than traditional solutions. A typical system uses a coolant distribution unit (CDU), which circulates a precisely regulated liquid from an external cooling source to an internal, closed cooling loop connected to the heat sources of servers and other ICT equipment. Liquid cooling is often used to cool particularly heat-generating components such as processors, while other parts are cooled by air. Indirect liquid cooling offers a significant opportunity to improve data center cooling without having to switch to direct contact liquid cooling, which can be more technically and maintenance challenging. (Khalaj A. H. & Halgamuge S. 2017, p.1175)

4.3.1.1 RDHx

The Rear Door Heat Exchanger (RDHx) system is one of the easiest ways to move from air to liquid cooling. In this method, a cooling unit is installed at the back of the server cabinet and consists of heat exchanger coils designed to circulate liquid. Hot air generated by the operation of the IT equipment is passed through the heat exchanger, where the liquid absorbs the heat. The cooled air is returned to the room, and the warm liquid is then passed on to the cooling equipment, where it is cooled again (Azarifar, M. et al., 2024, p. 5-6). The working principle of the RDHx method in Figure 9.

The RDHx system requires chilled water to operate, which is supplied to the system via the data center’s Cooling Distribution Units (CDUs). The CDUs regulate the temperature and flow rate of the water so that the RDHx can effectively cool the air leaving the servers (Simon, V. et al., 2022). RDHx can be implemented in either a passive or active version. In a passive solution, the servers’ own fans blow air through the heat exchanger, while in an active model, the RDHx includes its own fans to compensate for air pressure losses and improve airflow and heat transfer.

One of the most significant advantages of the RDHx system is that it can eliminate the need for a separate hot aisle insulation or air control plenum (Azarifar, M. et al., 2024, p. 5-6). According to Simon, V. et al. (2022), the RDHx also reduces the need for separate CRAH and CRAC units and eliminates hot spots more effectively, as heat is recovered directly at its source. In addition, the RDHx system can utilize waste heat to improve energy efficiency.

Azarifar, M. et al. (2024) state that the RDHx can improve the safety and predictability of data center operations, especially in situations where the power demand and airflow of the server cabinets change rapidly and significantly. Although RDHx is primarily a rack-based solution, it can be integrated into a row-based cooling system. This hybrid design can reduce operating costs, simplify layout design, reduce chiller pressure drops, and enable the use of larger, more energy-efficient fans (p. 5-6).

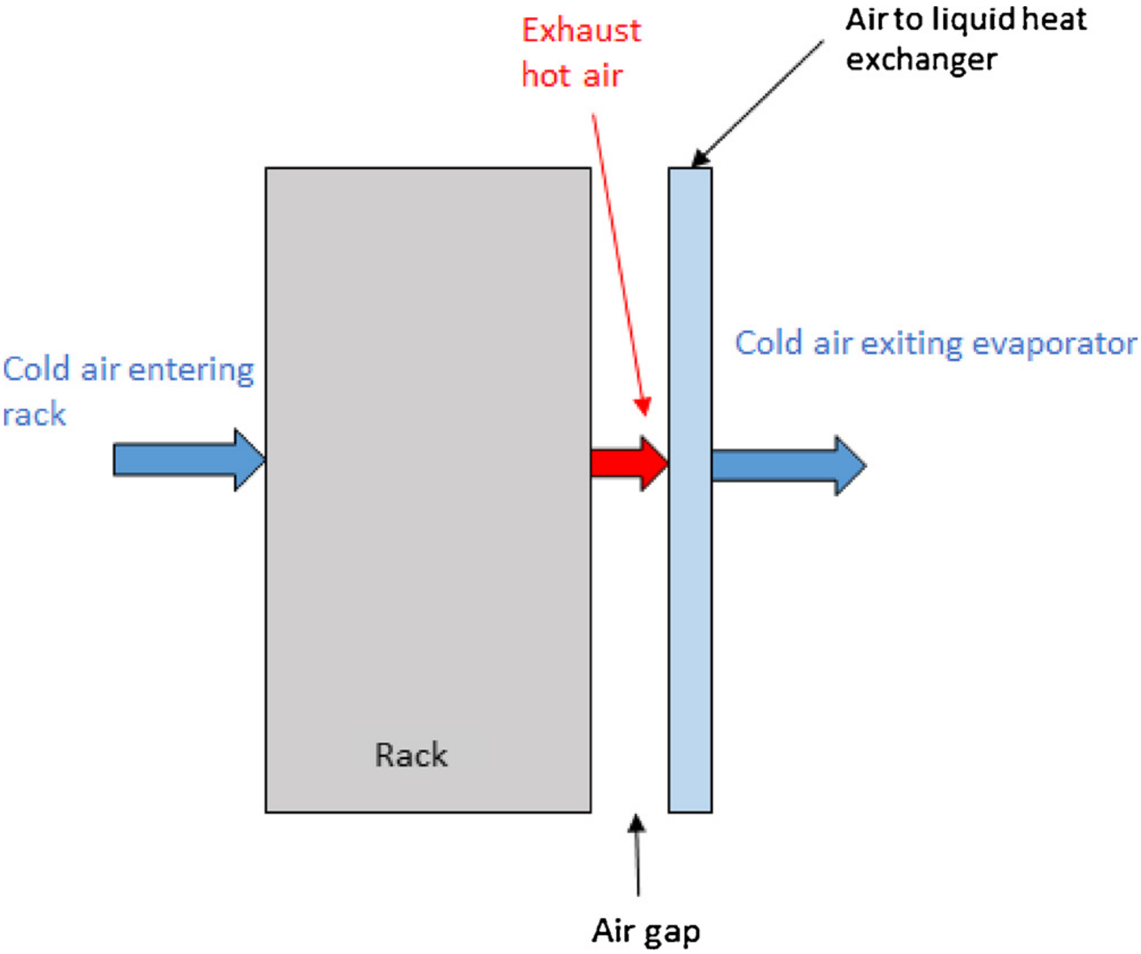


Figure 9. Simple schematic of the RDHx heat transfer process (Nadjahi, C. et al. 2018)

4.3.1.2 Cold plate liquid cooling

Cold plate liquid cooling is currently the most widely used liquid cooling solution in data centers. It is an indirect cooling method in which the coolant circulates in a closed system inside the cold plates without direct contact with the electronics. This makes it reliable and compatible with existing IT equipment, unlike direct liquid cooling solutions (Cai, S. & Gou, Z. 2024, p.9). Typically, cold plates are made of highly conductive metals, such as copper or aluminum, and are mounted on top of heat-generating components, such as processors (Wu, Z. et al., 2025, p. 3). Typically, the cooling plates are equipped with microchannels that further improve heat transfer performance (Azarifar, et al. 2024, p. 8).Usually, a cold plate cooling system consists of two loops, as seen in Figure 10. The inner loop transfers heat from the server to heat exchanger and the outer loop transfers heat outside (Pambudi, N.A. et al. 2022, p. 9511). In the inner loop heat is first transferred from the component to the plate and then to the coolant flowing in the plate, which is moved by a circulation pump in the cooling circuit. As the temperature of the liquid increases, it is led to a heat exchanger, where it cools by transferring heat to a cooler liquid, after which it is returned to the circulation via a coolant reservoir. (Wu, Z. et al., 2025, p.3).

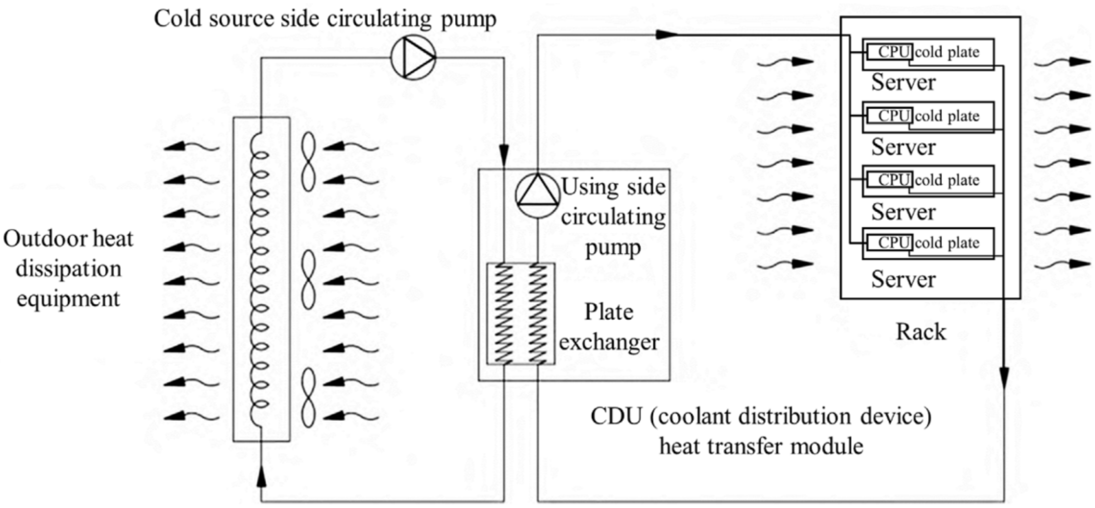


Figure 10. Schematic of cold plate cooling system (Cai S. & Gou Z. 2024)

Cold plate systems are particularly suitable for racks with a power density below 45 kW and are valued for their high energy efficiency and low noise levels (Xu, S. et al., 2022, p.12). One of the most significant advantages of cold plate liquid cooling is its low coolant consumption, which allows for a compact and lightweight design. This makes it well suited for traditional server racks. In addition, cold plate cooling systems can be flexibly combined with air cooling to form hybrid cooling solutions or other cooling technologies, forming so-called gradient cooling systems. Such arrangements enable precisely targeted cooling to high heat load points and prevent unnecessary cooling power from being wasted.

The flexibility of the technology allows it to be implemented in both new and existing data centers, which makes it attractive for retrofitting. A cold plate-based system is easy to maintain, and its reliability and compatibility make it a cost-effective solution in the long term (Wu, Z. et al., 2025, p.5).

Since the system is closed, it is very efficient in terms of water consumption. Compared to, for example, immersion cooling, cold plate liquid cooling consumes significantly less water, making it a more environmentally sustainable option. In addition, hybrid cooling solutions can further reduce water consumption. In general, data centers equipped with cold plate cooling systems typically have PUE values between 1.17 and 1.3, indicating good energy efficiency of the system (Wu, Z. et al., 2025, p. 4).

However, cold plate cooling systems come with challenges, such as the risk of leaks, complex control and maintenance, and the need to use cooling distribution units (CDUs) that pump and distribute liquid through manifolds. In addition, air cooling is often still required to cool peripherals and prevent condensation, which increases the overall energy consumption. (Azarifar, A. et al 2024, p. 14)

4.3.1.3 Two-phase cooling

Two-phase cooling process uses a liquid-vapor phase change of the circulating coolant for cooling (Zhang, Y et al. 2021, p. 7). Such phase change cooling often requires a liquid with a high heat of vaporization, which allows for more efficient heat transfer. (Zhan Q. et al 2021, p.6) The liquids are usually dielectric liquids with low boiling points or refrigerants that are suitable for this process. (Khalaja, A.H & Halgamugeb S.K. 2017, p. 1177)

Two-phase systems offer a higher heat transfer coefficient and a more even temperature distribution on the surface to be cooled compared to single-phase solutions. This reduces the flow rate required for heat transfer and reduces temperature fluctuations in the system. This results in more efficient and stable cooling. The system performance is further improved by designing more efficient microstructures, such as porous materials and microchannel coils directly on the chip surface. (Zhang Q. et al 2021, p. 6)

However, two-phase cooling also has challenges. These include flow instability, such as sudden changes in flow direction. In addition, pressure and temperature fluctuations can also cause overheating or even damage to the surface to be cooled. These limit the reliability of the method, especially in critical applications. (Zhan, Q. et al 2021, p. 6)
Two-phase cooling methods can be divided into heat pipe-based and thermosiphon-based cooling. (Cai S. & Gou Z. 2024, p.11)

4.3.1.4 Heat pipe

Heat pipe cooling consists of a hollow tube, the inner surface of which is coated with a structural material that allows capillary forces to arise and the working fluid to return. The tube consists of three parts: the evaporation section, the adiabatic section, and the condensation section. (Zhang, Y. et al. 2021) A heat pipe is a metal, often made of copper or aluminum, pressurized container, which contains a small amount of working fluid. (Alkrush A. et al 2024, p. 256). The basic operation of a heat pipe is shown in Figure 11.

