ČESKÉ VYSOKÉ UČENÍ TECHNICKÉ V PRAZE
FAKULTA STROJNÍ
ÚSTAV TECHNIKY PROSTŘEDÍ

SIMULATION-BASED DESIGN OF WASTE HEAT UTILIZATION SYSTEM FOR A DATA CENTER IN CAMPUS: REDUCING TU/E CARBON FOOTPRINT

DIPLOMOVÁ PRÁCE

VOJTĚCH DVOŘÁK 9 – TŽP – 2017

**FACULTY
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ENGINEERING
CTU IN PRAGUE**

MASTER THESIS ASSIGNMENT

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II. MASTER THESIS SPECIFICATION

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Simulační posouzení systémů pro využití odpadního tepla v datovém centru střední velikosti v univerzitním kampusu

Master thesis title (in English):

Simulation-Based Assessment of Waste Heat Utilization Systems for a Mid-Sized Data Center in a University Campus

Elaboration guidelines:

On the basis of computer simulations, assess waste heat utilization in a mid-sized data center (DC) located in the campus of Eindhoven University of Technology. Develop a computational energy model of the DC and its cooling system. Using this model, evaluate the potential for reduction of energy consumption and carbon emissions in different waste heat utilization system alternatives integrated with the existing aquifer thermal energy storage providing heating and cooling to the campus buildings.

Literature resources:

Harrison J., Hood P., Hughes D. et al. Data Centres : An Introduction to Concepts and Design. Norwitch: CIBSE, 2012.
ASHRAE TC 9.9. Data Center Design and Operation – ASHRAE Datacom Series. 2nd ed. Atlanta: ASHRAE, 2010.
Khosrow E., Jones G. F., Fleischer A. S. A Review of Data Center Cooling Technology, Operating Conditions and the Corresponding Low-Grade Waste Heat Recovery Opportunities. Renewable and Sustainable Energy Reviews, 31 (March 2014), p.622–38.
Hensen J. L. M. , Lamberts R. Building Performance Simulation for Design and Operation. Abingdon: Spon Press, 2011.
Spruijt T. J. G., Hensen J. L. M., Torrens J. I. Supporting the Eindhoven University of Technology to Reach Thermal Energy Balance at the Campus 2020. Eindhoven University of Technology, 2015.

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III. THESIS ASSIGNMENT RECEIVED

The student is aware that the thesis has to be accomplished through an independent and unassisted student's work, supported only by recognized consultations. Literature and other information resources as well as consultants' names have to be acknowledged in the thesis.

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Abstract

Exponential growth of energy consumption by data centers (DCs) in the world, very energy demanding buildings, brings along an opportunity to use the waste heat generated by DCs for other applications. The DC waste heat utilization system is meant to be integrated within the existing aquifer thermal energy storage that provides heating and cooling to the campus buildings. As part of the MSc. project, a computational energy model of a mid-sized DC and its air-based cooling system is developed. Based on this DC model, a performance assessment of a case-study where the mentioned mid-sized DC is located in the campus of Eindhoven University of Technology is carried out. The MSc. candidate evaluates the saving potential of energy and carbon emissions of different alternatives of a DC waste heat utilization system.

Posouzení využití odpadního tepla z datacentra v rámci univerzitního kampusu prosřednictvím simulačního programu: snížení uhlíkových emisí Technické Univerzity Eindhoven

Jelikož spotřeba energie datacentry po celém světe výrazně roste a budovy obecně spotřebují velké množství energie, nabízí se možnost využití odpadního tepla z datacenter. Součástí diplomové práce bylo vyvinutí numerického modelu středně velkého datacentra a jeho chladícího systému. Na základě tohoto modelu byla posouzena případové studie datacentra, jenž bylo teoreticky umístěno v kampusu Technické Univerzity Eindhoven. Diplomant vyhodnotil potenciál využití odpadního tepla z datacentra pro různé návrhové parametry s ohledem na snížení spotřeby energie a uhlíkových emisí. Odpadní teplo by bylo využito prostřednictvím existující zásobárny tepelné energie v podzemní vodě, která poskytuje jak chlad, tak teplo v budovách kampusu.

Prohlašuji, že jsem diplomovou práci s názvem: „Simulation-based design of waste heat utilization system for a data center in campus: Reducing TU/e carbon footprint“ vypracoval samostatně pod vedením prof. dr. ir. Jana L. M. Hensena, s použitím literatury, uvedené na konci mé diplomové práce v seznamu použité literatury.

V Eindhovenu 27.6.2017 Vojtěch Dvořák

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Nomenclatures

C	Thermal capacitance	[MJ/K]
C_{BP}	Flow coefficient	[$m^3/s.Pa^n$]
CT_add	Additional heat released by CT	[MWh]
dP	Pressure difference	[Pa]
EDW	Energy demand weight	[-]
MLC	Mechanical load component	[-]
n	Flow exponent	[-]
$P_{Cooling}$	Cooling load	[kW]
$P_{DataCenter}$	Total DC load	[kW]
P_{IT}	IT load	[kW]
$P_{Lighting}$	Lighting load	[kW]
P_{Power}	Power distribution system load	[kW]
PUE	Power usage effectiveness	[-]
Q	Bypassing flow	[m^3/s]
T_Amb	Ambient temperature	[°C]
T_SP	Temperature setpoint	[°C]
T_sup	Air supply temperature	[°C]
T_UF	Temperature in the underfloor	[°C]
T_WB	Wet-bulb temperature	[°C]
T_WB_SP	Temperature setpoint with respect to wet-bulb temperature	[°C]

η_PDU	Efficiency of power distribution unit	[-]
η_PSU	Efficiency of power supply unit	[-]
η_SG	Efficiency of switch gears	[-]
η_tot	Total efficiency of electricity delivery site	[-]
η_UPS	Efficiency of uninterruptible power supply	[-]

Abbreviations

ASHRAE	American society of heating, refrigerating and air-conditioning engineers
ATES	Aquifer thermal energy storage
CCS	Conventional cooling system
COP	Coefficient of performance
CPU	Central processing unit
CRAC	Computer room air conditioner
CRAH	Computer room air handler
CT	Cooling tower
DC	Data center
DH	District heating
DHW	Domestic hot water
DRAM	Dynamic random-access memory
HE	Heat exchanger
HPC	High-performance computing
IT	Information technology
Misc	Miscellaneous

NL	The Netherlands
ORC	Organic Rankine cycle
SHI	Supply heat index
SP	Set point
TRNSYS	Transient system simulation tool
TU/e	Eindhoven University of Technology
WSE	Water-side economizer

1 Introduction

Nowadays, in times of globalization and informatization, it is taken for granted that internet access is available anytime, anywhere. And to do so, data centers all over the world during our web browsing process enormous computational workload that needs to be powered by electricity. Recent energy statistics indicate that the DC industry is responsible for 1.3 % of the world and 2 % of the United States electricity consumption. Almost half of this power is used for cooling the electronics, generating a significant amount of waste heat [1]. This heat is normally released to the ambient air. The premise of this work is that the wasted heat can be reused, which will lead to a reduction of total carbon emissions considering both a DC system and a system of heat consumer [2]. However, the difficulty associated with recovering of waste heat is the low quality of the DC waste heat [1]. Although the typical mid/large-sized DC can dissipate around 1 MW of heat, which may cover the heating demand of hundreds of households [3], the temperature potential of the conventional cooling system is only up to 40 °C [4].

This thesis describes the major approaches available for the cooling of information technology (IT) servers and their potential for waste heat utilization. Mainly, this work assesses co-operation of the DC and sessional thermal storage, both for a scenario of the current situation and a future scenario.

Fundamentally, the motivation for the project was the eventual effort of the university to build a DC in the campus. And part of that design is the interest in understanding the benefits of using the DC waste heat for space heating in campus buildings through the aquifer thermal energy storage (ATES) system.

In the current situation, the storage already provides to connected buildings more cooling than heating. An integration of a DC, with additional cooling demand, will lead to an even higher imbalance of the seasonal storage. Thus, only DC can benefit from this co-operation, when the integration of the DC to the storage reduces utilization of the expensive mechanical cooling of the DC.

In the near future, the university policy plans reduction of the CO_2 emissions [24]. Based on this effort, the gas boilers are probably going to be partly replaced with heat pumps connected to the storage, which results in much higher heating load. Thus, buildings connected to ATES system would use the storage more for heating than cooling. In such a scenario, both DC and storage system can benefit, when the integration of the DC to the storage balances the yearly heating and cooling demand of the storage.

2 Data center as source of heat

In this chapter, the understanding of DCs and their waste heat utilization potential is presented. The influence of cooling approach on the quality of that harvested waste heat was investigated. Options for DC waste heat usage are provided with emphasis on the description of the co-operation of DC and ATES system, which is investigated later in the practical part of the thesis.

Basically, the energy use of data centers is much higher than usual office or commercial buildings and hence the DCs require special treatment. DC consumption has resulted in up to 100 times more energy per square meter than office accommodation [5]. Due to that energy use intensity, the waste heat utilization is offered. However, energy is not the major focus of interest by the DC community but the availability and reliability. Because as soon as downtime occurs DCs have to pay thousands of dollars per minute [6]. But if the DC community would be more interested in waste heat utilization approaches, that would lead to significant energy and carbon savings.

2.1 Data center waste heat utilization

Practically all the electrical power required in a data center is converted into heat, which has to be mechanically removed by a cooling system.

A server, which can be considered as the smallest data processing unit in a DC, typically features highly integrated microprocessors, additional memory and auxiliary components including input-output (I/O) devices, mass storage (disk drive) and a power supply. Microprocessor chips are the major power dissipation components in servers. A typical server with two processors consumes almost 50 % of the total server power through the microprocessors (refer to Fig. 2-1). Hence for a waste heat utilization, the focus should be aimed preferably on heat harvesting from the chips. The majority of the electronics thermal management research considers 85 °C as the maximum allow able junction temperature for the safe and effective operation of microprocessors (the main cause of CPU component failure is a high temperature [8]) [1]. This temperature limit also indicates what could be the temperature level of ideal waste heat utilization system.

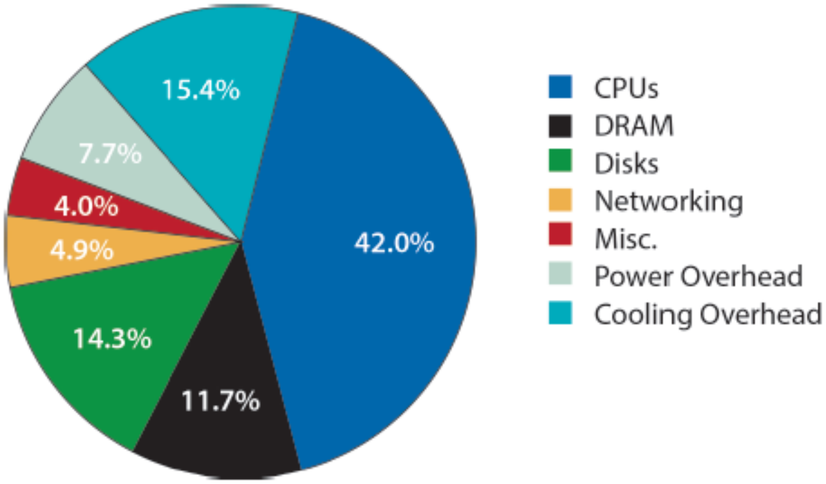

Figure 2-1 Approximate distribution of peak power usage by hardware subsystem in a modern datacenter using late 2012 generation servers [33].

However, to remove the heat directly from CPUs is technically very complex and this technique (for instance liquid cooling) is very marginal as depicted later in Fig. 2-3. The most used cooling approach is air-based cooling on room level – characterized by low technical complexity. Nevertheless, this cooling approach has very low thermal potential for waste heat utilization. It should be noted that the configuration of the cooling system has a large influence on waste heat utilization potential as is described in next chapters.

2.1.1 Cooling system configuration for waste heat harvesting

As the waste heat is captured through the cooling system, the exergy of waste heat strongly depends on the type and specification of the thermal management system. The cooling system should be designed to obtain a high energy efficiency, low cost, reliability, and should be designed to cover the worst-case scenario, although most servers generally work at much lower than full capacity [7]. In this subsection, two cooling system configurations for DCs are reviewed.

2.1.1.1 Waste heat potential of air-based and liquid-based cooling

Most of existing data centers use air cooling systems to maintain the desired operating conditions [11]. However, future DCs will most likely use a combination of both air-based and liquid-based cooling approaches to be able to cool down very powerful servers.

The low thermal capacity of the air and the relatively low rates of heat transfer between the electronics and the air result in the need for high temperature differences i.e. low server inlet air temperatures around 15–25 °C. Liquid-based cooling offers a higher thermal capacity than in the case of air-based cooling and higher convective heat transfer coefficients. So, direct contact with the server components gives much higher heat transfer rates (the [1]total thermal resistance in water-cooled systems is less than 20 % of total thermal resistance in air-cooling systems [12]). This permits lower temperature differences between the cooling liquid and the electronic components, and significantly higher liquid coolant inlet temperatures can be used. Consequently, much higher-grade waste heat utilization is possible for liquid cooling systems e.g. at temperatures of up to 60 °C [1], which is shown in Fig. 2- 2.

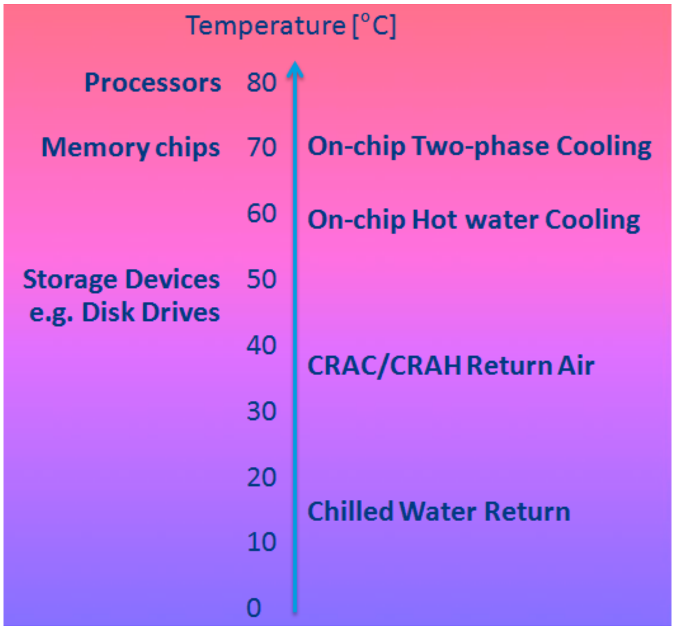

Figure 2-2 Typical temperatures of components and processes in data centers.

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[1] Total thermal resistance is meant to be the thermal resistance from the tranzistor junction to the ambient environment.

However, liquid-cooled systems are more technically complex and liquid in electronic equipment raises a concern about leakage leading to irrevocable damage of IT equipment.

In addition, the removal efficiency of liquid cooling is still overrated for most of the current-practice servers. Considering the technical complexity, the liquid-based cooling is not cost-effective yet. This is resulting in the relatively poor implementation of liquid-based cooling into DCs (depicted in Fig. 2-3). Consequently, in the practical part of this thesis, the focus was put on waste heat utilization from the DC where IT equipment is cooled only by air.

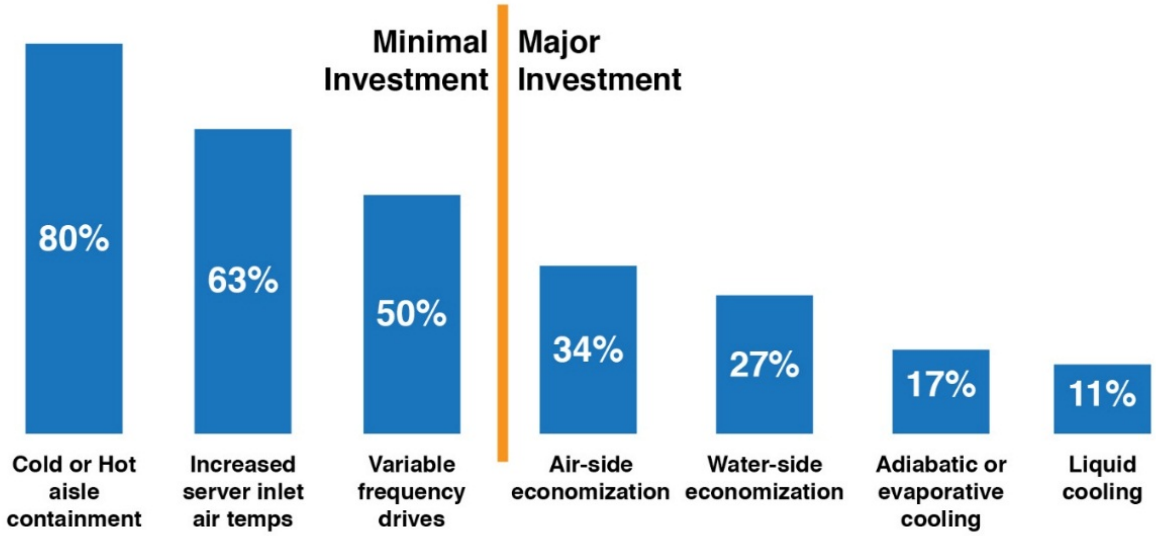

Figure 2-3 Advanced cooling technology adoption [14].

2.1.1.2 Harvesting the heat in the DC with liquid-based cooling

Many newer data center designs have power loads to levels that are difficult to remove with CRACs alone. Therefore, other cooling techniques, such as single phase forced liquid (water) system [12], phase change liquid system [35], or fully immersed direct liquid-cooled system [7] are now being adopted [1].

However, these variants are not so related to the hereafter investigated case and therefore those variants are not more described.

2.1.1.3 Harvesting the heat in the conventional DC with air-based cooling

At first, the principle of air-based cooling is explained. Air-cooled systems represent the basis among data center cooling systems, they are evolving over the years to cope with the advances in the IT equipment. The reason why this cooling approach is so favored is in the easiness and reliability.

The most common DC cooling approach at present uses computer room air conditioning (CRAC), or computer room air handling (CRAH) units with chilled water as coolant carrier. The cooling units are located within the DC room and are placed remotely to the IT servers. IT servers are housed in the racks, which are arranged in rows, usually in alternate so-called hot and cold aisles. Supply air is usually distributed beneath a raised floor to the cold aisles. The warm air exiting the servers into the hot aisles is then returned to the CRAC/CRAH cooling units under ceiling (shown in Fig. 2-4).

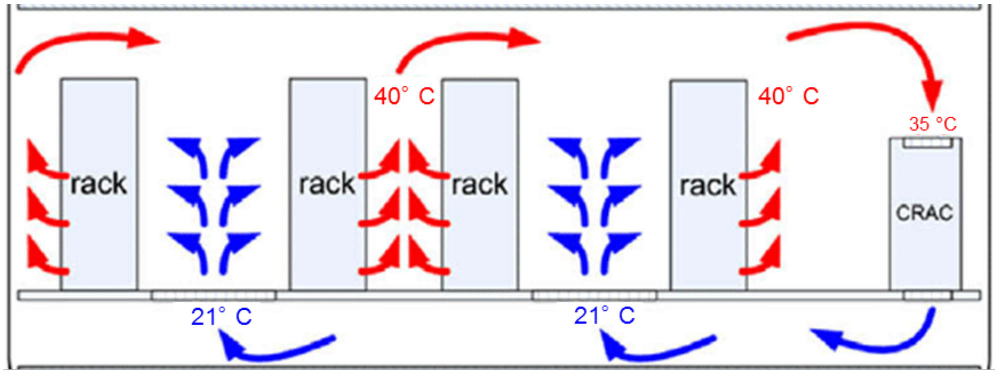

Figure 2-4 Air-based cooling.

The warm exhaust air leaving the racks is pushed by fans through the coils containing chilled water in the CRAC unit, where it exchanges heat and is cooled before returning to the racks. The heated cooling fluid leaving the CRAC coils is recirculated by pumps into a secondary loop chiller or cooling tower(s), where the heat removed from the coolant is expelled to the outside environment (depicted in Fig. 2-5) [11].

The mechanical cooling of the air requires a considerable amount of power. The power demand can account up to 40 % of the total electricity use of the DC [7]. The power-consuming equipment in air conditioning systems is the chiller, circulation fan, water pump, and cooling tower [9]. Typically, when the chiller is in operation, the cooling system can consume five times more power than if the system works in an economizer mode [5].

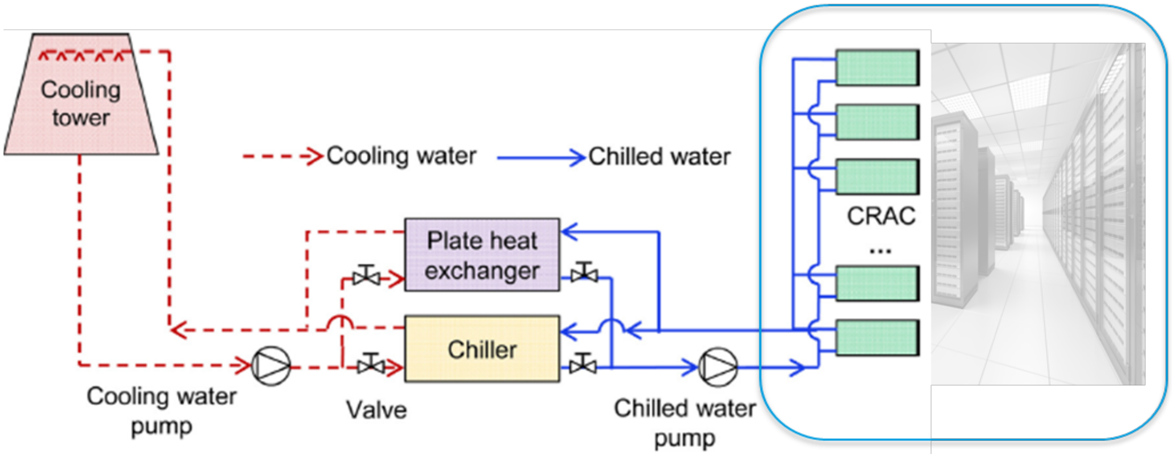

Figure 2-5 Conventional cooling system [10].

In recent years, many efforts have been made to substantially reduce energy use of DC cooling system applying energy efficiency measures listed hereunder such as [2]:

- application of hot aisle and cold aisle containment measures (to prevent mixing of the hot and cold airstreams i.e. recirculation and bypass);
- application of economizer configuration;
- application of direct and indirect evaporative cooling of the incoming air.

Economizer configuration (Free cooling)

The application of economizer to the cooling system, so-called free cooling, is an effective solution for energy savings. Economizer system uses outside ambient air as the primary cooling medium if its temperature and humidity are under certain level [11]. Hence, the economizer operational hours are strongly influenced by the geographical location of the DC. There are two configurations, water-side economizer and air-side economizer [7].

- **Air-side systems**. These systems may use direct, fresh air blown into the DC with hot air extracted back outdoors, or they may use an air-to-air heat exchanger. With the air-to-air heat exchanger, cooler outdoor air is used to partially or fully cool the interior DC air. Air-side systems may be enhanced with either direct or indirect evaporative cooling, extending their operating range.

- **Water-side systems**. These systems remove heat from the chilled water loop by a heat exchange process with outdoor air. Typically, there may be a heat exchanger that is piped in series with the chilled water return and in parallel with the chiller (shown in Fig. 2-5). The chiller is by-passed by this heat exchanger when the wet-bulb temperature of the outside air is low enough. This economizer configuration is used hereafter in the practical part of the work.

In fact, the economizer can compromise waste heat utilization (schematically shown in Fig. 2-6).

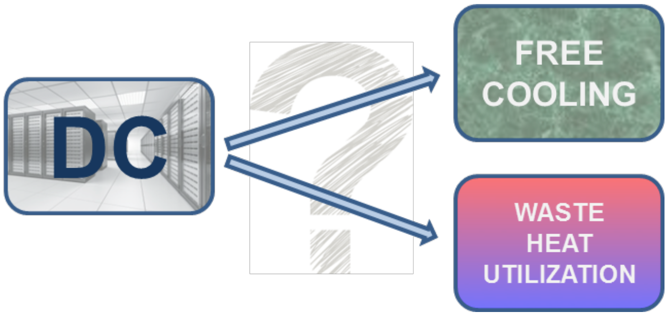

Figure 2-6 Two ways of DC energy reduction.

Temperature levels in air-cooled DC:

The waste heat can be captured at various locations and with different quality, as described below.

Typically, the coolant (i.e. chilled water) temperature is maintained in the range of 12 – 14 °C, the cool air leaving the CRACs is in the range of 16 – 20 °C and the cold aisle is about 18 – 22 °C (shown in Fig. 2-4) [11]. However, in some legacy DCs, the temperature of cooling air is even lower, mainly because of concerns of hot spots.

Although it might be challenging, the optimum location to capture the heat in air-cooled DC for maximum energy capture (~ 35 – 45 °C) will be directly at the rack exhaust to avoid the air mixing and exergy losses. Alternately, it is easier to capture the waste heat at the return to CRAC (~ 30 – 40 °C), or at the chiller water return (~16 – 18 °C), however, the lower temperatures available here limit usefulness [1].

2.1.2 Options for DC waste heat usage

Basically, there are two main challenges with data center waste heat utilization: the relatively low temperatures involved and the difficulty of heat transportation. Therefore, many of the waste heat utilization applications to date use the low-grade heat physically adjacent to the DC, such as a greenhouse or swimming pool in the building next door.

The known project is for instance made by IBM in Switzerland using DC heat to warm a local swimming pool. In Finland, 2 MW data center by Yandex and Academica shares heat with local residents, replacing the heat energy used by 500 – 1 000 homes with DC energy that would have been vented to the atmosphere. There are heat-reuse DCs in Canada, England, and the US. Cloud computing giant Amazon has gotten great visibility from reuse of a nearby DC’s heat at the biosphere project in downtown Seattle.

Thus, the waste heat utilization can be not “only” ecologically beneficial but also economically viable. The possible option for heat recovery of low-temperature heat collected from DCs is elaborated hereafter.

2.1.2.1 Space heating

Space heating is a relatively common and simple application for the waste heat utilization of low-quality heat. Temperature range of the captured waste heat is sufficient for space heating. The waste heat can be also used for preheating on-site domestic hot water (DHW), which is then upgraded using an external heat pump [1].

Alternatively, the modified servers with network connection can be deployed to individual homes to provide domestic heating. Such an application is referred to a “Data Furnace” by Liu et al. [16]. The study focuses on the opportunities and challenges associated with replacing large centralized DCs with distributed small scale “micro-data centers” which could be used as a primary source for domestic heating in homes, office buildings and apartment complexes.

2.1.2.2 District heating/Hot water production

Generally, district heating networks are an efficient approach of distributing heat generated centrally across a local populated area e.g. a town or city. They are also reported to be more convenient and cheaper to run for consumers, requiring less maintenance and repairs compared to using individual heating devices e.g. gas boilers [2].

The temperature of heat extracted from liquid-cooled DC can be in the range of 60 – 70 °C which is appropriate for both district heating and hot water production [1]. The low-temperature heat from air-cooled servers could also be used but would need to be increased using an external heat pump.

Ideal candidates for DC energy reuse are modern DH networks that accept lower liquid input temperatures. Smart combinations of supply and demand or use of seasonal storage can reduce the effective carbon footprint of a DC to zero [12].

2.1.2.3 Co-operation with Aquifer thermal energy storage

In ATES systems groundwater is used to carry the thermal energy into and out of an aquifer. For the connection to the aquifer, water wells are used. The energy is partly stored in the ground water itself and partly in the grains (or rocks mass) that form the aquifer [17].

There are several hundreds of these systems in operation, with the Netherlands and Sweden as dominating countries of implementation. Practically all systems are designed for low-temperature applications where both heat and cold are seasonally stored [18].

In summer, cold water is extracted from the cold well and used for cooling of the building. The heated water is then injected into the warm well. In winter, the flow is reversed and water is extracted from the warm well to heat the building, where it cools down and is subsequently injected into the cold well [18]. Fig. 2-7 illustrates that principle.

As DC waste heat is of low-quality and ATES system is designed for low-temperature applications, the co-operation of ATES and DC is offered.

The ATES system needs to be balanced in order to work properly throughout the whole year. It means that amount of heat extracted in the horizon of longer period (year) should be equal to the amount of cold extracted from ATES during that period. In case that ATES provides in that long period more heat than cold, the DC waste heat can be used to balance out the ATES system.