In the evaporation section, the liquid vaporizes and moves through the adiabatic section to the condensation section, where the vapor condenses back into a liquid. The vapor efficiently transfers thermal energy to the condensation section by pressure-driven advection. At the same time, the vapor releases heat to the environment. The liquid moves back to the evaporation section by capillary action. (Khalaj, A. H & Halgamugeb S. K. 2017, p.1177-1178). According to Kheirabadi & Groulx (2016), the effective heat transfer coefficients of heat pipe cooling are between 0.1-1.4 W/cm2. As can be seen from Figure 6, heat pipe cooling does not reach the level of other liquid cooling systems in terms of heat transfer coefficient. Nevertheless, the advantage of heat pipe heat exchangers is that they can transfer heat efficiently with small temperature differences and utilize outside air or other passive cooling sources, which makes them particularly interesting for improving the energy efficiency of data centers. (Alkrush A. et al 2024, p. 257)

The advantages also include reduced risk of leakage in servers. The systems can also be exceptionally reliable and hermetically sealed devices. No fluid connections are required at the processor level. Since the system is based on capillary action, no pumps or other moving parts are required in the system, as the fluid moves passively in the system. This makes the system more stable. (Zhang, Q. et al. 2021, p.6)

According to Cai S & Gou Z. (2024), heat pipe systems can be divided into separate and integrated evaporators. Separate evaporators do not require additional mechanical cooling, while integrated evaporators do. A separate heat pipe system consumes about three quarters less energy than a vapor compression system, while the cooling capacity is at the same level. Such solutions are particularly suitable for situations where the heat load to be cooled is local or the system requires flexible placement. Despite the efficiency of separate heat pipe systems, their application range is limited. For this reason, integrated systems have received increasing attention. The energy efficiency of integrated HP systems can be up to 2–3 times better than free cooling alone. They are particularly suitable for large or multiple heat loads and environments where uniform temperature distribution and efficient use of space are required. (p. 11-12)

Heat pipe systems can also be integrated directly into equipment racks. Such a system allows for rapid heat transfer from IT equipment to the heat pipe without intermediate stages. The systems have demonstrated good energy efficiency in various climate conditions. (Alkrush A. et al 2024, p. 257)

Heat pipe cooling can also be implemented with an adsorbent-based heat pipe and direct natural cooling on the air side. The adsorption heat pipe is able to overcome the limitations of traditional heat pipes, especially in terms of heat transfer rate. Computational analyses showed that the technology could reduce the peak temperature of servers by almost 7 °C and significantly improve energy efficiency. (Alkrush A. et al 2024, p.257)

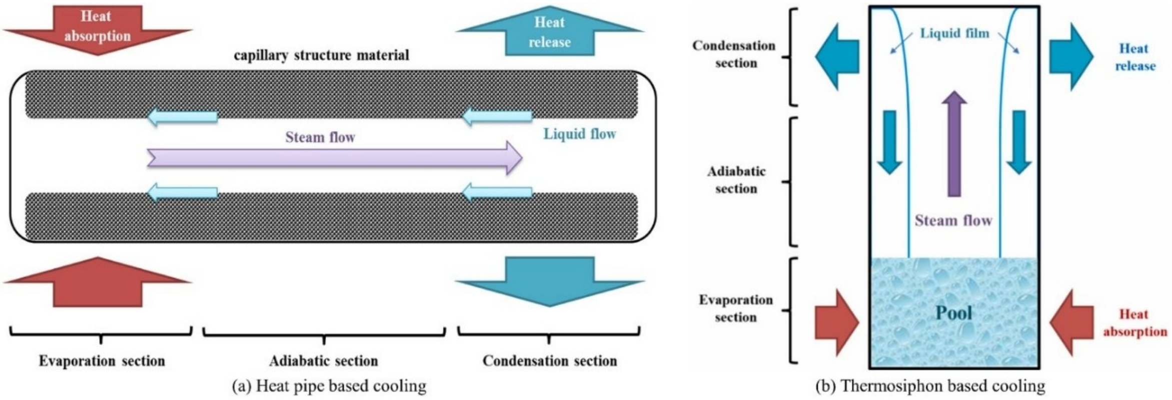


Figure 11. Fundamentals of heat pipe and thermosyphon based cooling systems (Cai, S. & Gou,Z. 2024)

4.3.1.5 Thermosyphon

Two-phase thermosyphon is also known as gravity heat pipe. Like horizontal heat pipe, this method includes an evaporator section, a condenser section and an adiabatic section. The liquid refrigerant evaporates under the influence of heat in the evaporator section, moves as a vapor through the adiabatic section up to the condenser, where the vapor condenses back into a liquid. After condensation, the liquid returns to the evaporator section by gravity. (Cai S & Gou Z. 2024, p.12)

Thermosiphon is commonly used for room or rack level cooling in air-cooled data centers. However, chip level thermosiphon solutions have also been developed, as shown in Figure 12.(Azarifar M. et al 2024, p.12).

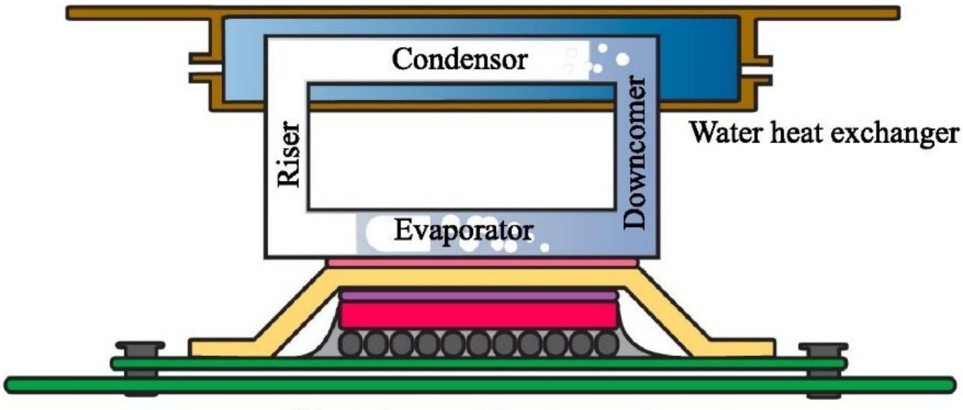


Figure 12. Thermosyphon cooling at chip level (Azifar M. et al 2024)

The main advantage of thermosyphon is its completely passive operation, meaning it does not require moving mechanical parts such as pumps. Additional cooling may be required at high outdoor temperatures (Alkrush A. et al 2024, p. 257)

Due to the energy saving potential of thermosyphon, its use has grown rapidly over the past decade. In data center applications, the optimal energy savings of thermosyphon can be up to 38.7%, and the achievable heat load can be up to twice as high as that of a traditional air cooling system (Cai S & Gou Z. 2024, p.12)

The most important parameters affecting the cooling efficiency of thermosyphon are the working fluids and the outdoor temperature. Among the working fluids, the efficiency of n-pentane has been observed to decrease by almost 84% when the temperature increases from 10 °C to 30 °C. (Zhang, Y. et al. 2021, p. 9)

The working fluids used in thermosyphons, such as acetone, isobutane, isobutene, and n-pentane, can be efficient but are often flammable. For this reason, more environmentally friendly and safer alternatives, such as carbon dioxide (CO_2), have attracted increasing interest. The use of CO_2 as the working fluid of a thermosyphon system in DC applications could be not only safer but also more economical, due to its excellent heat transfer properties. (Cai S & Gou Z. 2024p. 12)

4.3.2 Direct liquid cooling

In direct liquid cooling, components and electronic devices are cooled by a liquid that is in direct contact with them. This method uses dielectric, i.e. electrically insulating liquids, which allow safe contact with the electronics. One of the key advantages of direct cooling is its simple and flexible design: closed enclosures or complex piping are not required for circulating cooling liquids. In addition, other components can be cooled with the same liquid, eliminating the need for separate air and liquid cooling combinations. The downside of these liquids is that they have poorer thermophysical properties than water, so they do not transfer heat as efficiently as water. (Zhang, Q. et al 2021, p. 6-7) Because all server components are in contact with the liquid, there is no need for a hybrid air-liquid cooling method to cool them separately.

Direct cooling solutions can also take advantage of phase changes, i.e. the evaporation and condensation of the liquid, which helps to keep the temperature of the components constant. Direct liquid cooling systems operating atmospheric pressure do not use completely sealed housings, which allows components to be easily replaced by so-called hot swapping, i.e. without having to shut down the system. This makes them maintenance-friendly. However, such open systems require regular maintenance to prevent liquid evaporation and to remove air and moisture that can enter the system. In contrast, in fully sealed direct liquid cooling systems, these problems are less common, since the system is completely sealed. On the other hand, maintenance is more difficult: for example, if electrical components need to be replaced, the coolant must first be removed from the housing and then the system must be refilled, which makes maintenance more laborious. (Khalaj A., & Halgamugeb S. 2017, p.1178)

4.3.2.1 Immersion cooling

In immersion liquid cooling, the entire server is immersed in a cooling liquid. The heat transferred from the server to the liquid can be transferred directly to an external circuit for removal from the liquid or reuse. The liquids used in immersion liquid cooling are usually dielectric liquids that do not conduct electricity and are chemically stable. (Zhang, Y. et al. 2021, p. 6). For example, the dielectric liquids used can be mineral oils, synthetic fluorocarbons or silicone fluids (Carriero C. 2023). However, the liquids used do not transfer heat as efficiently as water, as their specific heat capacity is on average 66% and their thermal conductivity is up to 86% lower than that of water. Traditional systems often use a mixture of water and propylene glycol with corrosion inhibitors, which improves durability but weakens heat transfer properties by increasing the viscosity and density of the liquid. (Azarifar a et al 2024, p.13). The properties of the coolant directly affect the cooling efficiency. For example, Luo, Q. et al. (2022) investigated a novel coolant based on an oil-based fluid enriched with silicon carbide nanoparticles. This nanofluid significantly improved the heat transfer performance compared to traditional mineral oils and is seen to have potential for practical applications (p. 6-14). Immersion fluid cooling exists in two main forms: single-phase and two-phase immersion cooling. A typical system uses both internal and external circulation to move the coolant and remove heat from the equipment (Cai S. & Gou Z. 2024, p.9)

Immersion cooling systems have many advantages: energy savings, up to three times smaller space requirements than air cooling, easy commissioning and maintenance, and environmental friendliness due to lower noise and emissions (Azarifar, A. et al 2024, p. 13). Haywood A. et al. (2015) found that immersion cooling could reduce cooling costs by up to 50%. The study compared cold plate cooling to immersion cooling. The study found that immersion cooling reduced the temperature drop between the heat source and the exhaust line by up to 81%. The study also found that the exhaust line temperature of the immersion cooling system was on average up to 12.3 °C higher than that of cold plate cooling. (p. 302)

4.3.2.2 Single-phase immersion cooling

Single-phase immersion cooling (SPIC) is based on immersing electronic components in a non-conductive liquid with a high boiling point. Since heat is transferred to the liquid by conduction without the liquid evaporating, there is little evaporation loss, so the system maintenance is simple. Since single-phase immersion cooling does not utilize the latent vaporization, this cooling method does not reach the level of immersion cooling in two-phase cooling efficiency. (Kong R. et al 2024, p. 3) The operating principle of single-phase immersion cooling is shown in Figure 13.

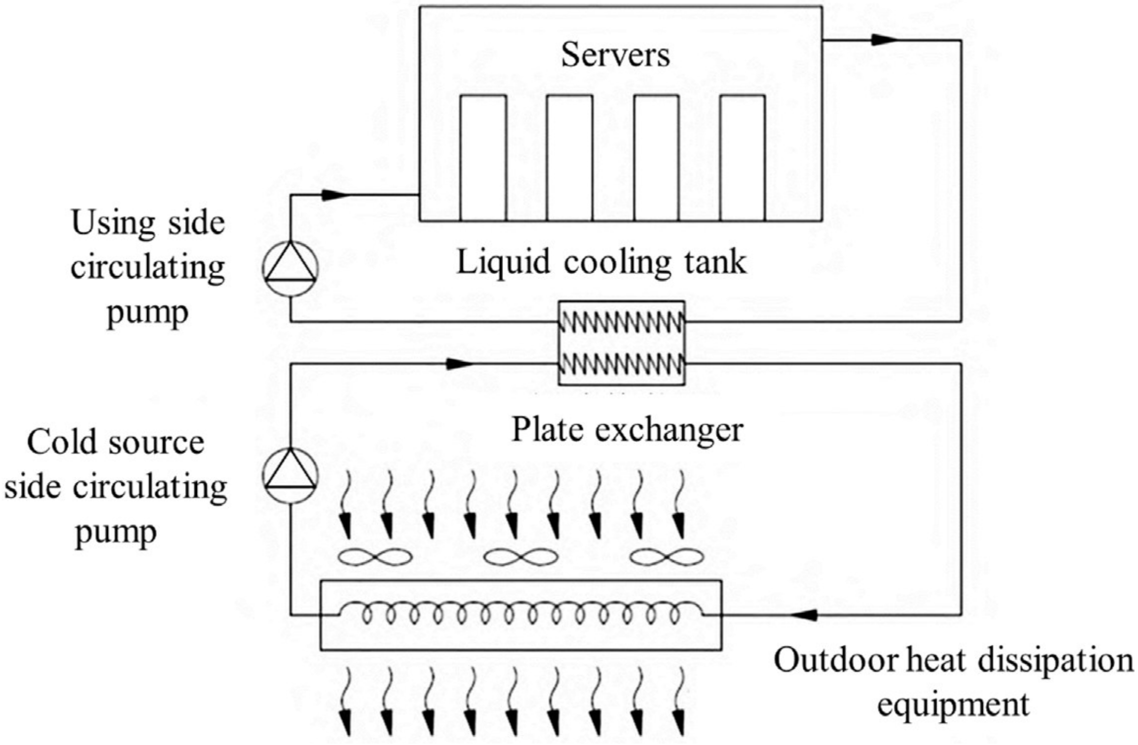


Figure 13. Single phase immersion cooling (Cai S. & Gou Z. 2024)

The key advantage of SPIC is its ability to effectively cool high-power density components over the entire component surface area, including memories and other peripherals.
In terms of cooling capacity, SPIC can exceed traditional air cooling by up to ten times, and the cooling capacity of a single cabinet can exceed 300 kW. (Zheng, S. et al. 2025, p. 3) Additionally, lower component temperatures reduce power consumption, with SPIC systems reported to reduce data center cooling power consumption by up to 95% and server power consumption by 10-20% (Zhou, K. et al. 2024, p.4). Additionally, servers using SPIC systems have an average component failure rate of approximately 50% lower than air-cooled servers, as it protects the electronics from air contaminants and moisture. Unlike cold plate systems, which still rely partially on air cooling, SPIC can completely eliminate the need for fans and cooling devices, reducing energy consumption and simplifying data center infrastructure.