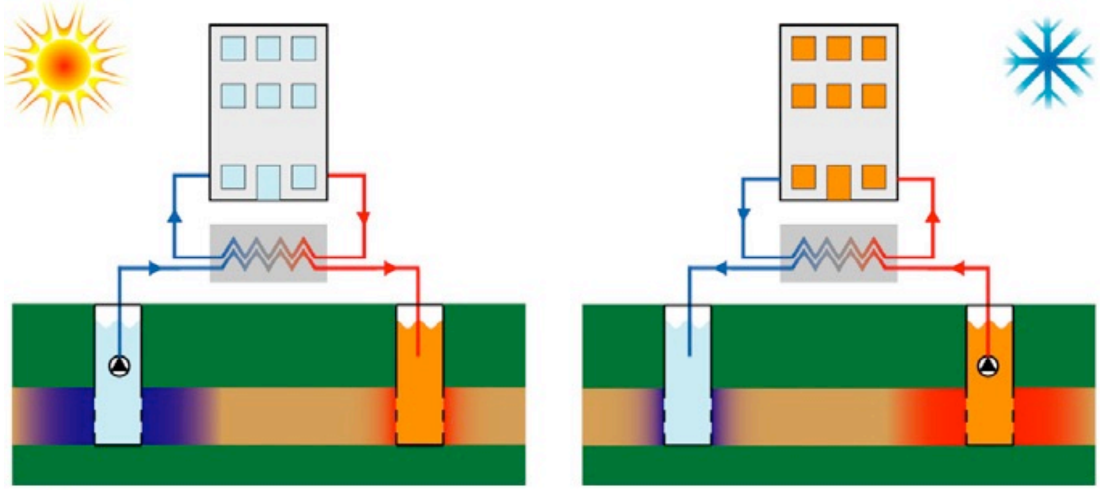

Figure 2-7 Principle of ATES system [19].

The co-operation of DC and ATES system can be under certain circumstances beneficial for both. Especially in a residential area where heating demand is usually higher than cooling demand. Then the waste heat from DC would, by the assistance of heat pumps, heat up the buildings and simultaneously the ATES system would provide cold water for a DC. Cold water would be used by DC either continuously or only at times to substitute the use of power-hungry chillers (depending on the balance of the ATES system). The most advantageous case is when ATES pumps the cold water to the CRAC units continuously. Then the DC cooling towers are also eliminated and the cooling electricity demand is reduced.

Another convenient variant (now only for DC side) occurs when DC inserts more heat into ATES than is requested for balancing out, hence "switches" the imbalance. To justify that, energy savings on DC side are higher than the increase of energy demand on the ATES side. Such an ATES system must be prepared to that by having own cooling towers to deal with the situation that annually more heat is inserted than cold. Basically, the advantage of this case from the global point of view is that ATES is storage, in the sense that the system can wait for better conditions for cooling the water through cooling towers. In other words, the system can wait until winter and then release the redundant heat when the temperature difference is the highest. Logically, the DC cooling towers cannot do that, they must release the heat to the ambient immediately even if the temperature difference is not so high which is compensated by higher fan speed resulting in higher electricity consumption. However, that variant must be allowed by ATES side.

Finally, one of the most important features of DCs, in general, they produce roughly an equal amount of heat the whole year, which does not match the heating demand by buildings. However, due to ATES system that mismatch in time can be overcome.

2.1.2.4 Other waste heat usage variants

Besides the mentioned possibilities of waste heat usage, there exist several other variants such as Power plant co-location, Absorption cooling or Organic Rankine cycle and more.

However, these variants are not very common and they are not related to this work. More information about those variants can be found in: [1].

3 DC waste heat utilization system: Case study description

In this chapter, the characterization of the case study is given. The definition of the DC waste heat utilization on the university campus is provided involving both the current situation and the potential future campus scenario. Mainly for the future scenario, the understanding of the university campus energy management was necessary.

Based on literature review, co-operation of DC and ATES system has great potential for efficient waste heat utilization. The thesis deals with the connection of mid-size DC to university ATES in the Netherlands.

The co-operation ATES – DC in the Netherlands's conditions is very promising and meaningful. Because in the Netherlands (NL) data center business growth is one of the fastest in the world [19] and also the NL is one the biggest protagonists of ATES systems in the world [17].

Specifically, the mid-sized DC follows the technical specification of IMB data center in Poughkeepsie, NY [4]. This work studies the co-operation of such a mid-sized DC to existing ATES system located in Eindhoven, Eindhoven University of Technology (TU/e) campus.

Within the project, energy and carbon emissions reduction potential of different DC's waste heat utilization system alternatives that are integrated with the existing ATES that provides heating and cooling to the campus buildings were evaluated.

3.1 Definition of DC infrastructure

According to ASHRAE Case Studies and Best Practices [4], the mid-sized data center with air-based cooling was chosen. The layout of the DC room was simplified, however, a cold-aisle/hot-aisle arrangement was respected. The systems in this DC are located on a raised-access floor in area 23 × 30 m which houses one hundred racks. The ceiling height, as measured from the raised-access floor to the ceiling, was 2.74 m, with a raised-access floor height of 0.7 m. Most racks within this area dissipate approximately 10.7 kW. Thus, total IT load equals to 1 090 kW. The DC uses the conventional cooling system with CRAC units inside the DC room and chiller with cooling towers located outside the room, however, measured data are available only in relation to CRAC units.

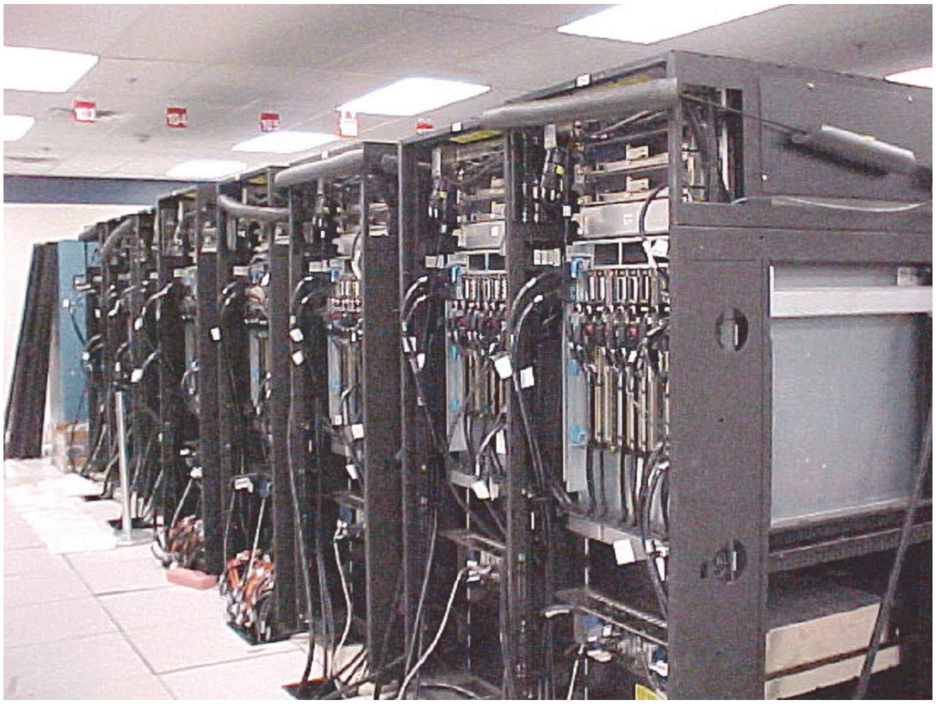

Figure 3-1 Row of racks in the hot aisle [4].

3.2 Definition of waste heat usage: application on the university campus

As for the connection between Eindhoven University of Technology and data centers, TU/e currently has no DC located in the campus but the university has some servers located in High Tech Campus in the south of Eindhoven.

In terms of heat transfer from the DC to the buildings in TU/e campus, there is located one of the largest ATES systems in the Netherlands. This system has been providing the TU/e with warm and cold water for the last 15 years. During this time two cooling towers have been emitting heat into the air to overcome the difference between the heat and cold extraction.

That indicates that for these 15 years, buildings in campus use ATES more for cooling than heating. Which is still true and it, unfortunately, does not open the field of application for DC to be used for balancing out the system. However, the situation might change.

Figure 3-2 TU/e campus from the perspective of DC waste heat utilization.

The most common heat and cold delivery system at the TU/e is direct cooling and heating via a heat pump, in most cases, a peak load system with boilers is installed to deal with outdoor temperatures below -5 °C [20]. However, some buildings still use for heating more gas boilers than heat pumps, resp. heat from ATES. Which is actually the base for assumptions about the future scenario when the DC would be used for balancing out the ATES system and thus providing the waste heat into the buildings. This assumption is more described in 3.2.2. TU/e energy management is described in Fig. 3-3. This Figure shows the use of heat and cold from ATES and the use of heat from gas combustion (it is assumed that 80 % of gas consumed by TU/e is used for heating). Also, heat released by ATES cooling towers (gray line) is shown there.

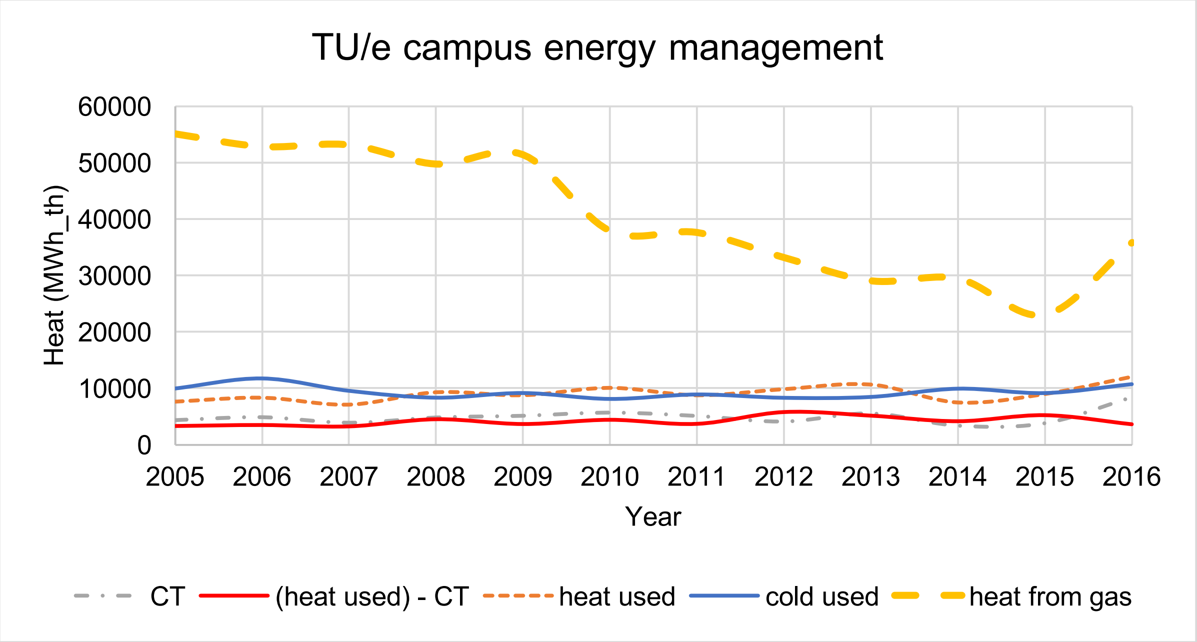

Figure 3-3 TU/e campus energy management.

Generally, the gas consumption is decreasing but still very substantial. However, in 2015 there was consumed around 2 880 000 m^3 of gas [21], in 2016 the amount significantly increased to 4 477 822 m^3 [22]. Most of the gas is consumed for heating, nevertheless, the accurate percentage is not monitored and can be only estimated.

3.2.1 Description of actual situation

In the case of TU/e, ATES system pumps groundwater from 20-80 m below the surface [23]. The system uses two wells: a “cold” well with water of 6 – 9 °C and a “warm" well with water of 14 – 17 °C (wells are shown in Fig. 2.7). Underground storage includes 32 wells divided over 3 warm and 3 cold clusters. These clusters (shown in Fig. 3-4) are connected to warm and cold ring each about 2 km long [23]. Cold and warm is relative to the natural temperature of the subsurface of 10 – 13 °C.

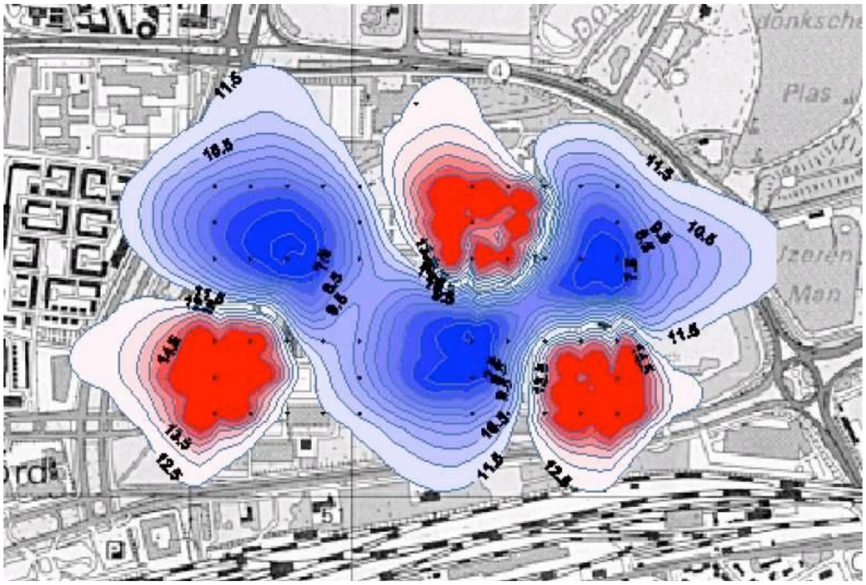

Figure 3-4 Six clusters of the TU/e ATES system [20].

According to Planning 2013-16 [24], the ATES system consumes only 3 % of TU/e electricity consumption.

Apart from imbalance matter, the ATES system works most of the year under half of the system capacity (as far as flow rates or heat insertion/extraction). Even in peaks, the system does not exceed the whole potentially capacity. Thus, it can be assumed that the ATES system has enough capacity to accommodate the mid-sized DC. The main barrier could be only continuous cooling demand of the DC leading to an aforementioned imbalance of the ATES system. As it is undesirable to have an imbalanced system, the facility management oversees compliance about the amount of heat inserted into ATES by particular buildings and also temperatures of returning water. Such a management is called in this thesis ”ATES policy”.

The illustrative pictures of existing ATES system are depicted in Fig. 3-5 and Fig. 3-6. Fig. 3-5 shows the infrastructure of the cold and hot ring connecting most of the university campus buildings.

Figure 3-5 Cold and warm ring [23].

Fig. 3-6 shows ATES cooling towers, which are used for balancing out ATES system. These cooling towers release redundant heat from the storage to the ambient, when the weather conditions are favorable.

Figure 3-6 Cooling towers [23].

3.2.2 Assumption for the future scenario

In accordance with an ecological policy of TU/e, it is assumed that in future ATES system would partly replace the use of gas for heating.

Gas consumption was reduced from 2005 to 2015 by 56 %. Moreover, according to Energy efficiency plan 2013-2016, TU/e has ambitions to be 25% energy neutral in 2020 and 50% energy neutral in 2030 [24]. This implies that there can be expected another reduction in gas consumption in next years.

Therefore, it is assumed that gas consumption will decrease by 50 % (compared to the situation in 2015) and in that case, would logically increase utilization of ATES for heating. Resulting in that on campus would be more heat extracted from the storage than inserted to it, and in that case, the heat from the DC would become very needed to balance out ATES.

Furthermore, it is assumed, that 80 % of gas consumed by TU/e is used for heating.

Comparison of gas and electricity through emitted emissions within the Netherlands:

Gas:

Emission factor = 1.884 kg CO_2/m^3 [21]

Let's assume that 1 m^3 of natural gas provides 10 kWh of heat, then adjusted emission factor:

0.188 kg CO_2/kWh_th

Electricity:

Emission factor = 0.54 kg CO_2/kWh [26]

Let's assume the use of heat pump with coefficient of performance (COP) = 4, then adjusted emission factor:

0.135 kg CO_2/kWh_th

4 Simulation-based assessment of DC waste heat utilization system in TU/e campus

In this chapter, the methods used for assessment of the waste heat utilization system are defined. The description of the numerical modeling approach is provided including the development of two models of DC cooling system. DC with the conventional cooling system was modeled to assess by comparison the benefit of DC cooling system connected to ATES system. Key performance indicators are reviewed in section 4.1 and the numerical models are described in section 4.2. Different DC operational scenarios were investigated.

As in DC field, the real experimentation is usually nearly impossible, numerical modeling is a suitable method for feasibility study/early design study of complex systems such as DC waste heat utilization. Numerical modeling enables quantifying the uncertainty of the DC energy use.

4.1 Key performance indicators for DC waste heat utilization

The performance of the waste heat utilization system is evaluated by following performance indicators to address multiple aspects of the performance.

- **Total DC electricity demand** is calculated for each operational scenario (DC operational scenarios are described in section 4.2.2.) to assess the energy performance of the DC system for tested period. Total DC electricity demand includes IT equipment, cooling, power delivery losses, and miscellaneous electricity demand (e.g for lighting).

- **Carbon emissions** are converted from the total DC electricity demand. The carbon emissions indicate the ecological footprint of the tested operational scenarios.

- The **Power Usage Effectiveness (PUE)** metric is the most common metric used in the DC industry. It measures the energy efficiency of the installation by dividing the total energy consumed by the facility with the IT energy consumed. PUE aims at the total DC infrastructure efficiency including efficiency of the cooling system, power delivery and other facilities (e.g. lighting, security system, etc.). PUE metric is described by Equation 4.1. In 2015, the average PUE value was 1.74 which is in line with the self-reported PUE's values from the Uptime Institute 2013 data center industry survey [30].

$$\mathrm{PUE} = \frac{\mathrm{P_{DataCenter}}}{\mathrm{P_{IT}}} = \frac{\mathrm{P_{Cooling}+P_{Power}+P_{Lighting}+P_{IT}}}{\mathrm{P_{IT}}} \quad [-] \qquad (4.1)$$

- **Mechanical Load Component (MLC)** metrics indicates solely the efficiency of DC cooling system (defined by Equation 4.2). Compared with PUE, MLC describes the suitability of cooling system better. For instance, DC with the very efficient cooling system can result in average PUE value which is caused by inefficient electricity delivery system or high miscellaneous power.

$$\mathrm{MLC} = \frac{\text{Cooling power}}{\text{IT load}} \quad [-] \qquad (4.2)$$

While theoretically ideal DC would have PUE equal to 1, MLC would be zero.

4.2 Numerical modeling of DC waste heat utilization system

As DC energy performance is strongly dynamic, the Transient System Simulation program (TRNSYS) was used to simulate the transient behavior of the system. Due to the developed model, the amount of reused heat and the reduction of the ecological footprint was determined. Secondly, CONTAM airflow network was implemented to describe the physics of air flow within the DC room represented as a five-zonal model. Different DC operational scenarios were involved. The model contains DC room site, DC cooling site, and electricity delivery site. All of those parts of the model are described in detail hereafter.

4.2.1 Description of the numerical model

The numerical modeling consists of three main parts: model of DC room, model of DC cooling and power delivery model. All these models follow the aforementioned specification of the case study. Individual components of the model were configurated based on the available technical specification. Parameters of these model's components are further described in Appendix Table A-1. Since the numerical model aims several domains, the modeling task is relatively complex and therefore several assumptions and a certain degree of simplification is required.

The humidity treatment within the DC space is not the interest of the study, therefore the humidity is assumed as a constant value.

Weather conditions are represented by data for the closest available location to our main case-study in Eindhoven, thus the Schiphol weather file is considered instead.

ATES system temperatures are assumed constant. Although the temperature of water in rings is slightly variable, in simulations it was assumed that temperature of water in cold ring is for cooling purposes equals to 7 °C. That might be slightly lower than the average value in reality, however, this difference would not have a large influence on results.

DC room model:

DC room with a floor area of 690 m^2 houses the servers with a total capacity of 1090 kW. The servers are utilized with variable IT workload profiles, which are described in detail later in 4.2.2. As was already mentioned, this IT workload is fully converted into heat.

DC room is modeled as a five-zonal model (Underfloor, Cold Aisle, IT, Hot Aisle, Plenum) through CONTAM program depicted in Fig. 4-1 and Fig. A-4 (in Appendix part). This multi-zonal model allows predicting the return air temperature considering the characteristic phenomena of DC space such as by-passing or recirculation.

Circulating air within the DC room is driven by a fan with constant speed and cooled down by CRAC unit described in next section. The DC room model considers also miscellaneous electricity power (e.g. lighting), which is fixed 81 kW.

DC cooling models:

Two models of cooling infrastructure were developed and it is schematically described in Fig. 4-3 and Fig. 4-5. The model with conventional DC cooling system was modeled to assess by comparison the benefit of DC cooling system connected to ATES system. These models are separately described below. The common aspects of both models are described over here.

The principle for both cooling systems is that regulation of air temperature inside the DC room is regulated by the variable temperature of chilled water in CRAC. All pumps in the system are modeled as pumps with constant flow rate. Thus, regulation is mediated through the diverting valve (valve “1” in Fig. 4-3, resp. Fig. 4-5) which is controlled by 3-stage thermostat connected to the sensor monitoring the temperature in underfloor.

The second valve (valve “2” in Fig. 4-3, resp. Fig. 4-5) switches between water-side economizer (WSE) mode or “Chiller mode”, resp. CT or ATES, according to the outlet wet-bulb temperature (T_WB). That valve is controlled by ON/OFF thermostat. Set point for T_WB defined as T_WB_SP is equal to set point for temperature in underfloor minus 10 (refer to Eq. 4.3) as fixed value for all operational scenarios described later in 4.2.2. This entire logic is described in detail hereafter.

$$\mathrm{T_{WB\_SP}} = \mathrm{T_{SP}} - 10 \qquad [°\mathrm{C}] \tag{4.3}$$

All heat exchangers used in the model are set to have Heat exchanger effectiveness equal to 0.7. Description of the heat exchanger can be found in [34] as “Heat Exchanger with Constant Effectiveness”).

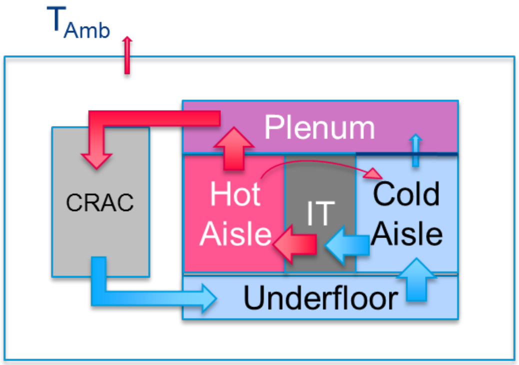

Figure 4-1 DC room as a five-zonal model.

Electricity delivery model:

While for DC room site and DC cooling site basic TRNSYS or TESS Libraries were used, for electricity delivery site "Green Data Centre Library" was chosen (refer to Fig. A-5). Electricity delivery model contains the electrical losses on electrical components before the servers (depicted in Fig. 4-2). These components are represented by efficiency (sorted systematically from the grid switchgear to the servers):

- Switch gears: η_SG = 99.7 %
- Uninterruptible power supply: η_UPS = 96 %
- Power distribution unit: η_PDU = 95 %
- Power supply unit: η_PSU = 92 %
- Total efficiency gained by multiplying particular efficiency above: η_tot = 84 %

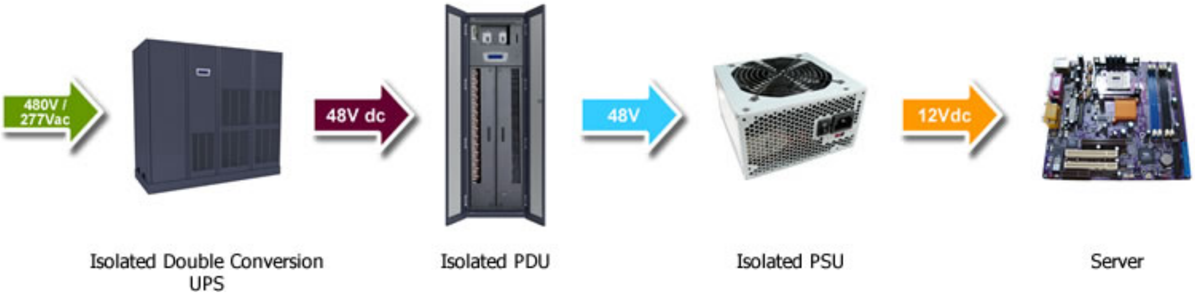

Figure 4-2 DC Power Distribution for the Server Room [27].

4.2.1.1 DC with conventional cooling system – Variant 1

This cooling system represents the typical DC cooling configuration. TRNSYS model of this variant is depicted in Appendix part in Fig. A-2.

This system can work in two modes according to external conditions – water-side economizer mode ("WSE mode") described in 2.1.1.3 or in the mode using cooling circuit composed of a compressor, condenser, expanse valve and an evaporator for cooling ("Chiller mode"). Thus, once the ambient temperature of the air is under a certain value, then cooling tower does not need the chiller to cool down the air and the system is able to work in "WSE mode" depicted in Fig. 4-3.

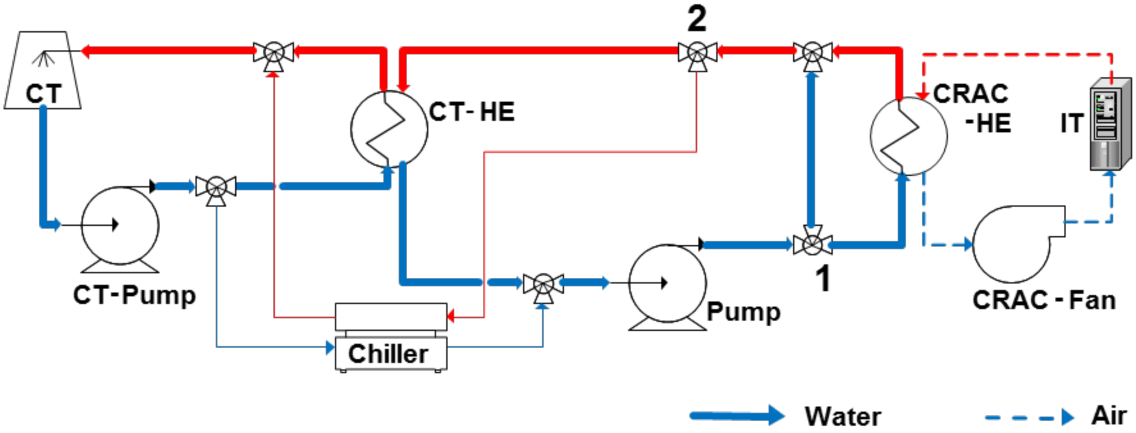

Figure 4-3 Schema of the conventional cooling system working in WSE mode.

Once the ambient temperature of the air is high, then the cooling tower of DC is not able to fulfill the cooling process and hence the chiller must be used (depicted in Fig. 4-4). Generally, when the DC manager wants to keep the very low temperature of air within the DC room, then it is probable, that most of the time the cooling system will have to work in "Chiller mode" and consequently will consume a significant amount of electricity through the compressor.

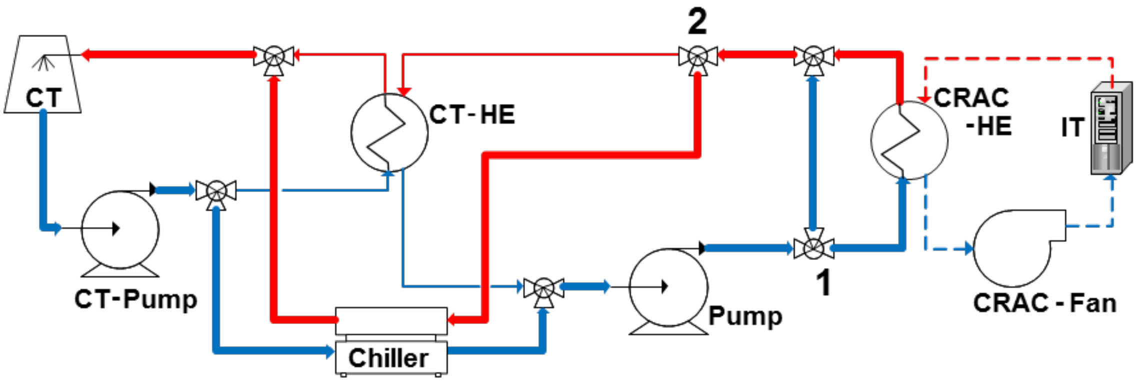

Figure 4-4 Schema of the conventional cooling system working in Chiller mode.

The component of chiller relies on catalog data provided as external text files to determine chiller performance. According to temperatures of cooling and chilled water different COP is generated. Example data file is provided in [28].