SPIC systems can be divided into natural and forced convection coolant circulation. In natural convection, the fluid moves due to density differences caused by temperature fluctuations. Heat is removed from the system through coils inside the immersion tank to the external environment. (Zheng, S. et al 2025, p. 3) Pumpless systems utilize Rayleigh–Bénard convection, where the warm server heat acts as a vertical heat source, and the heat is transferred to another wall that is connected to an external cooling system. (Azarifar M. et al 2024, p.13-14)

Forced convection uses a pump to control the flow, which allows for better heat removal and often more energy efficient operation. Heat is removed between the coolant and the cooling water via a heat exchanger located outside the cabinet. Forced convection systems have a faster total coolant flow rate than natural convection systems, which can achieve better heat removal efficiency. The better heat removal efficiency means that the coolant temperature can be maintained at a higher level, which can result in lower energy consumption on the secondary side of the systems. Forced convection systems can therefore be more energy efficient than natural convection systems. However, SPIC systems are more expensive in terms of initial investment and require careful evaluation of fluid and component compatibility. (Zheng, S. et al. 2025, p. 2-3)

4.3.2.3 Two phase immersion cooling

As in SPIC, in two-phase immersion liquid cooling (TPIC), the electronic components are immersed in a cooling liquid. In two-phase, the heat generated by the components causes the cooling liquid to boil into vapor, i.e. the liquid undergoes a phase change. The liquid absorbs latent heat as it evaporates. (Chang, Q. et al. 2024, p.21) The vapor is then converted back to a liquid state by condensing coils. (Wang, N. et al. 2024, p. 4) The evaporation process enables efficient heat transfer, and the design of TCIP systems aims to optimize this phenomenon by utilizing, for example, microporous surfaces and advanced heat transfer structures (Kong R. et al 2024, p. 5). The operating principle of two-phase immersion liquid cooling is shown in Figure 14.

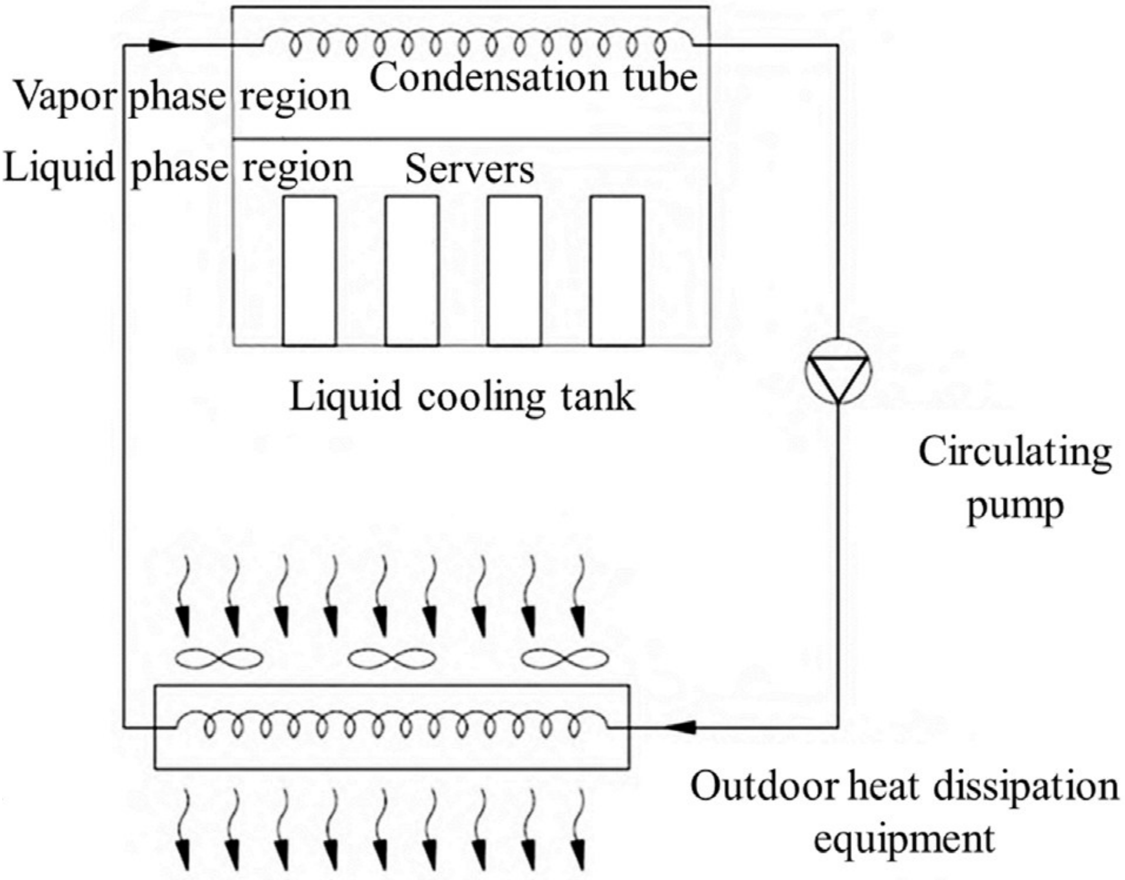


Figure 14. Two phase immersion cooling (Cai S. & Gou Z. 2024)

TPIC offers a higher heat removal capacity than SPIC (Wang, N. et al. 2024, p. 5). In addition, TPIC minimizes the temperature gradients across the heated surface. These improvements are due to the isothermal nucleation processes occurring in two-phase flow and the associated heat of vaporization (Azarifar M. et al 2024, p. 14-15). TPIC can have up to 79% better efficiency than SPIC. (Alkarush a., et al 2024, p. 255)

The limiting factor for heat removal of TPIC is the small surface area. This problem can be overcome by using advanced heat spreaders. (Azarifar, M. et al 2024, p. 14). According to Kong R et al. (2024, p.5), it would be possible to further improve the cooling efficiency of TPIC by up to 50% by using integrated cooling fins. Zhou, G. et al. (2022) research shows that cooling efficiency can also be increased with the help of various gradient capillary wicking structures in the vapor chamber. These vapor chamber heat sinks can safely transfer large heat loads of up to 900 W. These structures facilitate the circulation of the working fluid and improve the heat dissipation capacity of the vapor chamber. According to this study, a TPIC system using a vapor chamber heat sink would offer a much higher heat transfer capacity than other advanced cooling methods. This would make it a promising candidate for cooling high-flux-density data centers. (p. 1-8)

Concerns related to TPIC are related to pressure, temperature fluctuations, and flow direction reversals caused by flow instabilities. These can even lead to overheating and combustion of components (Azarifar M. et al 2024, p. 15). TPIC systems can experience leakage problems, and in addition, a small amount of coolant is constantly lost through evaporation. The pressure of the system has a significant impact on the boiling point of the coolant and thus on the entire cooling process. For example, keeping the system slightly below normal pressure allows for effective temperature control and lowers the operating temperature of the components. For this purpose, a variety of pressure control and vapor management mechanisms have been developed, such as vapor redirection structures and absorption/desorption-based solutions. (Kong, R. et al 2024, p.5)

The coolants used in TPIC are problematic for several reasons. These coolants can have a high global warming potential (GWP), and they can also pose health risks. TPIC coolants are also often more expensive than SPIC. In addition, there are challenges in properly recycling and disposing of coolants. In addition, servers are difficult to maintain frequently – they are typically only serviced once a year. The biggest challenge is that many of these coolants are PFAS compounds, so-called “forever chemicals.” Both the EU and the US are taking steps to limit the production of PFAS, and major manufacturers are phasing out their production by the end of 2025. This is a big problem for two-phase immersion cooling, as all current systems have used these PFAS chemicals. This is why there is a lot of research underway to find new, PFAS-free chemicals, such as HFO alternatives. These new alternatives would be more environmentally friendly, as they do not have an ozone depletion effect and have a low GWP value. This situation opens up many new opportunities for research and development (Azarifar, M. et al 2024, p.15). For example, immersion cooling directly into water has been studied. In this solution, the servers are coated with a thin protective layer made of parylene C. The purpose of the protective layer is to isolate the servers from the water. This method has proven to be very effective, as it is able to conduct away very large amounts of heat. (Birbarah et al. 2020, p. 10-12)

Although TPIC systems have significantly better thermal properties than SPIC, their investment costs, safety and maintainability are much worse. For this reason, SPIC systems are currently considered to be more suitable for commercial and large-scale applications. (Chang, Q. et al 2024, p.21-22)

4.3.2.4 Spray cooling

In the spray cooling process, a dielectric coolant is sprayed as small droplets onto the hot components using a nozzle. The droplets form a thin film of liquid on the surface, which effectively dissipates heat (Cai, S. & Gou, Z. 2024, p.9). This results in heat transfer to the liquid through convection, evaporation, or nucleate boiling. The heat removal process of spray cooling is shown in Figure 15.

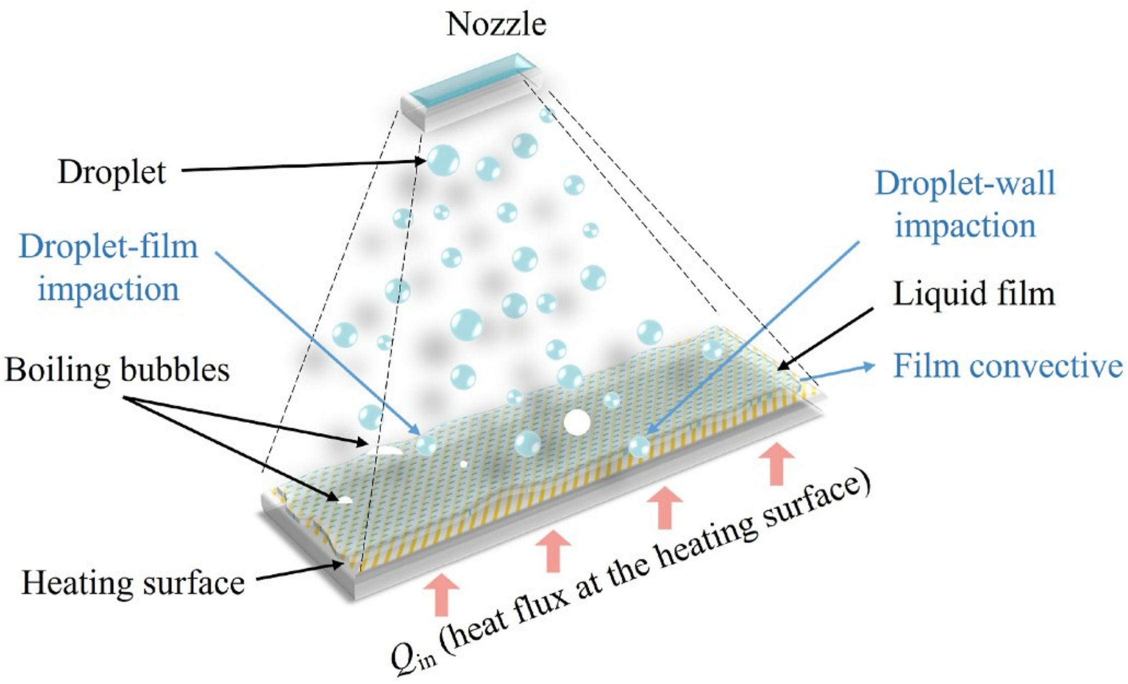


Figure 15. Spray cooling heat transfer process

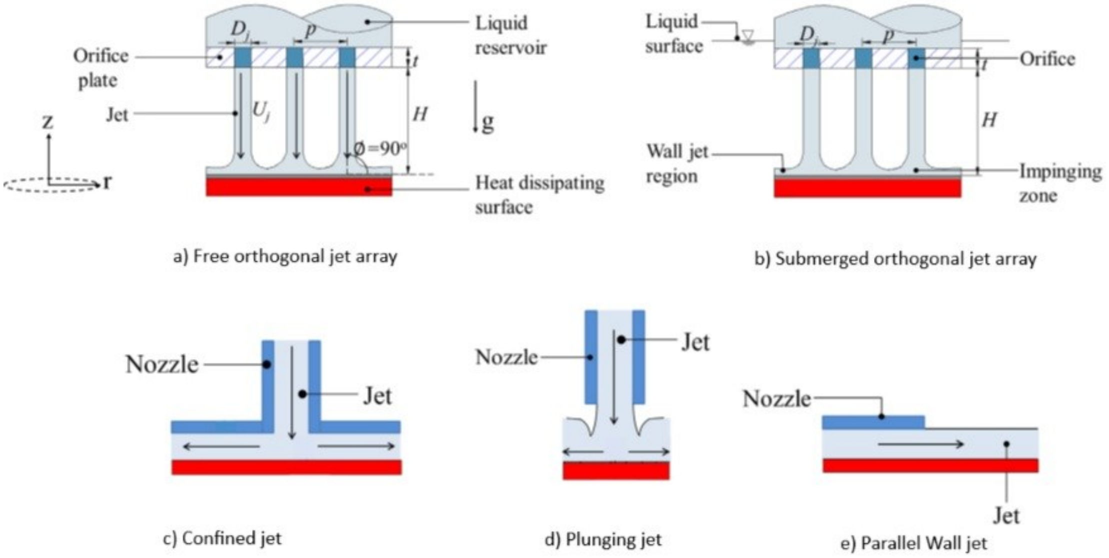
The efficiency of spray cooling is affected by many factors, such as the properties of the droplets, the structure of the surface to be cooled, the physical properties of the coolant, and the environmental conditions (Wang, N. et al. 2024, p. 5-6) .The technique is usually implemented as direct cooling, where the coolant is sprayed directly onto the components, but it can also be implemented indirectly using cold plates. (Khalaj, A.H. & Halgamuge S. K. 2017, p. 1179)