The place where cooling water interacts with ambient air is in the DC closed circuit cooling tower (in Figures 4-3 – 4-6 named as CT). This device is used to cool a liquid stream by evaporating water from the outside of coils containing the working fluid – in our case water. The working fluid is completely isolated from the ambient air which has many advantages. Closed circuit cooling towers are often referred to as indirect cooling towers or indirect evaporators [28]. The CT works with a constant flow rate of water and variable fan speed to reach the value of desired outlet temperature of water which is 7 °C, resp. 16 °C, for “WSE mode”, resp. “Chiller mode”. Mathematical description of the cooling tower component can be found in [28].

4.2.1.2 DC with cooling system connected to ATES – Variant 2

In a model of DC with a cooling system connected to ATES is in comparison with the previous model the chiller replaced by ATES. As mentioned before, the cold ring of ATES was simplified and modeled with a constant temperature of water (7 °C). The model concerning ATES policy monitors the temperature of water that is returning to a hot ring of ATES. With respect to that, the pump of ATES (not depicted in Fig. 4-5 or 4-6) was designed.

TRNSYS model of this variant is depicted in Appendix part in Fig. A-3.

In analogy with 4.2.1.1, the cooling system works in two modes. Firstly, in “CT mode” (described in Fig. 4-5) when the ambient temperature is low, thus appropriate for DC cooling tower. This mode is totally identical with “WSE mode”.

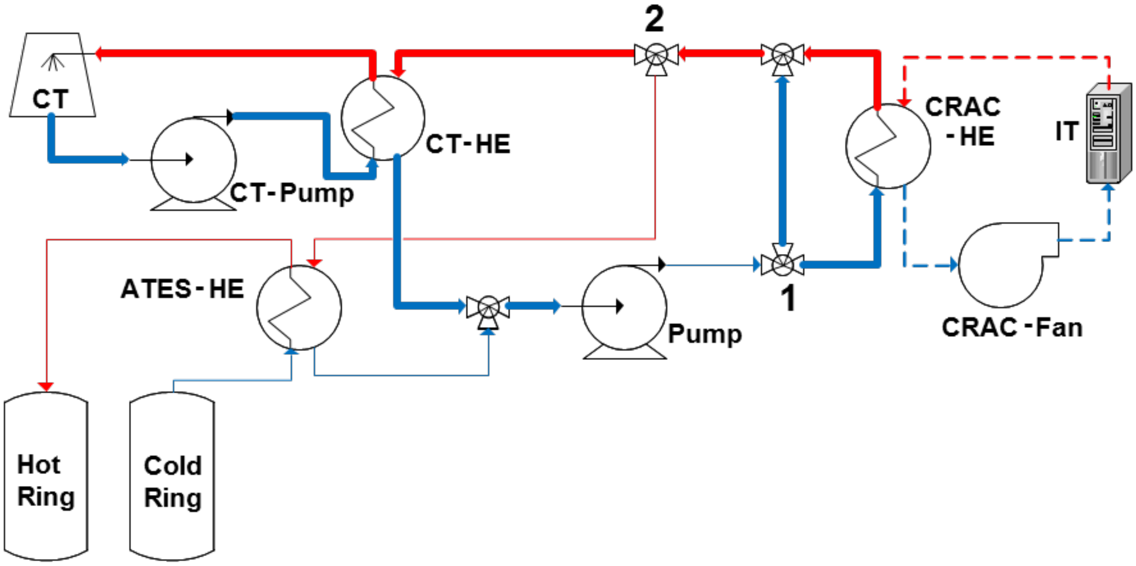

Figure 4-5 DC cooling system connected to ATES working in CT mode.

Secondly, once the ambient temperature of the air is too high, thus CT does not have that needed temperature difference between cooling water and the ambient air, then the system switches into the “ATES mode” (depicted in Fig. 4-6).

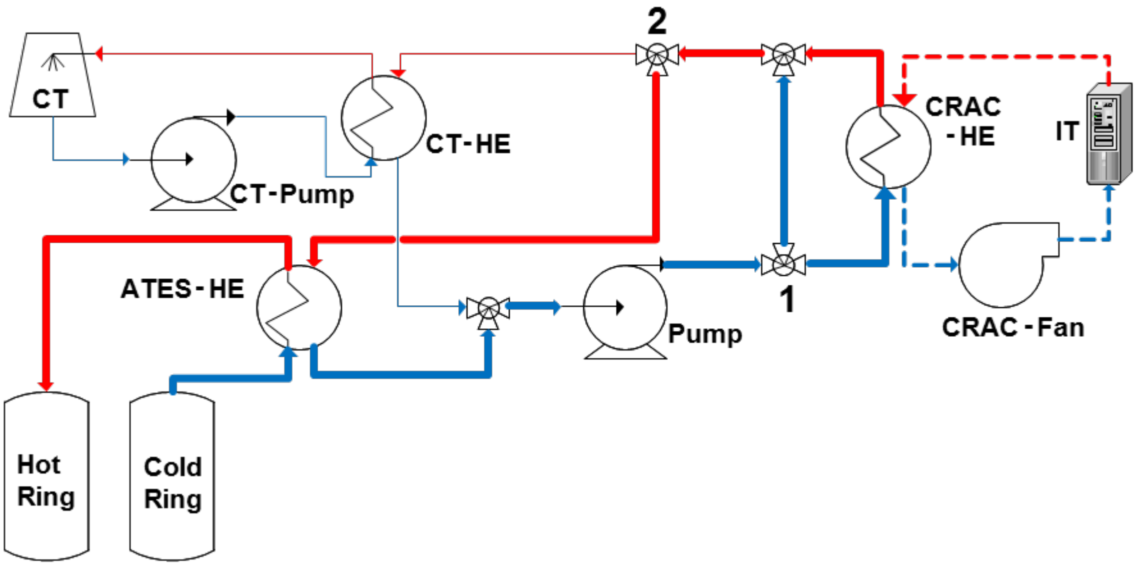

Figure 4-6 DC cooling system connected to ATES working in ATES mode.

The circulating pump driving the water from the cold ring to ATES-HE and subsequently to the hot ring was designed for the same flow rate as the circulating pump ("Pump" in Figures 4-3 – 4-6) driving the water to CRAC unit, thus equal to 50 l/s.

As CT, together with CT-pump consumes logically more energy than ATES-pump alone, then it is clear that due the actual situation with ATES policy the cooling system consumes less energy in summer than in winter which might be counter-intuitive and which is exactly the opposite than is valid for the conventional cooling system described in 4.2.1.1.

4.2.2 DC operational scenarios

To see the effect of particular operational parameters on the results a few operational scenarios were assessed. By cause of those alternatives, the simulation results are represented not like the specific value but the range.

Parameters that are subject to change are:

- Temperature of air in DC room

More precisely, it is the temperature of air in the underfloor which equals to the temperature of cold air supplied by CRAC unit that is slightly increased by losses on the CRAC fan.

4 temperatures were involved: T_UF = 13, 17, 21 or 25 (°C)

These temperatures were selected with respect to ASHRAE thermal guidelines (red lines in Fig. 4-7). It is important to mention, that ASHRAE limits the temperature of air entering IT equipment which does not correspond to the temperature of air supplied by CRAC or temperature in underfloor. Within the project, it was adopted to be in area A2 (refer to Fig. 4-7) which represents DCs with not tight but some control.

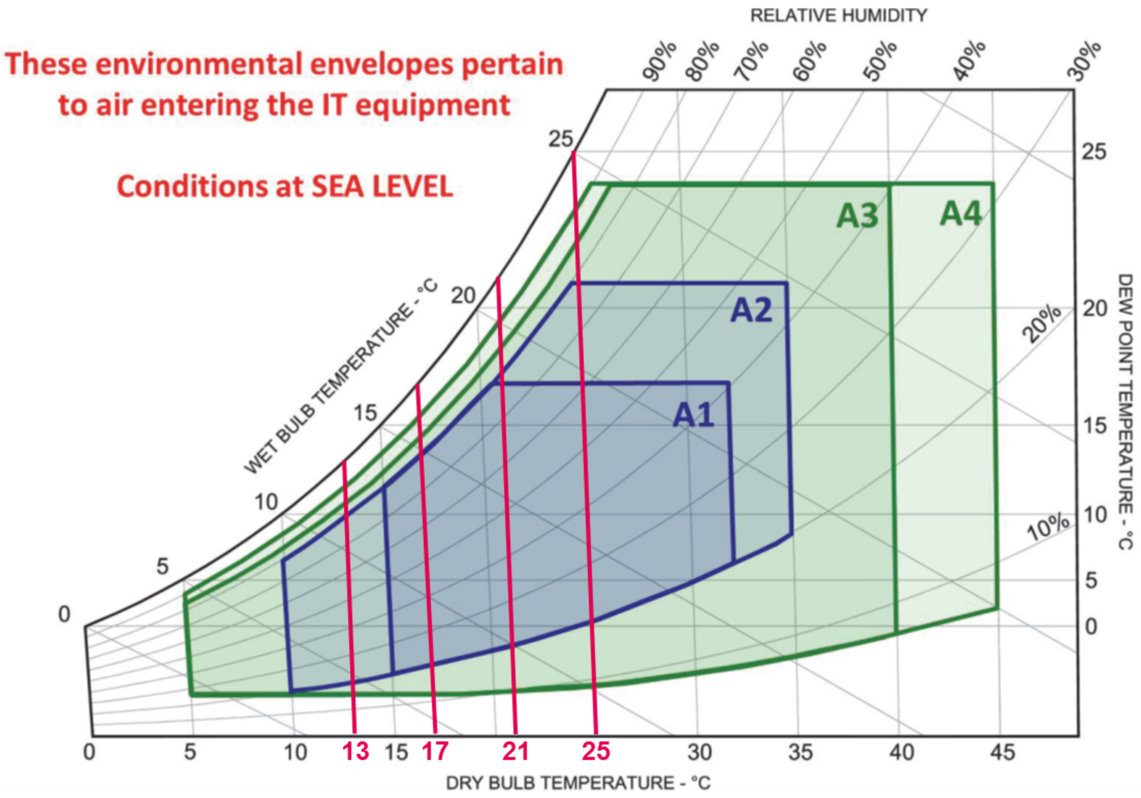

Figure 4-7 Environmental classes for data centers - SI Version [29].

While the lowest temperature represents the obsolete approach with high concern about hotspots, the higher temperatures (namely 21 °C and 25 °C) correspond to the advanced cooling approach with emphasis on energy savings. Increasing the IT room supply temperature was suggested as the easiest and most direct way to save energy in DCs [30].

- IT workload

It is assumed that the whole IT workload is transformed into heat that is in TRNSYS described as energy gain due to equipment.

Two different IT workload profiles from "RenewIT" library were used, both with a significantly variable profile in time:

- ○ HPC workload – this type of workload is typically CPU-intensive and perform a large amount of floating-point operations for scientific calculations [31].

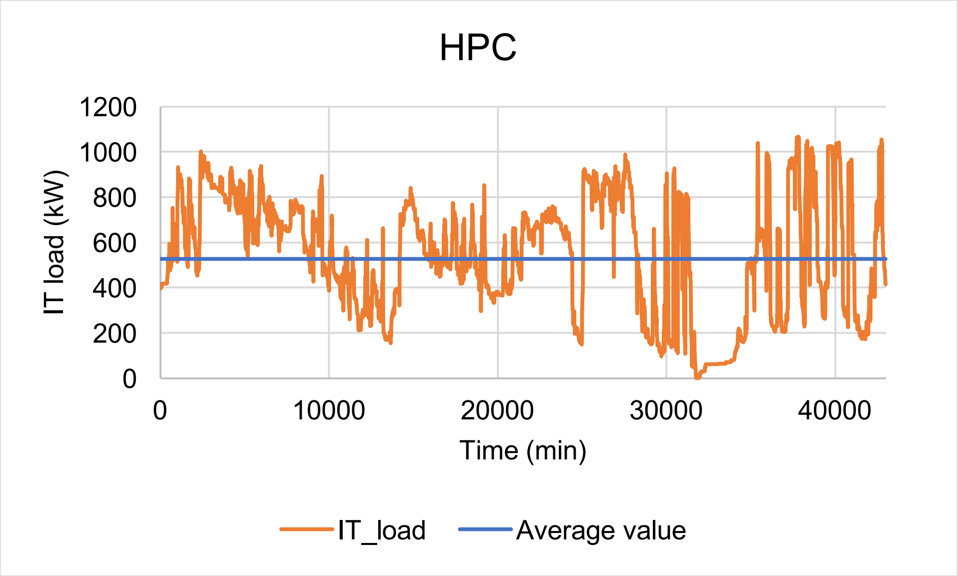

Figure 4-8 HPC IT workload profile.

- WEB workload – has real-time requirements: the users of such workload need to get a response to their petitions in few seconds (i.e. Google search, Facebook search, etc.). This workload has the particularity to follow a daily/weekly pattern [31].

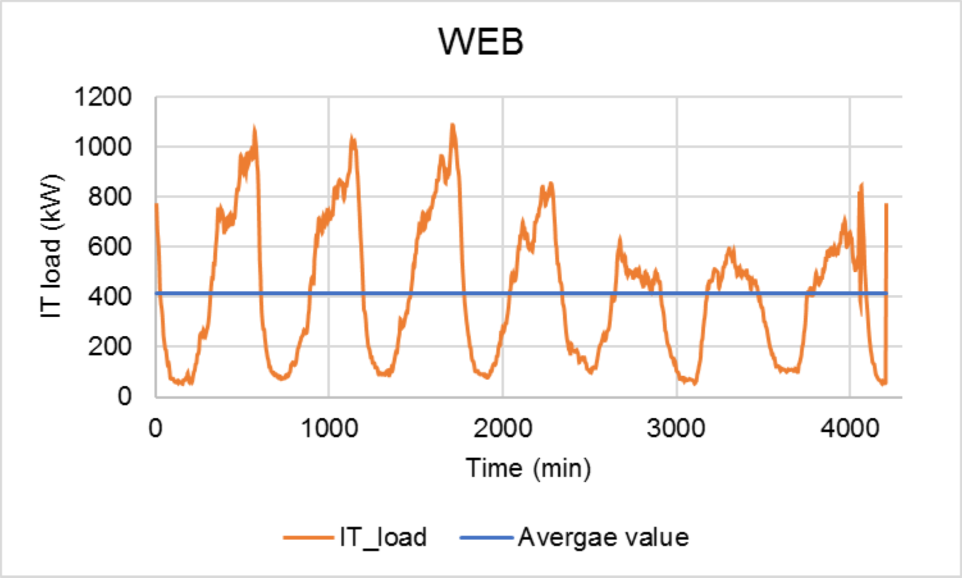

Figure 4-9 WEB IT workload profile during a week.