Studies have shown that adding surfactants to the coolant in spray cooling can improve the heat transfer of the method. For example, by adding certain salts to the coolant, it is possible to improve the heat removal capacity by up to 31%. Spray cooling can be directly applied to the cooling of server components. Spray cooling can be utilized in the cooling of servers directly at the component level. Experimental studies have shown that, for example, the flow rate and angle of the nozzles significantly affect the cooling results. Among the refrigerants, R134a has been commonly used in spray cooling, but R22 has also proven effective at higher heat fluxes. In addition, modifying the surface structures at the micro or macro level can improve the cooling efficiency by up to more than 30%. Various refrigerants and dielectric fluids, such as FC-72 and PF-5060, have been extensively studied, and the achieved heat fluxes have increased significantly in recent years. (Wang, N. et al. 2024, p. 6-7)

The advantages of the method are the low need for coolant compared to, for example, immersion cooling, which makes its implementation more economical. In addition, the advantages are the possibility of increasing the power density of IT equipment without the need for additional space. (Cai, S. & Gou, Z. 2024, p. 9) The spray cooling method has a lot of cooling and energy saving potential. According to Xu, S. et al. (2023), spray cooling can be used to cool a rack operating at up to 140 kW. In addition, the energy consumption of spray cooling is 25.8% lower than that of air cooling methods (p. 19). Despite these potentials, spray cooling is not yet widely used in data centers. The reasons for this are, among other things, that the method is difficult to maintain and overhaul, and that problems are caused by the evaporation and drift of the coolant. (Huang, X. et al. 2023, p. 20)

4.3.2.5 Jet impingement cooling

Like spray cooling, jet impingement cooling utilizes the process of liquid phase change to remove heat from IT equipment. The difference with spray cooling is that spray cooling uses a uniform liquid stream, while spray cooling breaks the liquid into small droplets. In jet cooling, a high-speed liquid stream is directed into a confined space, where a very thin thermal boundary layer is formed on the warm surface, which greatly improves heat transfer efficiency. (Kong, R. et al. 2024, p.9) As the liquid moves outward from the impact point, the boundary layer begins to thicken, which reduces heat transfer. Therefore, using a single jet is not sufficient to effectively cool larger chip surfaces, but multiple jets are needed to cover the entire area. Jet cooling requires an efficient pumping system that produces sufficient pressure to move the liquid. Jet cooling can be divided into five different categories: submerged, free, confined, plunging and wall jet. These methods of jet cooling are shown in Figure 16.



a) Free orthogonal jet array

b) Submerged orthogonal jet array

c) Confined jet

d) Plunging jet

e) Parallel Wall jet

Figure 16. Jet impingement cooling methods (Sarkar, S. et al. 2023)

The advantage of jet cooling is that it can effectively remove heat precisely from the points where it is generated most. The effectiveness of the technology depends on the flow geometry, the properties of the fluid and the structure of the surface to be cooled. Systems can be made more efficient, for example, by surface treatments that improve the contact of the fluid with the surface and direct the flow in the desired direction. This results in better heat transfer – which is critical for the increasingly hot electronic components of the future. (Sarkar, S. et al 2023, p. 19)

5 Waste heat recovery

Modern data centers have managed to significantly improve sustainability in recent years, especially in terms of electricity and water use. The next big step towards carbon neutrality could be the utilization of waste heat. Data centers are the second largest source of waste heat in the world, right after industry (Yuan, X. et al. 2025, p. 4) Up to 97% of this energy used by IT equipment is converted into heat. (Yin, P. et al. 2024, p.1) If energy is not recovered, this causes significant energy loss and would weaken energy efficiency. In addition, thermal energy that is not recovered can lead to increased cooling needs and heat pollution in outdoor spaces, which can increase operating costs and energy costs. However, this energy can be recovered and reused for many different purposes. (Yuan, X. et al. 2025, p. 4) Figure 17 illustrates the relationship between the data center and possible waste heat utilisation, in this case district heating system.

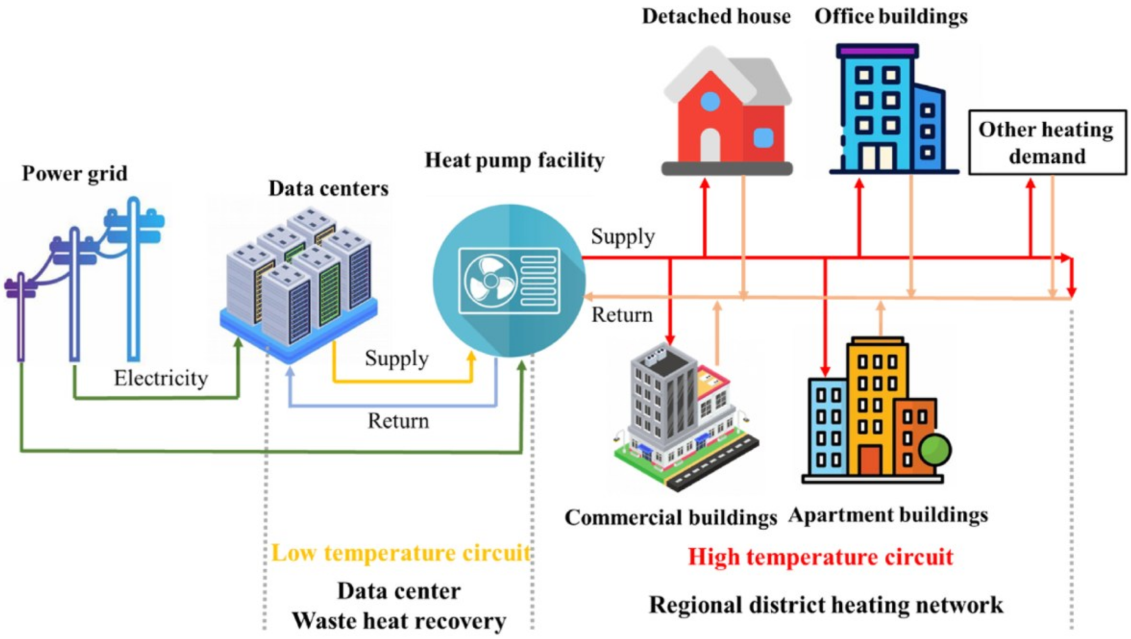


Figure 17. Connection between data center waste heat recovery system to the district heating network (Yuan, X. et al 2025)

Waste heat can be recovered from both air- and liquid-cooled data centers. However, the cooling technology used in the data center affects the amount and quality of waste heat. Liquid-cooled data centers allow for a higher quality waste heat recovery temperature of around 50-60 °C, while air-cooled ones allow for around 25-35 °C. This is because liquid transfers heat more efficiently than air, so the temperature of the circulating fluid can be higher and therefore the quality of the recovered heat is also higher. (Walhroos, M. et al. 2017, p. 1753). The temperature of the heat recovered from data centers using cold plate heat exchangers can reach up to 60-70 °C, while two-phase cooling systems can produce waste heat of up to 70-80 °C (Ebrahim, K. et al. 2014, p. 630). According to Amiri, L. et al. (2024) waste heat can be divided into four categories based on temperature levels: high-degree (>600 °C), medium-degree (200-600 °C), low-degree (80-200 °C) and very low-degree (45-80 °C) waste heat. This would make most of the waste heat from data centers very low-degree waste heat. (p. 2)

However, it is possible to improve the quality of waste heat by using, for example, heat pumps (HP) (Zhou, C. et al 2025, p. 2). Heat pumps can improve low-degree waste heat to higher temperatures using a small amount of electricity (Wang R. et al. 2025, p. 2). In this case, waste heat can be utilized, for example, in district heating networks or in various process industry applications. The use of pumps increases energy consumption, but they can still improve the energy efficiency of the entire system by reducing the ERE value (Walhroos, M. et al. 2017, p. 1753). Currently, heat pumps are seen as the most promising technology for data center waste heat recovery, and they can be utilized with both air- and water-based heat sources. (Yuan, X. et al. 2025, p. 5)

The best locations for data center waste heat recovery depend on the cooling method used. For air-cooled data centers, the best place to recover heat is in the return air flow of CRAC/CRAH devices, as seen in Figure 18. As shown in Figure 19, in liquid-cooled data centers, it is possible to recover heat closer to the heat-generating components (Walhroos, M. et al. 2017, p. 1753).

Sorknæs, P. et al. (2022) calculated that air-cooled data centers significantly increase the total cost of waste heat recovery compared to direct liquid-cooled systems. According to their study, using liquid cooling could save 1.7-1.9 M€/TWh in heat supply costs. (p. 7)

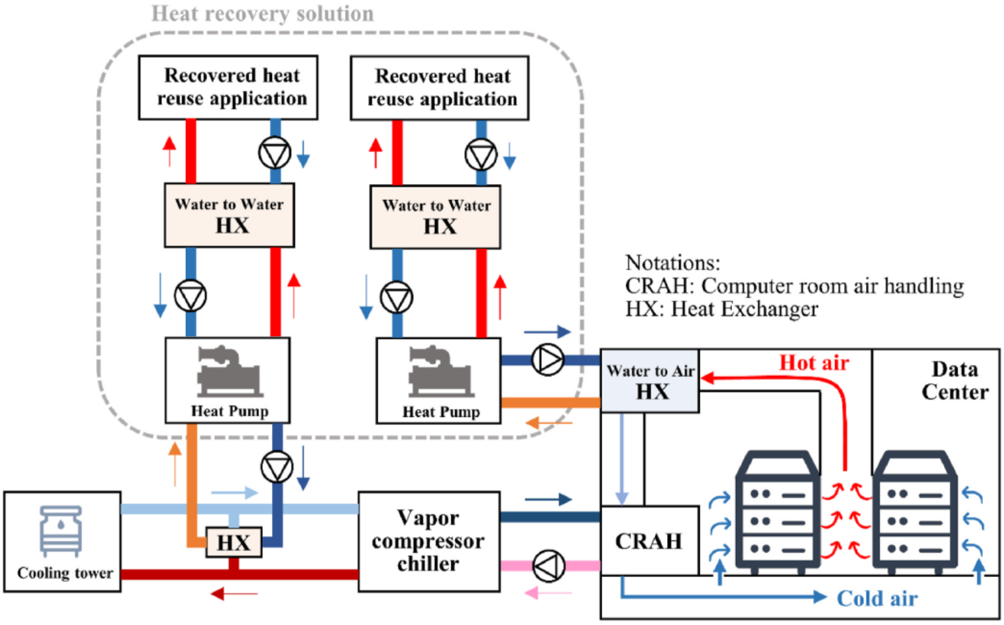


Figure 18. Waste heat recovery in air cooled data center (Yuan, X. et al. 2023)

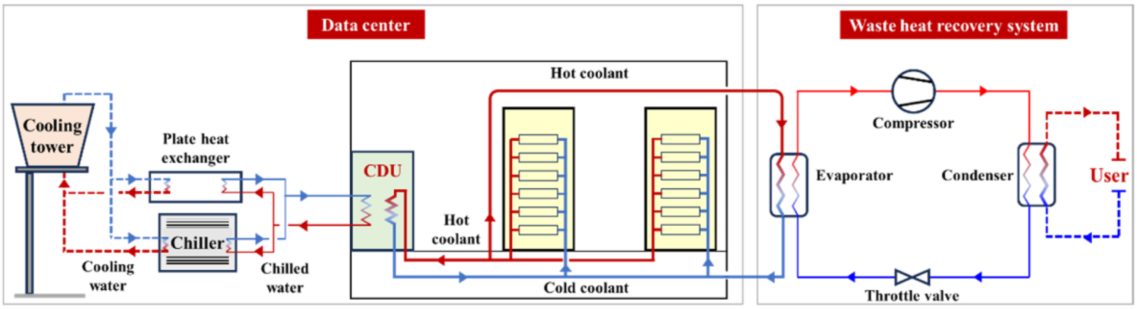


Figure 19. Waste heat recovery in liquid cooled data center (Wang, R. et al 2025)

Yuan, X. et al. (2025) estimates that the annual waste heat generated by data centers could be 70-170 TWh. Of this, an estimated 50-70% can be recovered and reused. This would mean that up to 35-85 TWh of waste heat from data centers could be utilized annually. For example, in France, the recoverable waste heat from data centers was approximately 1 TWh in 2020, which is equivalent to the heating needs of one million homes. By 2030, this figure is expected to increase to 3.5 TWh. In some countries, waste heat recovery is already regulated: in Germany, a new energy efficiency law requires 10% waste heat recovery by 2026, and a 20–30% target for 2028. Similar targets have been set in other European countries, such as France (15–25% by 2030–2035), Sweden and Denmark (25–35% by 2025–2030) and the Netherlands (20–30% by 2030). (p.3)

Waste heat recovery is considered a key method for improving the energy efficiency of data centers. However, the technology has challenges, the main one being the relatively low temperatures caused by the operating restrictions of IT equipment. (Hao, Y. et al. 2025, p. 6) This means that additional heat generation is often needed to help. Other problems include high investment costs and difficult infrastructures (Wahlroos, M. et al. 2017, p. 1754).

Waste heat utilization can be divided into two parts: waste heat recovery for electricity generation and heat utilization, the latter of which can be further divided into two main categories: waste heat recovery for heating and cooling. (Wang, P. et al. 2024, p.2) Waste heat can also be used for various other purposes, such as industrial and agricultural use.

5.1 Thermal energy storage

In addition to heat pumps, an effective way to improve the efficiency of waste heat recovery in data centers is thermal energy storage (TES), which balances the heat production of the waste heat system and optimizes the use of the recovered heat (Yuan, X. et al., 2023, p. 4). TES systems store excess heat when production exceeds demand and release it when heat demand is higher, reducing dependence on other heat sources (Yuan, X. et al., 2025, p. 13). Storage technologies include traditional water-based thermal storage and, in some cases, battery storage systems. Wang R. et al. (2025) divide TES systems into short-term and seasonal thermal storage. Short-term thermal storage smooths out diurnal variations and consumption peaks, such as during holidays, by storing heat during times of low demand and releasing it during peak demand. Seasonal thermal storage (STES), on the other hand, allows the utilization of excess waste heat produced in the summer during the winter season, when the heat demand is at its highest (p. 17). Montagud-Montalvá, C. et al. (2023) studied a system in the Mediterranean region that combined a heat pump and a thermal storage. The results showed annual thermal energy savings of over 254,000 kWh and annual CO_2 emission reductions of over 64,000 kg (p.9). According to the study by Li, H. et al. (2022), a water-based thermal storage system utilizing waste heat from a data center increased the utilization rate of waste heat from 79% to 96%. In addition, the thermal storage system reduced the peak load demand from 10.8 MW to 6.6 MW, or about 39%. (p. 12)

5.2 Waste heat recovery for heating

WHR systems use steam compressors (MVC) and heat pumps (HP) for heating.
The waste heat generated in data centers can be utilized for building heating, especially when liquid cooling methods are used for cooling. However, it must be pre-treated before using the heat. According to studies, when data centers operate at full load, the reuse of waste heat for building heating could meet the entire heat demand of the data center, while being more energy efficient and economically viable than heat pumps (Wang, N. et al. 2024, p. 7-8). The waste heat from data centers for heating can be utilized in district heating networks or directly for heating other buildings. This is one of the most practical and effective waste heat utilization strategies (Zhou, C. et al. 2025 p.9).

One of the easier ways to reuse waste heat is to heat local spaces and provide hot water for data centers and nearby buildings (Wang, R. et al. 2025, p.2). Lü, X. et al. (2024) studied the reuse of waste heat from an 18 MW data center for office and greenhouse heating. According to their analysis, 71% of the data center waste heat can be reused to heat this total area of 400,000 m2. This would reduce the cooling load of the data center by 71%. According to their estimate, this would lead to savings of more than 55 million euros in district heating consumption and reduce carbon dioxide emissions by 603,366 tons over 25 years. (p. 65-70)

Lu, T. et al (2024) studied the use of waste heat from a liquid-cooled data center for office building heating. Their study shows that a heat pump is not necessarily necessary for local space heating when using a liquid cooling method. This leads to significant energy and carbon dioxide emission savings.(p. 15)

A problem for heating nearby buildings is that the amount of waste heat generated by data centers often significantly exceeds the local absorption capacity. A more efficient and realistic solution requires connecting data centers to a larger, year-round heat distribution infrastructure, such as municipal district heating networks. This allows for higher utilization rates and improves the profitability of waste heat utilization both technically and economically. (Wang, R. et al. 2025, p. 9-11)

5.2.1 WHR for district heating

Waste heat from data centers can also be used in advanced district heating systems.
Current 3rd generation district heating systems (3GDH) and 4th generation systems (4GDH) operate at lower temperatures: 3GDH typically up to 100 °C and 4GDH 50-60 °C (Wang, P. 2024). This means that a data center using direct liquid cooling could feed waste heat directly to a 4GDH, and indirectly to a 3GDH with the help of a heat pump. (Sorknæs, P: et al. 2022, p.4)

5th generation district heating networks (5GDH) could utilize waste heat from data centers even better than 4GDH. 5GDH systems operate at very low and close to ambient temperatures, often even below 40-50 °C. (Yuan, X. et al. 2025, p .3)
The Nordic countries would be well suited for utilizing waste heat from data centers, due to their developed and extensive district heating networks, cold climate and cheap electricity prices. (Wahlroos, M. et al. 2018, p. 1754-1755))

For example, in Finland, an estimated 90% of the heat demand of the largest cities is met by district heating. Wahlroos et al. (2018) estimate that in the future, Finnish data centers will use 5 TWh of electricity per year, most of which can be reused as a heat source for district heating. In theory, this would mean that the waste heat produced by data centers could replace 20% of Finland's annual district heating demand. (p. 1754-1755) According to one analysis, a data center operating with a 4 kW cooling load could heat up to 110,000 m² of buildings in the long term (30 years), which produced an economic return of almost 12%. (Wang, N. et al. 2024, p. 8)

According to the analysis of Tervo, S. et al. (2024), the use of waste heat from data centers in a district heating network reduces the CO2 emissions and production costs of district heating networks, compared to district heating networks that do not use waste heat from data centers (p. 11). According to Pärssinen, M. et al. (2019), the recovery and sale of waste heat to district heating companies is not profitable for small data centers. According to their study, the amount of heat recovered and sold does not cover the costs of waste heat recovery equipment. However, for medium and large data centers, this business is profitable. (p. 435)

The limitation of using waste heat from data centers in district heating networks in Europe is that most European countries still use 2GDH or 3GDH systems. Only the Nordic countries and Central European countries use 4GDH systems to some extent. In addition, challenges include the mismatch between heat supply and demand, high initial investments and the need for long-term and stable operation. The advantages of using data centers are that they provide a continuous and steady source of waste heat. Data centers also improve the energy efficiency of district heating systems and also reduce the need for primary energy. Utilizing waste heat can bring savings to both data centers and district heating companies, reducing the need for cooling and the use of fossil fuels. Connecting waste heat from data centers to district heating significantly reduces carbon dioxide emissions and supports the transition of the energy system towards carbon neutrality (Yuan, X. et al. 2025, p.4-5)

5.3 Waste heat recovery for cooling

Waste heat generated in data centers can be utilized for cooling in two ways: absorption cooling and adsorption cooling. Both systems utilize thermal energy to produce cold water without the need for a compressor in a steam compressor system. (Hao, Y. et al. 2025, p. 8)

5.3.1 Absorption cooling

Absorption cooling systems offer an alternative way to produce cooling power without the traditional electric compressor. In these systems, the compressor of a vapor compression machine is replaced by three main components: an absorber, a generator and a brine pump. These components perform the role of a compressor, utilizing thermal energy, to drive the cooling process. The system can thus, for example, use waste heat from a data center as a heat source, generating chilled water for cooling other equipment. Absorption cooling's ability to convert low-value thermal energy into usable cooling makes it a potential solution for improving the energy efficiency of data centers that continuously generate low-temperature waste heat (Hao, Y. et al. 2025, p. 8). For example, Haywood et al. (2012, p. 34) found that by utilizing 85% of the data center waste heat in a lithium bromide ($LiBr/H_2O$) absorption chiller, significant energy efficiency gains can be achieved. When an external renewable heat source, such as solar heat, was added to the system, the PUE value was reduced to below one. Amiri L. et al. (2021) estimated that the implementation of an absorption cooling system could enable annual energy savings of up to 4.3 GWh in a 4.5 MW data center and 13 GWh in a 13.5 MW unit. In addition, this system would reduce greenhouse gas emissions by 3068 and 9208 tons of CO_2 equivalent per year, respectively. (p. 6-9)

However, the technology is limited by certain physical and operational factors. Absorption systems are often bulky and have a low power-to-weight ratio, making them particularly challenging in densely built data centers where space is limited. In addition, their operating efficiency drops significantly if the temperature of the heat used is below approximately 65°C, which may limit the suitability of the system for some applications. (Hao, Y. et al., 2025, p. 8)

The most commonly used working fluid pair in absorption cooling is LiBr/H_2O, while for adsorption cooling, for example, the preferred working fluid pair is silica gel/H_2O. According to studies, both technologies are already technically mature and have a potentially short payback period. In addition, absorption systems can offer a more energy-efficient alternative compared to traditional electrically powered vapor compression-based systems, especially when external waste heat is readily available. (Wang, N. et al 2024, p. 11-12)

5.3.2 Adsorption cooling

Adsorption cooling works by utilizing thermal energy to circulate the refrigerant without a compressor. The system has four main parts: adsorber, desorber, evaporator and condenser. Both the adsorber and desorber contain porous material that is able to bind (adsorb) or release (desorb) refrigerant depending on whether the system is being heated or cooled. The system is based on the fact that heat causes the adsorbent to bind and release refrigerant, creating a cooling effect through the conversion of thermal energy. (Gado, M. et al. 2017, p. 3-4)

One significant advantage of adsorption refrigeration is its low operating temperature: the system operates effectively at or below 60 °C (Hao, Y. et al. 2025, p.8). In addition, newer systems have managed to extend the operating temperature range to 40–95 °C (Wang, N. et al 2024, p. 11). Like absorption systems, adsorption chillers also require a lot of physical space, which limits their use, especially in tight equipment environments, such as large data centers. (Hao, Y. et al. 2025, p. 8). Despite this, their economic profitability is often good: the payback periods for investments are short, and the systems can generate significant savings in the long term (Wang, N. et al 2024, p. 11)

5.4 Waste heat recovery for energy production

Although waste heat from data centers is often directly or indirectly utilized for low-temperature applications, such as building heating or district heating, it is also possible to use it to produce higher-quality energy, such as electricity. This is achieved through heat-utilizing power plant processes, of which the Organic Rankine Cycle (ORC) is the most promising technically and economically. (Yuan, X. et al. 2023, p. 12)

ORC systems are a thermodynamic cycle that operates like steam power plants, but use organic liquids with lower molecular weight and lower boiling points as working fluids. A typical ORC system is suitable for small-scale applications, where the electrical power is usually 1 kW – 10 MW. Therefore, the technology could be well suited for data center cooling systems, for example. (Corigliano, O. et al., 2024, p.7)

Figure 20 shows the operating principle of an ORC system. The ORC system operating process consists of 4 parts (Araya, S. et al. 2018, p. 2):
1. The working fluid is pressurized and pumped into the evaporator by a pump.
2. In the evaporator, the working fluid is heated and evaporated using waste heat from the data center equipment.
3. The steam is transferred to an expansion device attached to the generator, where the steam expands, producing electricity.
4. The expanded steam is transferred to a condenser, where the liquid condenses and is transported back to the pump.

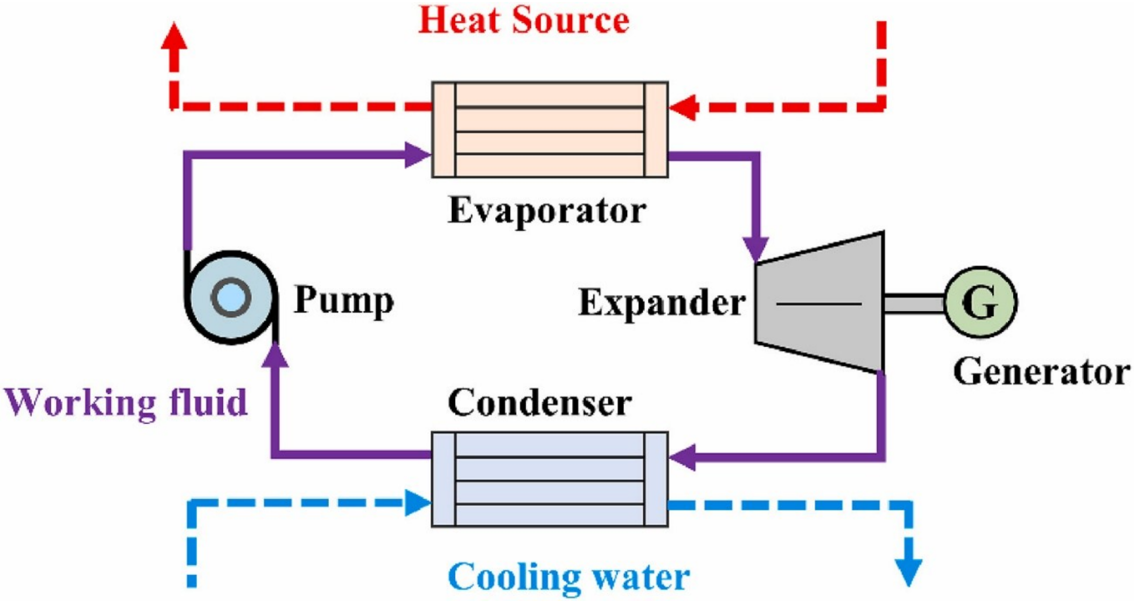


Figure 20. Schemtatic of an ORC system. (Yan, X. et al. 2023)

Although the ORC system usually requires a higher temperature (above 65 °C) for efficient operation, liquid cooling in data centers can produce heat at a sufficiently high temperature, especially when heat pumps are used for pre-heating. ORC systems traditionally use organic compounds such as R134a or R245fa as working fluids. These working fluids have high GWP values (Wang N. et al. 2024, p. 12-13). Marshall & Duquette (2022) investigated low GWP working fluids in ORC systems. The study showed that low GWP working fluids, such as R161 and Pentane, have similar or even better thermodynamic performance than traditional working fluids. According to the study, these more environmentally friendly working fluids not only reduce climate impacts but are also economically viable alternatives. (Marshall & Duquette, 2022, p. 12)

Low temperature limits efficiency, but systems can be economically viable. Ebrahimi, K. et al. (2017, p. 405) economic analysis suggested that the payback period of an ORC system would be 8-4 years in data center environments. The variability in the payback period in the analysis was mainly due to the variation in regional costs of commercial electricity.