To compare these two profiles, WEB workload is much more periodical and in average has a lower value.

- Additional thermal capacity of the housed IT

As the thermal capacity of the room is hard to estimate, two scenarios with high and low thermal capacity were investigated. Both servers and DC room whitespace can have the significantly different thermal capacity. Therefore, the analogy with thermal insulation was applied.

Caused by the different ability of the room to accumulate heat, the DC rooms with low capacitance might have larger problems to keep the temperatures in desired range.

Generally, the DC is assumed to have walls, ceiling, and floor made from concrete with a thickness of 0.1 m and thermally insulating layer with a thickness of 0.05 m which is installed from outside, resp. from inside, for high capacitance variant, resp. for low capacitance variant.

The capacitance is shared mainly by the concrete, then by the metal of the racks and also negligible by air in the room. Particular values are described in Table A-2 in Appendix part.

- High capacitance (C = 243 MJ/K)

The variant with high capacitance represents the case with the high thermal capacity of servers and DC room. To reach this condition in the model it is assumed that DC room is thermally insulated from outside and thus all inner surfaces (wall, ceiling, and roof) participate on the capacitance of the volume leading to a more stable temperature in DC. It is assumed that half of the concrete in construction (0.05 m) participates on the accumulation of heat and contributes to the higher capacitance [25].

- Low capacitance (C = 61 MJ/K)

The variant with low capacitance represents the case with the low thermal capacity of servers and DC room. To reach this condition in the model it is assumed that the DC room is thermally insulated from inside and thus all inner surfaces (wall, ceiling, and roof) almost do not participate on the capacitance of the volume leading to a more variable temperature in DC which, of course, is undesirable.

- Thermal management: cold aisle with or without containment

The arrangement of racks within the DC room has a large influence on inefficiencies such as air recirculation (causing hot spots) and by-passing that increase the energy consumption of the DC. Therefore, the evolution of the air-cooled system is going towards localized cooling units and physical separation - aisle containment approach (depicted in Fig. 4-10) [7]. Application of containment was carried out through CONTAM software defining the flow of bypassing air and Supply heat index (SHI) within TRNSYS defining recirculation air flow. SHI is described by Equation 4.4.

$$\mathrm{SHI} = \frac{\text{Recirculated air flow}}{\text{CRAC unit air flow}} \qquad [-] \qquad (4.4)$$

Bypassing flow Q is defined by Equation 4.5 where:

C is Flow coefficient

n is Flow exponent

dP is Pressure difference calculated by CONTAM

$$\mathrm{Q} = \mathrm{C}(\mathrm{dP})^{\mathrm{n}} \qquad [\mathrm{m}^3/\mathrm{s}] \qquad (4.5)$$

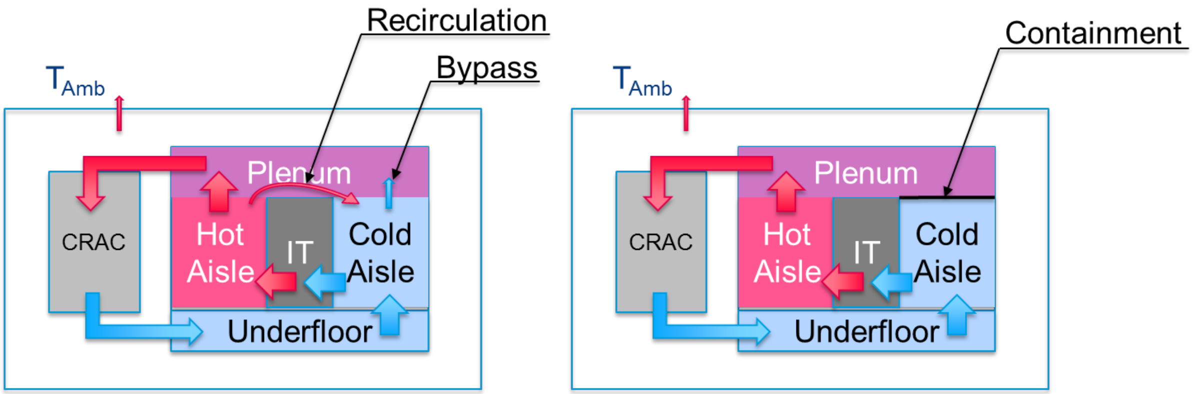

Figure 4-10 Effect of the aisle containment on heat flows in DC.

- Without the aisle containment

In that case, the inefficacy of cooling occurs due to recirculation and bypass phenomena. Recirculation entails that temperature in the cold aisle is significantly higher than the temperature in underfloor. Bypass results in the significantly higher temperature of air in hot aisle than in plenum. That is leading in, for instance, the higher risk of hot spot creation in an upper part of the rack or from the perspective of waste heat utilization it is leading to the lower potential of heat at a return to CRAC unit where that heat could be potentially harvested.

For a variant without the aisle containment:

SHI = 0.15.

Flow coefficient C = 0.9 $m^3/s.Pa^n$

Flow exponent n = 0.5

- With the aisle containment

Due to the aisle containment recirculation and bypass are almost eliminated. Hence temperature of air in the underfloor and cold aisle is almost equal and the temperature of air in the hot aisle is almost equal to the temperature of air in the plenum. This was achieved by a reduction of SHI and the reduction of the flow coefficient C:

SHI = 0.02

C = 0.009

5 Simulation Results

This section shows the simulation results of two DC cooling variants. The first variant refers to the DC with a conventional cooling system that does not utilize the waste heat. The second variant refers to the DC whose cooling system co-operates with ATES system thereby utilizes the waste heat in the buildings on the university campus.

The simulation results are presented systematically from DC scale to Campus scale extended by the assumption of the future campus scenario. The results are presented through key performance indicators for DC waste heat utilization defined in chapter 4.1. The influence of different DC operational scenarios on key performance indicators is shown.

While for the current campus scenario, due to the imbalance of the storage, the DC co-operates with ATES only to substitute power-hungry chillers (described in 5.1). In the potential future scenario, the DC co-operates with ATES system continuously, which is described later in 5.2.

5.1 Comparison of Conventional DC cooling system and DC Cooling system connected to ATES with respect to actual situation

The reason for partition of the simulation results into DC scale and then Campus scale is in gradually understanding of the topic. Firstly, it is important to understand the effect of certain cooling circuit elements or specific operational scenarios on the cooling consumption, resp. total energy consumption of DC. Only then it is possible to properly assess the whole waste heat utilization approach with emphasis on the reduction of a carbon footprint on a higher level like TU/e campus.

As for the year 2016, all required data were not available, the year 2015 was selected as the reference year for actual campus situation.

5.1.1 Results at scale of DC building

At the DC building scale, the focus lays on annual cooling electricity demand of both simulated design variants for all operational scenarios. In addition, the thermal capacitance variants were observed as an important parameter from the perspective of the temperature stability. For the case with low capacitance and a high temperature of the air, results were in collision with ASHRAE regulation about the temperature of air entering IT equipment.

Finally, the amount of heat inserted into ATES by DC cooling system was determined. This information is figuratively speaking such a connector between the scale of DC building and Campus scale.

The influence of operational scenarios on annual cooling electricity demand:

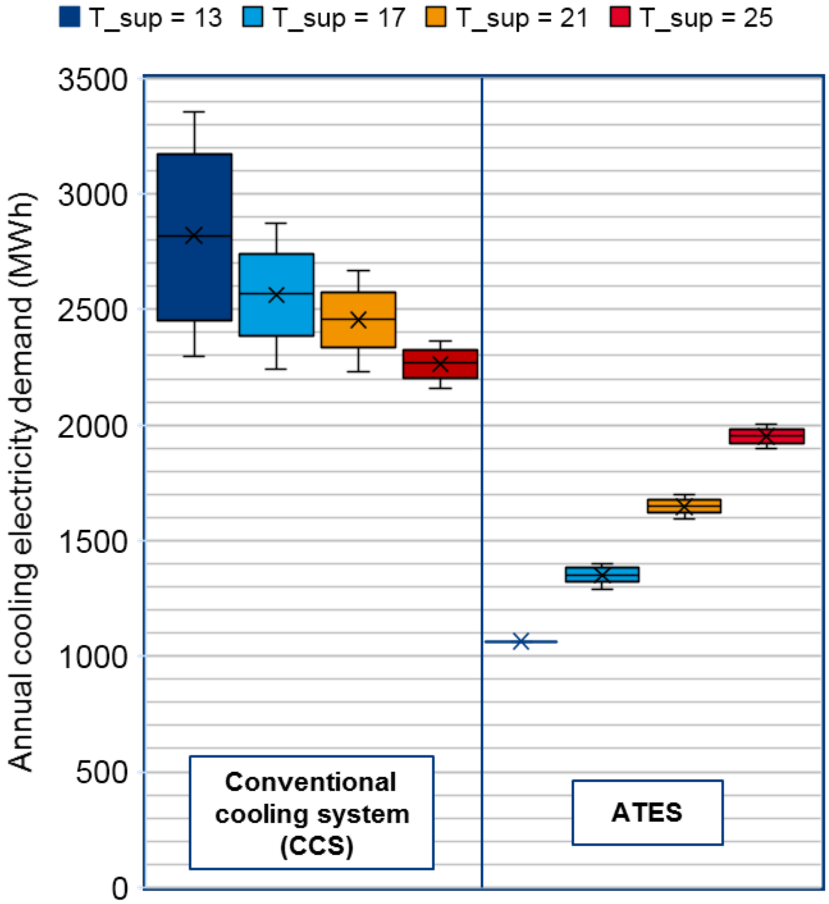

Figure 5-1 The influence of the different temperature setpoints in DC room on annual cooling electricity demand of DC cooled by the conventional cooling system and ATES with policy.

Fig. 5-1 describes the influence of the different temperature of air in DC room on annual cooling electricity demand of DC cooled by the conventional cooling system (using WSE) and the system connected to ATES (limited by ATES policy). The cooling system's task is to hold the temperature of air supplied by CRAC unit (temp. in underfloor) on, resp. in close proximity, the setpoint temperature. The box plot representing the case with the coolest air (13 °C) has dark blue color, the DC with the hottest air (25 °C) is shown by red box plot.

Refer to eq. 4.3, the cooling system switches from WSE mode, resp. CT mode, to Chiller mode, resp. ATES mode, when the ambient temperature exceeds certain value according to DC temperature SP. It means, that for instance the case with the lowest DC temp. SP works in Chiller mode, resp. ATES mode, 80 % of the time. And the case with the highest DC temp. SP works in Chiller mode, resp. ATES mode, only 11 % of the time which might result in counter-intuitive results in ATES variant, where with a higher temperature of air in DC there is higher cooling electricity demand. However, this is just the effect of ATES policy due to which the DC cooling system works with DC cooling towers without the help of ATES and only if the system is not able to hold the DC temp. SP then ATES system is used.

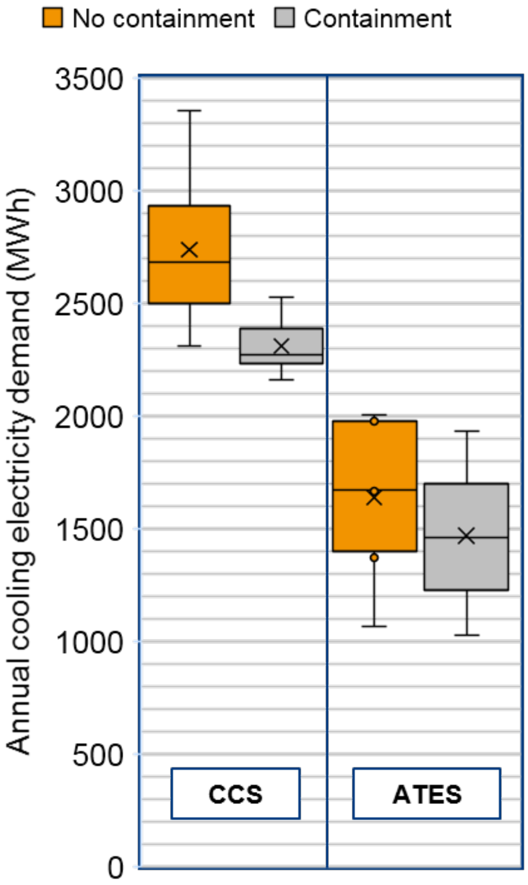

Figure 5-2 The influence of application of containment on annual cooling electricity demand of DC cooled by the conventional cooling system and ATES with policy.

Fig. 5-2 describes the influence of application of the aisle containment to physically separate the cold aisle and plenum on annual cooling electricity demand for systems cooled by conventional cooling system and system connected to ATES. From this figure, it is apparent that the aisle containment increases the efficiency of cooling significantly, mainly for CCS variant. This relatively effective and cheap enhancement of cooling efficiency corresponds to Fig. 2-3 where is shown the frequent application of this approach.

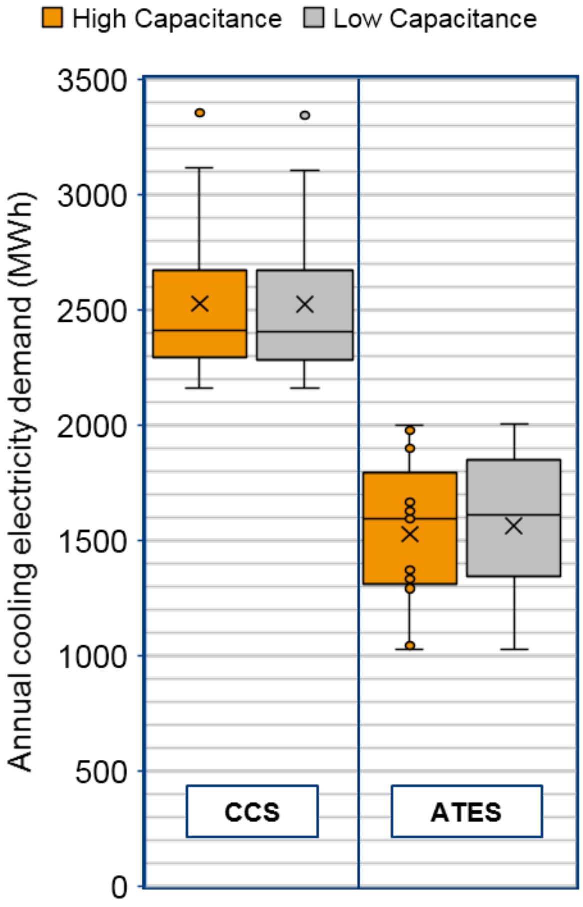

Figure 5-3 The influence of different capacitance of DC room on annual cooling electricity demand of DC cooled by the conventional cooling system and ATES with policy.