Data centers can achieve significant energy and environmental performance improvements through ORC integration. Study by Corigliano, O. et al. (2024, p. 18) shows that integrating an ORC system into a data center can significantly improve both energy efficiency and environmental performance. According to the study, an ORC system can generate electricity that covers approximately 4.1% of the total data center consumption. At the same time, greenhouse gas emissions are significantly reduced, up to approximately 22.7 kg CO_2-equivalent savings per megawatt hour. According to Araya, S. et al. (2020, p. 11) study, an ORC system combined with two-phase cooling can achieve an efficiency of 4.6% when the waste heat temperature is 80 °C. They estimate that the efficiency could be 4-8% when the temperature rises to 90 °C.

5.5 Other potential uses for waste heat

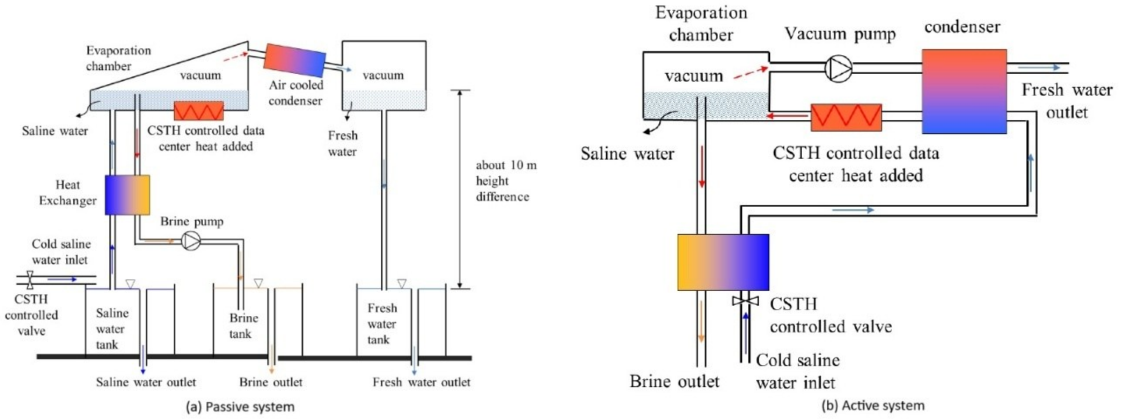
There are also other potential uses for data center waste heat. These uses can include, for example, various industrial and agricultural applications where heat is needed all year round, as opposed to, for example, district heating and local space heating, which need heat seasonally. (Wang, R.et al. 2025, p. 9)

5.5.1 Industrial applications

One of the most promising industrial applications of data center waste heat is seawater desalination, which is particularly relevant due to the growing demand for fresh water and the need to reduce energy consumption. Thermally driven desalination systems offer an alternative to electrically driven processes, utilizing waste heat as an energy source for water purification (Wang, R. et al., 2025, p. 15).

The most technically interesting thermal-based desalination methods are newer technologies such as membrane distillation (MD), adsorption desalination (AD) and humidification-dehumidification (HDH). These have the advantage of being able to operate at significantly lower temperatures compared to traditional processes such as multi-stage flashing (MSF) or multiple-effect distillation (MED). Lower temperature requirements mean lower energy requirements, making these methods particularly well suited for utilizing low-temperature waste heat. This not only improves energy efficiency, but also brings economic and environmental benefits, reducing fossil fuel consumption and greenhouse gas emissions (Elsaid, K. et al., 2020, p. 8-11).

In their study, Sondur, S. et al. (2018) designed two waste heat seawater desalination systems that enable good desalination conversion efficiency with only a heat source of 40–50 °C. The systems are presented in Figure 21. The systems operate based on the low evaporation temperature of seawater at low pressures. In the systems, a vacuum is created in the upper part of the evaporation chamber. In the passive system, the vacuum is created by gravity, so the system does not need anything other than a good and stable heat source, while the active system needs additional energy for the vacuum pump. (p. 4)



(a) Passive system

(b) Active system

Figure 21. Desalination systems (Sondur, S. et al 2018)

In addition to seawater desalination, waste heat from data centers can also be used in many other industrial applications, such as wastewater treatment and feedwater preheating, where it reduces external energy requirements and improves overall process efficiency. In addition, waste heat is suitable for thermal processes in the food and beverage, chemical, and pulp and paper industries, such as preheating, low-temperature evaporation, washing, and cleaning – all processes that operate in the temperature range to which waste heat from data centers is well applicable (Wang, R. et al., 2025, p. 15).

5.5.2 Agricultural applications

Data center waste heat is used in a variety of ways for agricultural needs, such as drying processes, greenhouse heating, and livestock heating (Wang, R. et al. 2025, p. 15). For example, Ljungqvist et al. (2021) studied the use of 1 MW data center waste heat for greenhouse heating and found that in small, 2,000 m² greenhouses, up to 97.9% of the heat demand can be covered with waste heat, while in large, 10,000 m² greenhouses, the share was 50–61. This solution would improve food security and self-sufficiency, especially in northern and cold climates. (p. 7-8)

Ge, Z. et al. (2024, P. 10-11) examined the data of a waste heat heat pump system in the tobacco drying process, where the drying efficiency was up to 36.69% and 20.21% for air-source heat pumps and air-source heat pumps, respectively. At the same time, the life cycle carbon dioxide emissions were reduced by 26.94% and 16.80%, which corresponded to 1,036.92 kg and 567.1 kg of CO_2 reduction per ton of dry tobacco produced. In addition, the annual energy costs were reduced by 16.8% and 2.07% compared to traditional methods. Chen, X. et al. (2023, p. 3-10) studied the use of waste heat in an organic farm, where the heat was utilized to maintain the indoor temperatures of the barn, greenhouse and drying room. The data center's daily heat production of 17.4 MWh enabled the farm to reduce its annual electricity demand by 764 MWh, which corresponded to the acceptance of 230 tons of carbon and 168 tons of CO_2 emissions.

6 Discussion

Based on this literature review, improving the energy efficiency of data centers requires the development of both measurement and technical solutions. Many different measurement standards have been developed for measuring energy efficiency of data centers, but PUE is still used for the most part for measuring energy efficiency, even though the limitations and weaknesses of PUE have been known for a long time. PUE does not take into account, for example, computing power, water consumption, carbon dioxide emissions, or waste heat reuse. In the future, it would be important to develop and standardize metrics that take these aspects into account and enable comparison of different technologies in a consistent manner.

Based on the literature review, it is noted that the largest single source of energy consumption in data centers is cooling. Currently, air cooling is still the most common cooling method in data centers. The problems with air cooling are poor cooling performance and large space requirements. However, various studies have shown that it is possible to improve the efficiency and energy efficiency of air cooling with different methods. The main way to improve air cooling seems to be to regulate the airflow by various means. An effective way to improve the efficiency of air cooling is to move from room-based methods to row and rack-based methods. In addition, it is possible to use various free cooling methods, which can currently save up to over 60% energy compared to traditional air cooling methods. However, the problem with free cooling is that it is not suitable for all climate zones, but usually requires a cooler climate to produce energy savings. This limits the use of free cooling globally.

However, as the power densities and thermal loads of servers continue to increase, it is clear that the limits of its cooling efficiency are beginning to be met due to the physical properties of air. The poor cooling efficiency of air cooling directly leads to a deterioration in the performance of the equipment. In addition, this can lead to overheating of the equipment, which leads to a reduction in its service life, which can even lead to irreversible damage.

Since liquids have better heat transfer properties than air, liquid cooling methods are more efficient than air cooling methods in terms of cooling capacity. This also makes them more energy efficient, as better cooling capacity means that the system can remove heat more efficiently if the equipment is sized correctly. Better heat transfer properties also make them better for recovering waste heat. There are several different types of liquid cooling solutions and they can often be divided into indirect and direct liquid cooling methods.

Indirect liquid cooling solutions are not as efficient as direct ones in terms of cooling capacity, as they have additional heat transfer layers that reduce the heat transfer capacity. Indirect methods often use air to transfer heat, so they are usually dependent on the physical properties of the air. However, indirect methods can also be integrated directly into racks or even directly into heat-generating components, which significantly improves cooling capacity. The advantages of indirect liquid cooling over direct cooling are generally lower leakage risks and easier installation. Cold plate and two-phase cooling are the most promising indirect cooling methods.

Based on the literature review, direct liquid cooling methods are often the most effective way to implement cooling in data centers. Their advantages are that the coolants are in direct contact with the heat-generating components, which makes the cooling very efficient. In addition, this allows for a higher waste heat temperature. Another advantage of direct liquid cooling is that they do not require a lot of space. In addition, more efficient cooling allows for a longer service life and more stable operation of the equipment, which reduces long-term operating costs. This makes often the biggest challenges are high leakage risks and expensive initial investments, in addition to problems with possible maintenance measures. Direct liquid cooling usually uses dielectric fluids with a high global warming potential. Which does not make them the most environmentally friendly methods. However, more environmentally friendly alternatives are constantly being developed, so this is unlikely to be a problem in the future.

The most important technological cooling solutions for the future are direct liquid cooling solutions, such as immersion, spray and jet impingement cooling. These have the best cooling capacities and are also considered energy-efficient solutions. These are best suited especially for large and high-power density data centers. In addition, their cooling capacity can be further improved by combining them with two-phase cooling. Other hybrid cooling methods, which combine different types of liquid and air cooling, can also be effective cooling methods, especially in medium and smaller data centers.

Although this work focused only on cooling solutions, it is important to recognize that future energy efficiency is not only created by the choice of cooling equipment. Energy efficiency can also be improved through various optimization methods. In the future, artificial intelligence and machine learning could improve the efficiency of cooling systems in real time with intelligent control, based on server load, outdoor temperature and electricity price. It is also clear that the location of the data center can have a major impact on energy efficiency.

Waste heat is a valuable resource and its recovery is one of the best methods to improve the energy efficiency of data centers, as it transforms the data center from an energy consumer to a producer. The efficiency of waste heat recovery processes is greatly affected by waste heat temperatures, so liquid cooling methods are better suited for waste heat recovery than air cooling. In cases where the waste heat temperature is too low, a heat pump can be used to raise the waste heat temperature. Waste heat can be utilized in many ways for heating, cooling, energy production and various industrial and agricultural activities. Based on the literature, the most common and efficient way to utilize waste heat on a large scale is as a heat source for district heating. This is best suited to countries with developed district heating networks.

In areas where there is no need for district heating or there are no developed district heating networks, waste heat can be utilized for industrial use. The most promising applications would be seawater desalination. This would provide a sustainable alternative to solving water shortages in arid regions and coastal areas. Another alternative is energy

production using an ORC system. Although the efficiency of ORC systems is not very high at the moment, their development will continue, and the efficiency will increase.
Waste heat from data centers is also suitable for various agricultural needs. The most important of these would be heating greenhouses, which would provide food security and self-sufficiency in cold climates.

Utilizing waste heat therefore creates a new source of income for data centers and improves the overall profitability of data centers. In addition, utilizing waste heat reduces carbon dioxide emissions, for example by reducing the need for fossil fuels for heating. However, waste heat recovery is not yet very common. The reasons for this are likely to be large initial investments, lack of infrastructure and the locations of data centers far from heat needs.

The aim of this literature review was to provide a comprehensive overview of data center cooling solutions and waste energy recovery. However, as with all studies, this review also has certain limitations that are important to be aware of.
This review focused mainly on scientific articles, and may not include various industry publications, such as commercial publications, that could contain important practical information. The results are also affected by the quality of the sources and reporting methods. In addition, the rapid technological development in the field may make some sources partially outdated. The review focused only on English-language publications, which is also a limitation of the review, as it may exclude relevant literature. These limitations show that energy efficiency in data centers is a broad and complex topic that requires continuous research and consideration of different perspectives.
Based on this literature review, the technical benefits of cooling solutions and waste energy utilization are undeniable.

There are few comparative studies in the literature where different cooling solutions have been tested under identical conditions. In the future, it would be useful to study these technologies using uniform metrics and to assess their life cycle impacts, including emissions during manufacture and use and potential environmental impacts. In the future, it would also be important to investigate the comparison of different investment costs and payback periods in data centers of different sizes. In addition, the economic and technical feasibility of utilizing waste heat requires more case studies in different types of climate and infrastructure conditions.

7 Conclusion

The aim of this master's thesis was to examine the energy efficiency of data centers through a literature review and to answer three research questions: What are the key factors affecting the energy consumption of data centers? What are the most common cooling solutions in data centers and how do they affect energy efficiency? What technologies have been developed to utilize waste energy?

The first research question can be stated that the energy consumption of data centers is affected by IT equipment, cooling devices, electrical devices and other miscellaneous components. Of these, cooling constitutes the largest single source of energy use. The most used metric in assessing energy efficiency is still PUE, but its limitations have been widely recognized, and in the future it would be necessary to develop more comprehensive metrics that also take into account water consumption, carbon footprint and waste heat reuse.

In response to the second research question, the work showed that air cooling is still the most common solution in data centers. Its energy efficiency can be improved, for example, by row and rack level methods and free cooling, but due to the poor heat transfer capacity of air, the cooling capacity of air cooling is starting to reach its limits. Liquid cooling solutions offer better cooling performance and energy efficiency while also enabling higher heat dissipation. Liquid cooling methods can be divided into direct and indirect. The cooling performance of indirect solutions does not reach the level of direct solutions, as heat is not transferred from the components directly to the liquid, but usually either via a cold plate or air. The advantage of indirect methods is that the system is often easier to deploy in existing data centers without significant changes to the infrastructure. Other advantages include cost-effectiveness, safety and easy maintenance. Direct liquid cooling solutions offer superior cooling performance and energy efficiency, as the liquid is in direct contact with the components, which enables very high power densities for servers. This greatly reduces the space requirement and enables a higher waste heat temperature. Problems arise from leakage risks and higher investment and maintenance costs.

Regarding the third research question, the literature review identified several promising technologies for utilizing waste heat from data centers. District heating is the most significant application in areas with existing infrastructure. In addition, organic Rankine processes (ORC) enable the conversion of waste heat into electricity. In industrial and agricultural applications, such as seawater desalination, wastewater treatment and greenhouse heating, waste heat offers a low-emission alternative to fossil fuels. Waste heat offers great potential to improve the energy efficiency of data centers and reduce the use of fossil fuels.

In summary, the energy efficiency of data centers depends on many factors, but it can be improved by choosing more efficient cooling solutions and utilizing waste heat. The focus of development is to move to more comprehensive energy efficiency assessment methods, as well as to move to technologies that reduce energy consumption and bring added value to the environment.

8 Summary

This thesis examines the energy efficiency of data centers through a literature review. This thesis focuses mainly on cooling solutions and waste heat utilization.

The study states that many factors affect the energy consumption of data centers, of which the largest single source of energy consumption is the cooling systems. Although PUE is still the most commonly used metric in assessing energy efficiency, its shortcomings highlight the need for indicators that also take into account, for example, water consumption and waste heat reuse.

The most widely used cooling solutions in data centers are still air-cooled solutions. Their efficiency can be improved, for example, with free cooling and row- or rack-level cooling systems. However, the cooling efficiency of air-cooled cooling systems is limited by the poor heat transfer capacity of air, which impairs the performance and energy efficiency of the equipment. Liquid cooling solutions offer significant advantages in performance and energy efficiency. Liquid cooling systems enable higher power density and more efficient waste heat recovery. However, challenges with liquid cooling solutions include potential leakage risks, higher initial investments and infrastructure requirements.

Utilizing waste heat is one of the most promising ways to improve sustainability. Waste heat can be used, for example, as a heat source for district heating, for energy production using ORC systems, and also for industrial or agricultural applications. Reusing waste heat shows strong potential in reducing dependence on fossil fuels and providing environmental benefits.

The results of the study suggest that improving the energy efficiency of data centers requires both the introduction of innovative cooling technologies and the integration of waste heat recovery. Future developments should also prioritize comprehensive measurement methods to better consider environmental impacts.

References

Abdullah, S. Zubir, M., Muhamad, M., Newaz, K., Öztop, H., Alam, M. & Shaikh, K. (2023) Technological development of evaporative cooling systems and its integration with air dehumidification processes: A review, *Energy and Buildings*, Volume 283, 2023, https://doi.org/10.1016/j.enbuild.2023.112805

Ahmed, K. M. U., Bollen, M. H. J. & Alvarez, M. (2021) A Review of Data Centers Energy Consumption and Reliability Modeling, in *IEEE Access*, vol. 9, pages 152536-152563, 2021, doi: 10.1109/ACCESS.2021.3125092

Alkrush, A., Salem M., Abdelrehim, O. & Hegazi A.A. (2024) Data centers cooling: A critical review of techniques, challenges, and energy saving solutions, *International Journal of Refrigeration*, Volume 160, 2024, Pages 246-262, https://doi.org/10.1016/j.ijrefrig.2024.02.007.

Amiri, L., Madadian, E., Bahrani, N., & Ghoreishi-Madiseh, S. A. (2021). Techno-Economic Analysis of Waste Heat Utilization in Data Centers: Application of Absorption Chiller Systems. *Energies*, *14*(9), 2021. https://doi.org/10.3390/en14092433.

Araya, S., Jones, G. F. & Fleischer, A.S. (2018). Organic Rankine Cycle as a Waste Heat Recovery System for Data Centers: Design and Construction of a Prototype. *17th IEEE Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems*. 2018, https://doi.org/10.1109/ITHERM.2018.8419530

Araya, S., Wemhoff, A., Jones, G. F. & Fleischer, A. (2020). Study of a Lab-Scale Organic Rankine Cycle for the Ultra-Low-Temperature Waste Heat Recovery Associated With Data Centers, *Journal of Electronic Packaging*, 143, 2018, https://doi.org/10.1115/1.4047843

Ashtine, M. & Mytton, M. (2021, October 19). *We are ignoring the true cost of water-guzzling data centres*. The Conversation. Retrieved March 17, 2025, from https://theconversation.com/we-are-ignoring-the-true-cost-of-water-guzzling-data-centres-167750

Azarifar, M., Arik, M. & Chang, J. (2024). Liquid cooling of data centers: A necessity facing challenges. *Applied Thermal engineering*, *247*, 387–397. https://doi.org/10.1016/j.applthermaleng.2024.123112

Barroso, L., Hölzle, U., & Ranganathan, P. (2019). *The Datacenter as a computer: Computer: Designing Warehouse-Scale Machines* (Third Edition). Springer. ISBN: 978-3-031-01761-2

Belady, C., Azevedo, D., Patterson, M., Pouchet, J. & Tipley, R., (2010) Carbon Usage Effectiveness (CUE): A Green Grid Data Center Sustainability Metric, *the green grid*, White paper #32, 2010, https://www.thegreengrid.org/en/resources/library-and-tools/241-WP%2332---Carbon-Usage-Effectiveness-%28CUE%29%3A-A-Green-Grid-Data-Center-Sustainability-Metric

Birbarah, P., Gebrael, T., Foulkes, T., Stillwell, A., Moore, A., Pilawa-Podgurski, R. & Miljkovic, N. (2020) Water immersion cooling of high power density electronics, *International Journal of Heat and Mass Transfer*, Volume 147, 2020, https://doi.org/10.1016/j.ijheatmasstransfer.2019.118918.

Cai, S. & Gou Z. (2024). Towards energy-efficient data centers: A comprehensive review of passive and active cooling strategies. *Energy And Built Environment*. https://doi.org/10.1016/j.enbenv.2024.08.009

Cao, S., Hasan, A. & Sirén, K.(2013) On-site energy matching indices for buildings with energy conversion, storage and hybrid grid connections, Energy and Buildings, Volume 64, 2013, Pages 423-438, ISSN 0378-7788, https://doi.org/10.1016/j.enbuild.2013.05.030.

Carriero, C. (2023, December, 8) What Is Immersion Cooling for Data Centers? – How It Works, *Park Place Technologies*, https://www.parkplacetechnologies.com/blog/what-is-immersion-cooling-data-centers/

Chang, Q., Huang, Y., Liu, K., Xu, X., Zhao, Y., & Pan S. (2024). Optimization Control Strategies and Evaluation Metrics of Cooling Systems in Data Centers: A Review. Sustainablity, 16, https://doi.org/10.3390/su16167222

Chen, X., Bai, J., Fu, L., Lei, Y., Zhang, D., Zhang, Z., Luo, Q., Gong, S. & Shen, B. (2024). Complementary waste heat utilization from data center to ecological farm: A technical, economic and environmental perspective, *Journal of Cleaner Production*, 435, https://doi.org/10.1016/j.jclepro.2023.140495.

Chethana G.D. & Sadashive Gowda, B.(2020) Thermal management of air and liquid cooled data centres: A review, *Materials Today: Proceedings*, Volume 45, 2021, Pages 145-149, https://doi.org/10.1016/j.matpr.2020.10.396.

Corigliano, O., Algieri, A., & Fragiacomo, P. (2024). Turning Data Center Waste Heat into Energy: A Guide to Organic Rankine Cycle System Design and Performance Evaluation. *Applied Sciences*, 14, 2024, https://doi.org/10.3390/app14146046

Dai, J., Ohadi, M., Das, D. & Pecht, M. (2014). *Optimum Cooling of Data Centers*. Springer. ISBN: 978-1-4614-5602-5.

Daraghmeh, H. M. & Wang, C. (2016) A review of current status of free cooling in datacenters, *Applied Thermal Engineering*, Volume 114, 2017, Pages 1224- 1239, https://doi.org/10.1016/j.applthermaleng.2016.10.093.

Dincer, I. & Rosen, M. (2015) Chapter 4 - Heat Pump Systems, Exergy Analysis of Heating, Refrigerating and Air Conditioning, *Elsevier*, 2015, Pages 131-168, https://doi.org/10.1016/B978-0-12-417203-6.00004-1.

Dunlap, T. & Rasmussen, N. (2012) Choosing Between Room, Row, and Rack-based Cooling for Data Centers , *APC Whitepaper*, Volume 130, 2012Lei, https://www.apc.com/us/en/download/document/SPD_VAVR-6J5VYJ_EN/.

Ebrahimi. K., Jones, G. & Fleischer A. (2014). A review of data center cooling technology, operating conditions and the corresponding low-grade waste heat recovery opportunities. *Renewable brotherand Sustainable Energy Reviews* ,31.622–638. https://doi.org/10.1016/j.rser.2013.12.007

Ebrahimi. K., Jones, G. & Fleischer A. (2017,). The viability of ultra low temperature waste heat recovery using organic Rankine cycle in dual loop data center applications. *Applied Thermal Engineering*, 126, Pages 393-406, https://doi.org/10.1016/j.applthermaleng.2017.07.001

Elsaid. K., Sayed, E. T., Yousef, B. A. A., Rabaia, M., Abdelkareem, M. A. & Olabi, A. G. (2020). Recent progress on the utilization of waste heat for desalination: A review, *Energy Conversion and Management*, 221, 2020, https://doi.org/10.1016/j.enconman.2020.113105.

Efficient, Demand Flexible Networked Appliances EDNA (2022). *Energy Efficiency Metrics for Data Centres*. Retrieved February 23, 2024, from https://www.iea-4e.org/wp-content/uploads/2022/10/EDNA-Studies-Metrics-for-data-centre-efficiency-Final.pdf

Fan, C., Zou, B., Liao, Y. & Zhou, X (2024) Evaluation of energy performance and ecological benefit of free-cooling system for data centers in worldwide climates, *Sustainable Cities and Society*, Volume 108, 2024, https://doi.org/10.1016/j.scs.2024.105509.

Geng, H. (2015). *Data center Handbook*. Wiley. ISBN 978-1-118-43663-9.

Gado, M., Elgendy, E., Elsayed, K. & Fatouh, M. (2017). Parametric Study of an Adsorption Refrigeration System Using Different Working Pairs, *International Conference on Aerospace Sciences and Aviation Technology*. 17. Pages 1-15. https://doi.org/10.21608/asat.2017.22455.

Ge, Z., Zhou, Y C, Li, J., Zhang, X., Xu, J. & Yang, F. (2024) Multi-objective optimization and benefit evaluation of heat pump system for tobacco drying using waste heat from data center, *Journal Of Cleaner Production*, 448, 2024, https://doi.org/10.1016/j.jclepro.2024.141623.

Gynther, L., Kiuru, T., & Meetteri, J. (2022). *Energy Efficiency of Data Centers in Finland – Indicators, Policies and Good Practices. Motiva*. https://www.motiva.fi/files/20768/Energy_Efficiency_of_Data_Centers_in_Finland_-_November_2022.pdf

Haywood, A., Sherbeck, J., Phelan, P., Varsamopoulos, G. & Gupta, S. (2012) Thermodynamic feasibility of harvesting data center waste heat to drive an absorption chiller, *Energy Conversion and Management*, 58 , 2012, Pages 26-34, ISSN 0196-8904, https://doi.org/10.1016/j.enconman.2011.12.017.

Haywood, A., Sherbeck, J., Phelan, P., Varsamopoulos, G. & Gupta, S. (2015) The relationship among CPU utilization, temperature, and thermal power for waste heat utilization, *Energy Conversion and Management*, Volume 95, 2015, Pages 297-303, ISSN 0196-8904, https://doi.org/10.1016/j.enconman.2015.01.088.

Hao, Y., Zhou, H., Tian, T., Zhang, W., Zhou, X., Shen Q., Wu, T. & Li, J. (2025) Data centers waste heat recovery technologies: Review and evaluation, *Applied Energy*, Volume 384, 2025, https://doi.org/10.1016/j.apenergy.2025.125489.

Huang, X., Yan, J., Zhou, X., Wu, Y. & Hu, S. (2023) Cooling Technologies for Internet Data Center in China: Principle, Energy Efficiency, and Applications. *Energies* , Volume 16, 2023 https://doi.org/10.3390/en16207158.

International Energy Agency (2024) *Electricity 2024 Analysis and forecast to 2026*. Retrieved February 20, 2025, from https://www.iea.org/reports/electricity-2024

Khalaj, A. H. & Halgamuge, S. K. (2017) A Review on efficient thermal management of air- and liquid-cooled data centers: From chip to the cooling system, *Applied Energy*, Volume 205, 2017, Pages 1165-1188, https://doi.org/10.1016/j.apenergy.2017.08.037.

Kheirabadi, A. C. & Groulx, D. (2016) Cooling of server electronics: A design review of existing technology, *Applied Thermal Engineering*, Volume 105, 2016, Pages 622-638, https://doi.org/10.1016/j.applthermaleng.2016.03.056.