Fig. 5-3 describes the influence of different capacitance of DC room on annual cooling electricity demand of DC cooled by the conventional cooling system or by a system connected to ATES. According to simulation results, there is almost no influence of capacitance on cooling demand. However, the influence of different capacitance was shown differently, and that in temperature stability, which is described in Fig. 5-4.

The influence of operational scenarios on temperature stability within DC room:

It is investigated whereas the maximal allowable temperature of air entering IT equipment defined by ASHRAE (35 °C (refer to Fig. 4-7)) is exceeded in the horizon of one year. Fig. 5-4 compares three cases, all for HPC IT load with different capacitance, resp. if the aisle containment is applied. As can be easily expected, the highest temperatures are reached in a variant with low capacitance and without the aisle containment (refer to the right column in Fig. 5-4). The limit temperature was exceeded 2.1 % of the time (that area is highlighted in Fig. 5-4 by the red circle).

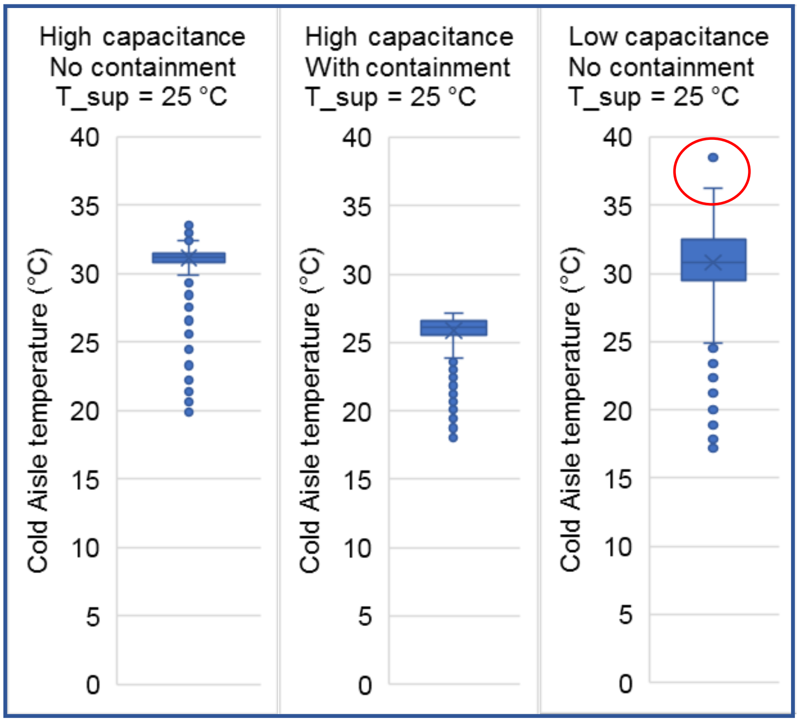

Figure 5-4 The influence of different capacitance on the temperature of air in Cold Aisle.

The influence of operational scenarios on the amount of heat inserted into ATES by DC:

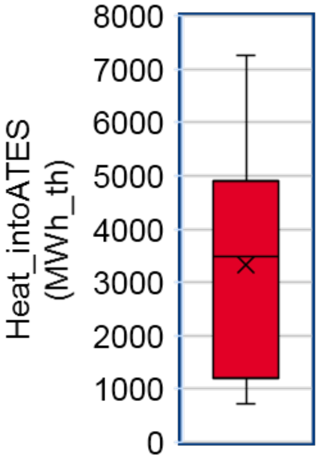

Figure 5-5 Heat inserted into ATES by DC under “ATES policy”.

Figure 5-5 describes the range of heat inserted by DC cooling system into ATES system (under ATES policy). Data which from that box plot was built contain cases from on the one side with a large co-operation (80 % of the time) DC – ATES for low DC temp. SP to on the other side with a low co-operation (11 % of the time) for high DC temp. SP. The average and median values are around 3 400 MWh_{th}.

5.1.2 Campus scale

At first, to put Fig. 5-5 into campus context as appropriately as possible ATES load for reference year (2015) is shown in Fig. 5-6.

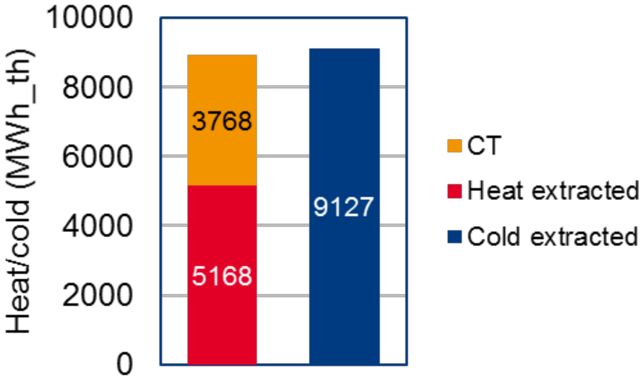

Figure 5-6 The use of ATES system in 2015.

Figure 5-6 shows the use of ATES system in 2015 (refer to data from [21]). In accordance with chapter 3.2, ATES was used more for cooling of buildings (blue bar – cold extracted from ATES) then their heating (red bar – heat extracted from ATES) and hence, a significant amount of heat had to be realised by ATES cooling towers (CT) into ambient (orange bar) to balance out the system.

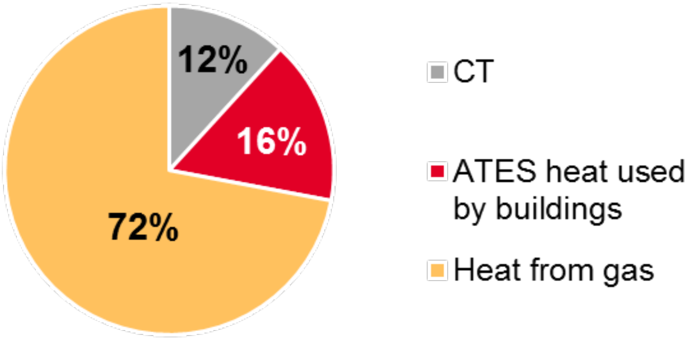

Figure 5-7 Sources of heat within TU/e campus (in the case of CT the heat is released into ambient without useful utilization).

Under the assumption that 80 % of gas consumed in TU/e campus is used for heating, then in the pie chart shown in Fig. 5-7, it is demonstrated the current dominance of gas as a source of heat for the campus buildings. Natural gas is covering most of the heating demand, in fact, natural gas was providing 4.5 times more heat than ATES in the TU/e campus in the reference year.

By connecting DC into ATES system, the undesirable imbalance would be significantly increased. In terms of feasibility, according to Fig. A-1, it is assumed that ATES CTs can release that excessive heat without any major problems. Because in last years the amount of heat released by ATES CTs has been varying greatly, while electricity consumption by ATES has stayed almost constant and the capacity of ATES system is not fully utilized by far.

Fig. 5-8 and Fig. 5-9 describe the ATES situation that would occur if the DC would be connected to ATES system in the reference year.

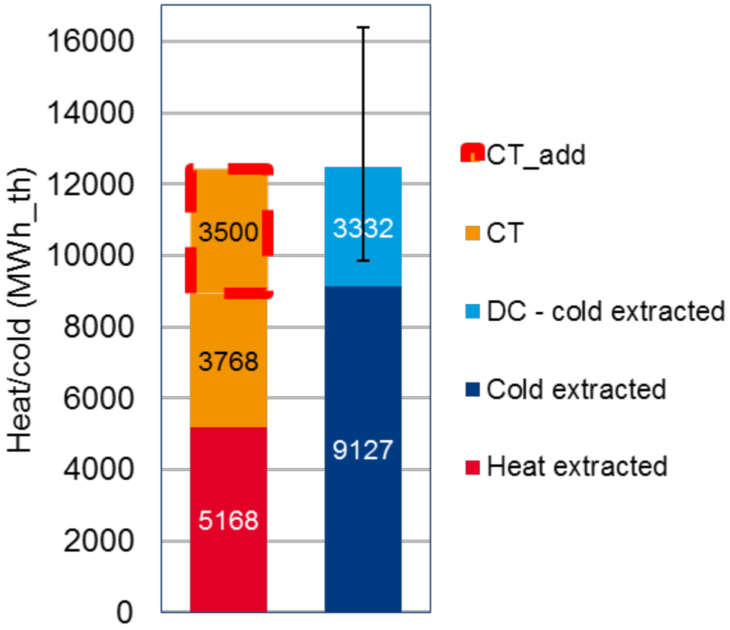

Figure 5-8 The theoretical use of ATES system in 2015 after connection of DC.

In Fig. 5-8, the light blue bar represents cold extracted by DC, resp. heat inserted into ATES by DC, and orange bar with red dashed edge (CT_add) pictures the amount of heat that would be needed to release by ATES CTs on top of the actual situation. In that case, paradoxically more heat would be extracted from ATES and consequently “destroyed” by ATES CTs then meaningfully used by the heating system of buildings in the campus.

To complete the description of Fig. 5-8, the size of CT_add refers to the case where DC inserts into ATES 3 332 MWh_{th}. This mean value refers to the case when DC co-operates with ATES approximately 50 % of the time.

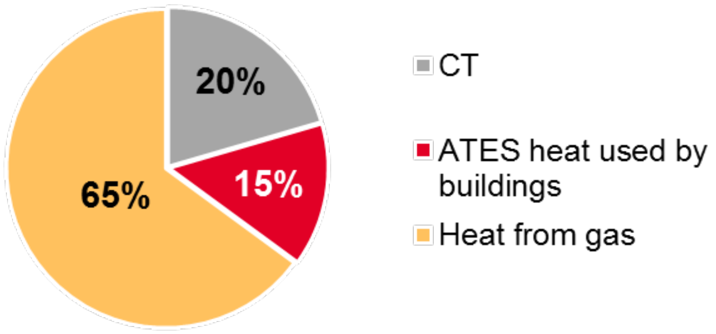

Figure 5-9 Sources of heat within TU/e campus (in the case of CT the heat is released into ambient without useful utilization).

Already from Fig. 5-8 it is evident that connection of DC into ATES would mean enormous change in use of ATES. Of course, it depends on how much the DC would be allowed to co-operate with ATES with respect to ATES policy.

Figures 5-10 and 5-11 describe the use of ATES by particular buildings and notably Fig. 5-11 demonstrates the large potential utilization of the storage by DC against other buildings (black bar in the figure).

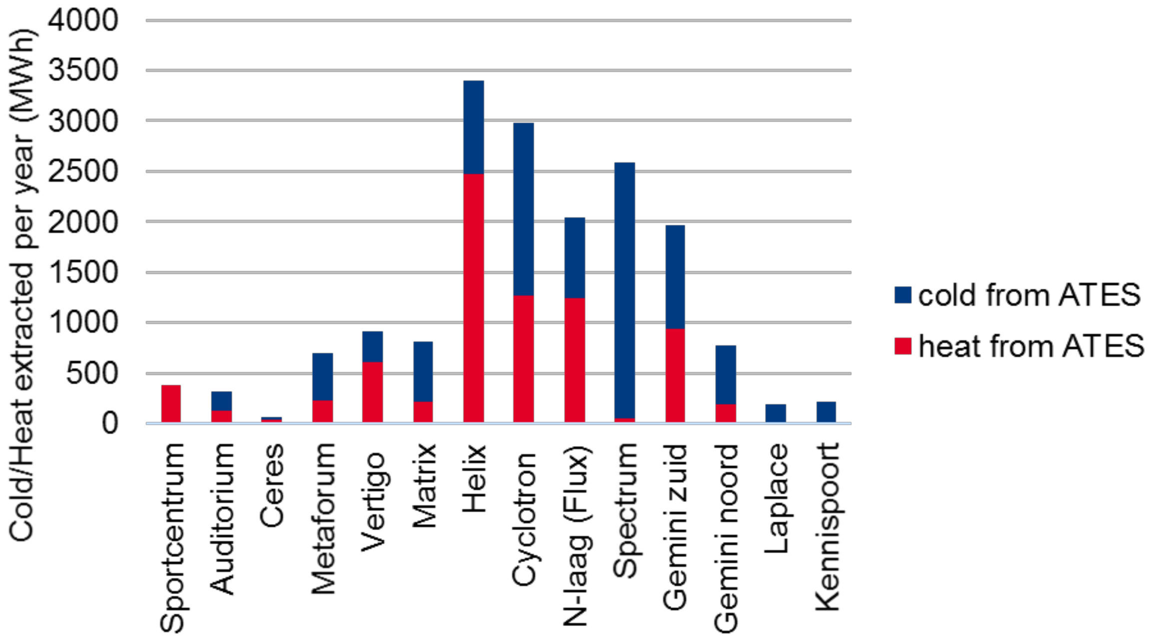

Figure 5-10 Use of ATES by particular buildings in 2015.

Furthermore, the EDW (energy demand weight) parameter was defined (described by Eq. 5.1). That indicates the weight of specific building within the whole ATES system.

$$\mathrm{EDW} = \frac{\text{Building } \mathrm{X}_{\text{heating}} + \text{Building } \mathrm{X}_{\text{cooling}}}{\mathrm{ATES}_{\text{total}}} \quad [-] \qquad (5.1)$$

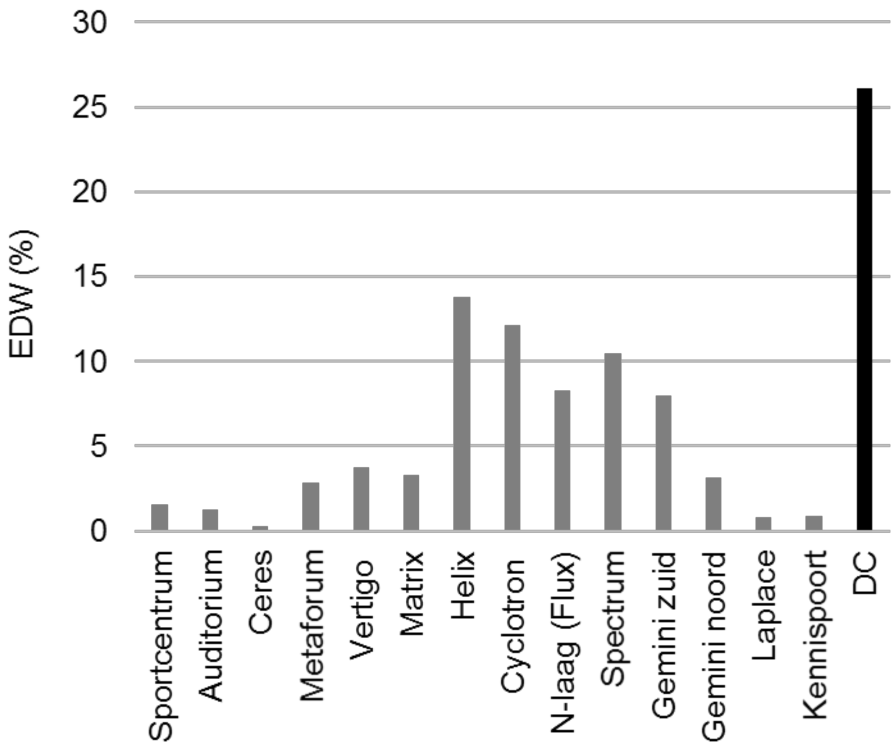

Figure 5-11 Energy demand weight of specific buildings within the whole ATES system.