Kong, R., Zhang, H., Tang, M., Zhou, H., Tian, C. & Ding, T. (2024) Enhancing data center cooling efficiency and ability: A comprehensive review of direct liquid cooling technologies, *Energy*, Volume 308, 2024, https://doi.org/10.1016/j.energy.2024.132846.

Lee, K. & Chen, H. (2013) Analysis of energy saving potential of air-side free cooling for datacenters in worldwide climate zones, *Energy and Buildings*, Volume 64, 2013, https://doi.org/10.1016/j.enbuild.2013.04.013.

Li, H., Hou, J., Tian, Z., Hong, T., Nord, N. & Rohde, D. (2022) Optimize heat prosumers' economic performance under current heating price models by using water tank thermal energy storage, *Energy*, Volume 239, 2022, https://doi.org/10.1016/j.energy.2021.122103.

Li, M., Jiang, X. Z., Zheng, D., Zeng, G. & Shi, L. (2016) Thermodynamic boundaries of energy saving in conventional CCHP (Combined Cooling, Heating and Power) systems, *Energy*, Volume 94, 2016, Pages 243-249, https://doi.org/10.1016/j.energy.2015.11.005.

Liu, Y., Wei, X., Xiao, J., Liu, Z., Xu, Y. & Tian, Y. (2020) Energy consumption and emission mitigation prediction based on data center traffic and PUE for global data centers, *Global Energy Interconnection*, Volume 3, 2020, Pages 272-282, https://doi.org/10.1016/j.gloei.2020.07.008.

Ljungqvist, H.M., Mattson, L., Risberg, M. & Vesterlund, M. (2021). Data center heated greenhouses, a matter for enhanced food self-sufficiency in sub-arctic regions, *Energy,* 215, 2021, https://doi.org/10.1016/j.energy.2020.119169.

Lu, T., Lü, X., Välisuo, P., Zhang, Q. & Clements-Croome, D., (2024). Innovative approaches for deep decarbonization of data centers and building space heating networks: Modeling and comparison of novel waste heat recovery systems for liquid cooling systems, *Applied Energy,* 357, 2024, https://doi.org/10.1016/j.apenergy.2023.122473.

Luo, Q., Wang, C., Wen, H. & Liu L. (2022). Research and optimization of thermophysical properties of sic oil-based nanofluids for data center immersion cooling. *International Communications in Heat and Mass Transfer,* 131, 2022. https://doi.org/10.1016/j.icheatmasstransfer.2021.105863

Marshall. Z.M. & Duquette, J. (2022). A techno-economic evaluation of low global warming potential heat pump assisted organic Rankine cycle systems for data center waste heat recovery. *Energy,* 242, 2022. https://doi.org/10.1016/j.energy.2021.122528.

Maagøe. V., (2022). Energy Efficiency Metrics for Data Centres. *IEA 4E EDNA,* 2022. https://www.iea-4e.org/wp-content/uploads/2022/10/EDNA-Studies-Metrics-for-data-centre-efficiency-Final.pdf.

Moazamigoodarzi, H., Tsai, P. J., Pal, S., Ghosh, S. & Puri I. K. (2019) Influence of cooling architecture on data center power consumption, *Energy*, Volume 183, 2019, Pages 525-535, https://doi.org/10.1016/j.energy.2019.06.140.

Montagud-Montalvá, C., Navarro-Peris, R., Gómez-Navarro, T, Masip-Sanchis, X. & Prades-Gil, C. (2023) Recovery of waste heat from data centres for decarbonisation of university campuses in a Mediterranean climate, *Energy Conversion and*

Management, Volume 290, 2023, Pages 525-535, https://doi.org/10.1016/j.enconman.2023.117212 .

Nadjahi C., Louahlia, H. & Lemasson, S. (2018) A review of thermal management and innovative cooling strategies for data center, *Sustainable Computing: Informatics and Systems*, Volume 19, 2018, Pages 14-28, https://doi.org/10.1016/j.suscom.2018.05.002.

Pambudi, N.A., Sarifudin, A., Firdaus, R.A., Ulfa, D.K., Gandidi, I.M.& Romadhon, R (2022) The immersion cooling technology: Current and future development in energy saving, *Alexandria Engineering Journal*, Volume 61, 2022, Pages 9509-9527, https://doi.org/10.1016/j.aej.2022.02.059.

Patterson, M. (2010) *ERE: A metric for measuring the benefit of reuse energy from a data center.* The Green Grid https://www.thegreengrid.org/en/resources/library-and-tools/242-WP%23-29---ERE%3A-A-Metric-for-Measuring-the-Benefit-of-Reuse-Energy-From-a-Data-Center

Porumb, B., Ungureşan, P., Tutunaru, L., F., Şerban, A. & Bălan M. (2016) A Review of Indirect Evaporative Cooling Technology, Energy Procedia, Volume 85, 2016, Pages 461-471, https://doi.org/10.1016/j.egypro.2015.12.228.

Pärssinen, M., Wahlroos, M., Manner, J. & Syri, S.(2019) Waste heat from data centers: An investment analysis, *Sustainable Cities and Society*, Volume 44, 2019, Pages 428-444, https://doi.org/10.1016/j.scs.2018.10.023

Sarkar, S., Gupta, R., Roy, T., Ganguly, R. & Megaridis, C. (2023) Review of jet impingement cooling of electronic devices: Emerging role of surface engineering, *International Journal of Heat and Mass Transfer*, Volume 206, 2023, https://doi.org/10.1016/j.ijheatmasstransfer.2023.123888.

Shao, X., Zhang, Z., Song, P., Feng, Y. & Wang, X. (2022) A review of energy efficiency evaluation metrics for data centers, *Energy and Buildings*, Volume 271, 2022, Pages 112308- 112320, https://doi.org/10.1016/j.enbuild.2022.112308.

Simon, V., H, Sivaraju, KB, Bansode, P, Saini, S, Shahi, P, Karajgikar, S, Mulay, V, & Agonafer, D. (2022) Feasibility Study of Rear Door Heat Exchanger for a High Capacity Data Center, *ASME 2022 International Technical Conference and Exhibition on*

Packaging and Integration of Electronic and Photonic Microsystems, 2022, https://doi.org/10.1115/IPACK2022-97494

Sondur, S., Gross, K., & Li, M. (2018) Data Center Cooling System Integrated with Low-Temperature Desalination and Intelligent Energy-Aware Control, *Ninth International Green and Sustainable Computing Conference*, 2018, Pages 1-6, https://doi.org/10.1109/IGCC.2018.8752108.

Sorknæs, P., Nielsen, S., Lund, H., Mathiesen, B., Moreno, D.& Thellufsen, J. Z. (The benefits of 4th generation district heating and energy efficient datacentres, *Energy*, Volume 260, 2022, https://doi.org/10.1016/j.energy.2022.125215.

Tervo, S., Syri, S., & Hiltunen, P. (2025) Reducing district heating carbon dioxide emissions with data center waste heat – Region perspective, *Renewable and Sustainable Energy Reviews*, 2025, https://doi.org/10.1016/j.rser.2024.114992.

Tozzi, C. (2025, January, 17) A Guide to Data Center Water Usage Effectiveness (WUE) and Best Practices, *Data Center Knowledge*, https://www.datacenterknowledge.com/cooling/a-guide-to-data-center-water-usage-effectiveness-wue-and-best-practices

van de Voort, T., Zavrel, V., Torrens, I. & Hensen, J. (2017). Analysis of performance metrics for data center efficiency. *REHVA journal*, *1/2017*, 5–11. https://doi.org/10.1016/j.sbspro.2016.07

von Hassler A. (2021, December 10). *CRAC vs. CRAH Cooling Units: What's the Difference?* Data span. Retrieved march 29, 2025, from https://dataspan.com/blog/crac-vs-crah-cooling-units-whats-the-difference/

Wahlroos, M., Pärssinen, M., Manner, J. & Syri, S. (2017) Utilizing data center waste heat in district heating – Impacts on energy efficiency and prospects for low-temperature district heating networks, *Energy*, Volume 140, 2017, Pages 1228-1238, https://doi.org/10.1016/j.energy.2017.08.078

Wahlroos, M., Pärssinen, M., Rinne, S., Syri, S. & Manner, J. (2018). Future views on waste heat utilization – Case of data centers in Northern Europe*, Renewable and Sustainable Energy Reviews*, 82, 2018, Pages 1749-176. https://doi.org/10.1016/j.rser.2017.10.058.

Wang, F., Nian, V., Campana, P., Jurasz, J., Li, H., Chen, L., Tao, W. & Yan, J. (2022). *Do 'green' data centres really have zero CO2 emissions?* Sustainable Energy Technologies and Assessments, 35. https://doi.org/10.1016/j.seta.2022.102769

Wang, N., Guo, Y., Huang, C. & Shao, S. (2024) Advances in direct liquid cooling technology and waste heat recovery for data center: A state-of-the-art review, *Journal of Cleaner Production*, Volume 477, 2024, https://doi.org/10.1016/j.jclepro.2024.143872.

Wang, R., Wang, T., Li, Z., Luo, H., Liu, H., Wang, Z., Liu, H., Jiang, Y., & Xu, L., (2025) Waste heat utilization of data centers based on heat pump technology from the perspectives of supply and demand: an overview, *Sustainable Cities and Society*, 130, 2025, https://doi.org/10.1016/j.scs.2025.106543.

Wang, P., Kowalski, S., Gao, Z., Sun, J., Yang, C., Grant, D., Boudreaux, P., Huff, S.& Nawaz, K., (2024) District heating utilizing waste heat of a data center: High-temperature heat pumps, *Energy and Buildings*, 315, 2024, https://doi.org/10.1016/j.enbuild.2024.114327.

Wilson, M. (2023, April 15). *Data Center Basics*. Nlyte Software. Retrieved march 1, 2025, from https://www.nlyte.com/blog/data-center-basics/

Wu, Z., Zhang, G., Lu, S., Leng, P., Yu, Y., Deng, J. & Huang, W. (2025) A comprehensive review of cold plate liquid cooling technology for data centers, *Chemical Engineering Science*, Volume 310, 2025, https://doi.org/10.1016/j.ces.2025.121525.

Xu, S., Zhang, H., & Wang, Z. (2023). Thermal Management and Energy Consumption in Air, Liquid, and Free Cooling Systems for Data Centers: A Review, *Energies*, 16, https://doi.org/10.3390/en16031279.

Yin, P., Guo, Y., Zhang, M., Wang, J., Zhang, L., Feng, D., & Ding, W. (2024). Performance Analysis of Lake Water Cooling Coupled with a Waste Heat Recovery System in the Data Center, *Sustainability*, 16, https://doi.org/10.3390/su16156542

Yuan, X., Liang, Y., Hu, X., Xu, Y., Chen, Y. & Kosonen, R. (2023) Waste heat recoveries in data centers: A review, *Renewable and Sustainable Energy Reviews,* Volume 188, 2023, https://doi.org/10.1016/j.rser.2023.113777.

Yuan, X., Liu, J., Sun, S., Lin, X., Fan, X., Zhao, W. & Kosonen, R. (2025) Data center waste heat for district heating networks: A review, *Renewable and Sustainable Energy Reviews,* Volume 219, 2025, https://doi.org/10.1016/j.rser.2025.115863.

Yuventi, J. & Mehdizadeh, R. (2013). A critical analysis of Power Usage Effectiveness and its use in communicating data center energy consumption. *Energy and Buildings*, 664, 90–94. https://doi.org/10.1016/j.enbuild.2013.04.015

Zhang, Q., Meng, Z., Hong, X., Zhan, Z., Liu, J., Dong, J., Bai, T., Niu, J. & Deen M. (2021) A survey on data center cooling systems: Technology, power consumption modeling and control strategy optimization, *Journal of Systems Architecture*, Volume 119, 2021, https://doi.org/10.1016/j.sysarc.2021.102253.

Zhang, Y., Zhao, Y., Dai, S., Nie, B., Ma, H., Li, J., Miao, Q., Jin, Y., Tan, L. Ding, Y. (2021) Cooling technologies for data centres and telecommunication base stations – A comprehensive review, *Journal of Cleaner Production*, Volume 334, 2022, https://doi.org/10.1016/j.jclepro.2021.130280.

Zheng, S., Su, C., Yang, X., Zhang, Y., Duan, K., Zhang, Y., Huang, Z., Zhang, Y., Liu, F. & Wei, J. (2025) A comprehensive review of single-phase immersion cooling in data centres, *Applied Thermal Engineering*, Volume 272, 2025, https://doi.org/10.1016/j.applthermaleng.2025.126385.

Zhou, C., Hu, Y., Liu, R., Liu, Y., Wang, M., Luo, H., & Tian, Z. (2025). Energy Performance Study of a Data Center Combined Cooling System Integrated with Heat Storage and Waste Heat Recovery System. *Buildings*, 15, 326. https://doi.org/10.3390/buildings15030326

Zhou, G., Zhou, J., Huai, X., Zhou, F. & Jiang, Y. (2021) A two-phase liquid immersion cooling strategy utilizing vapor chamber heat spreader for data center servers, *Applied Thermal Engineering*, Volume 210, 2021, https://doi.org/10.1016/j.applthermaleng.2022.118289.

Zhou, K., Yu, X., Xie, B., Xie, H., & Fu, W. (2024) Immersion cooling technology development status of data center, *Science and Technology for Energy Transition*, Volume 79, 2024, https://doi.org/10.2516/stet/2024022.