In Fig. 5-11, it is assumed that DC cools through ATES 80 % of the time. Significant weight is observed.

Simulation results via carbon emissions:

Through carbon emission factor (Emission factor for electricity in NL = 540 g CO_2/kWh [26]), total electricity demand of both cooling variants was recalculated into CO_2 emissions. Further, values for both cooling systems were compared and put into campus context by comparison emissions that are released through gas and electricity consumption by particular buildings (refer to Fig. 5-13).

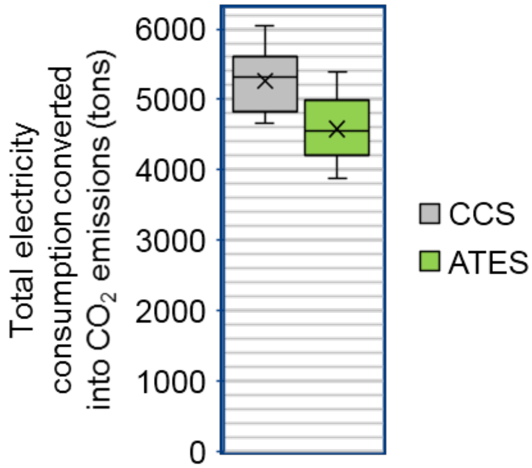

Figure 5-12 Emissions emitted by DC cooled by cooled by the conventional cooling system and ATES with policy.

Total electricity demand used for the construction of Fig. 5-12 consists of electricity for IT, electrical losses on distribution elements (UPS, etc.), miscellaneous electricity demand and electricity for cooling which is variable the most and mainly that part of total electricity demand causes the difference between left and right box plot in Fig. 5-12.

The difference between average values of CCS and ATES variant in Fig. 5-12 is **630 tons of CO_2**. This value corresponds to black dashed line in Fig. 5-13 leading to better insight what does this amount of carbon emissions can be compared with.

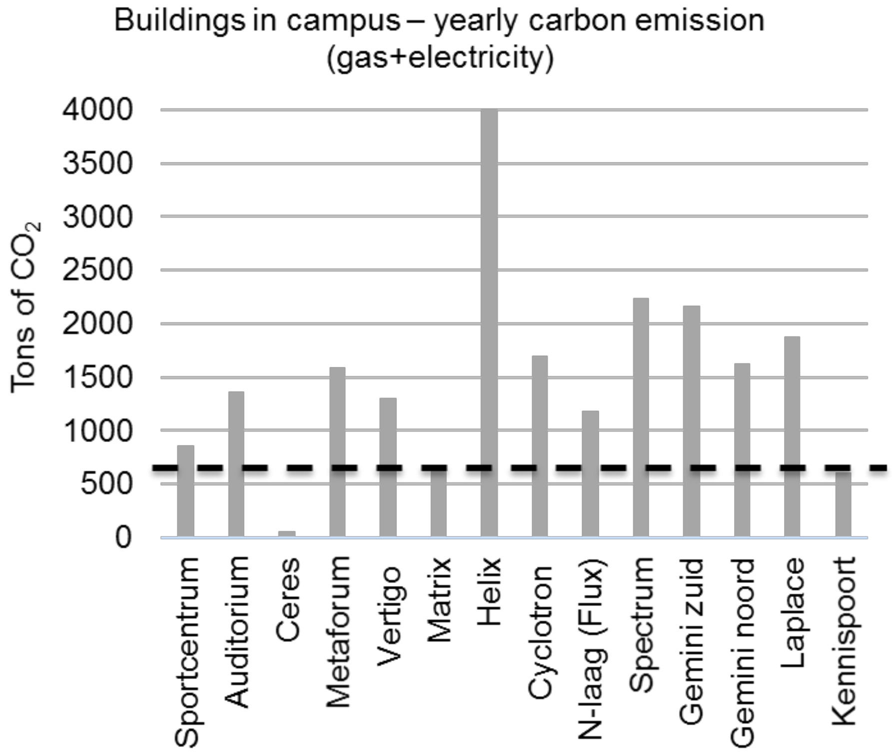

Figure 5-13 Annual carbon emissions by use of the particular buildings in TU/e campus.

5.2 Results with respect to the future scenario

The reason for defining the future scenario, which was already mentioned in 3.2.2, rests on searching the case when waste heat from DC would become very needed on campus. This assumption is based on the effort of TU/e to become more sustainable. Which would result in a reduction of gas for heating within the campus and that heat from combustion of gas would be replaced by heat from ATES (schematically depicted in Fig. 5-14). This would lead to a situation that ATES system would be used more for heating than cooling of campus buildings, respectively the storage system would become imbalanced and would need some extra heat to balance out itself. And that heat would be provided by DC resulting in unlimited co-operation of DC and ATES in terms of heat. This nonstop use of cold water from ATES yields on the lowest values of DC cooling electricity demand, which is depicted in Fig. 5-15. (extension of Fig. 5-1) and simultaneously balanced ATES system.

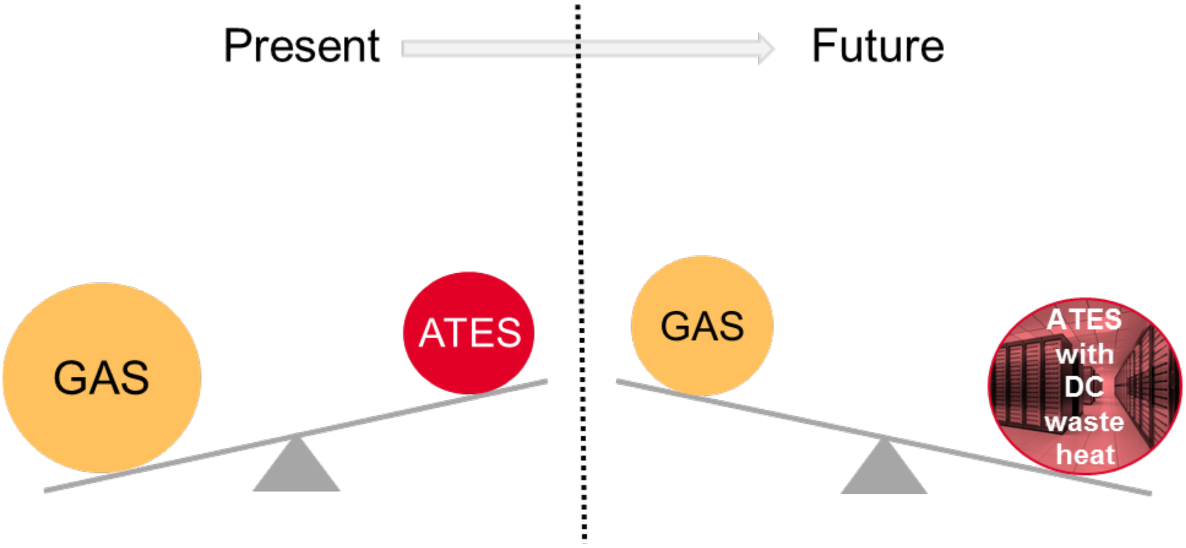

Figure 5-14 Schematic image of future scenario.

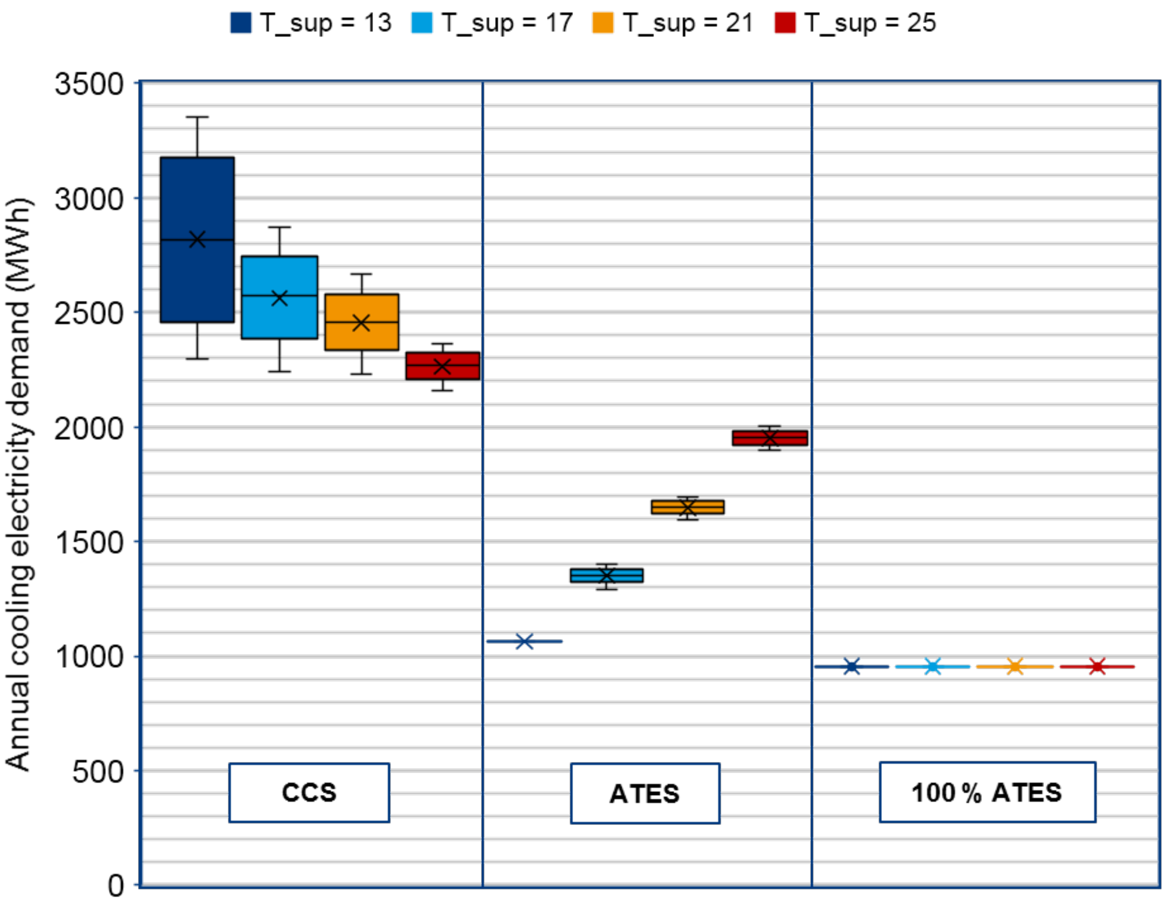

Figure 5-15 The influence of the different temperature setpoints in DC room on annual cooling electricity demand of DC cooled by the conventional cooling, ATES with policy and ATES without policy.

In Fig. 5-15, there is no difference in cooling electricity demand for cases with a variant temperature of air in DC. That is caused by the fact, that all pumps were modeled as constant speed pumps with constant power. Consequently, the different temperature of air within DC is aimed by valve “1” (in Fig. 4-6 for instance) which by-pass water going to CRAC more for cases with higher DC temp. SP and less for cases with lower DC temp. SP.

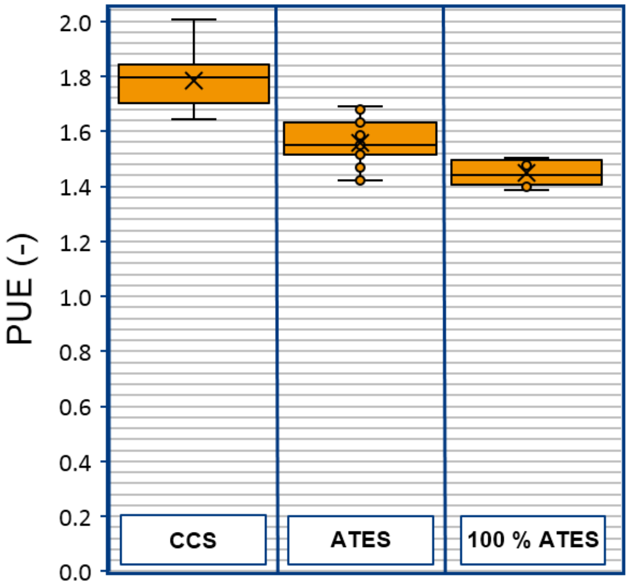

Figure 5-16 PUE metric of DC cooled by the conventional system, ATES with policy and ATES without policy.

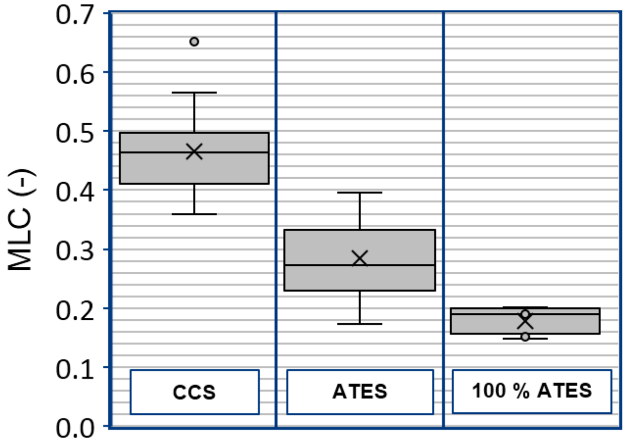

Figure 5-17 MLC metric of DC cooled by the conventional system, ATES with policy and ATES without policy.

In Figures 5-16 and 5-17, there are compared three cooling variants (CCS, ATES, “100 % ATES”) through PUE and MLC metrics. Taking the obtained PUE values to the ongoing values of state of the art DCs, even for “100 % ATES” variant PUE might seem not so stunning, however, that is caused by relatively highly chosen a value for miscellaneous electricity demand. In that case, a better understanding about the suitability of DC cooling system that uses ATES nonstop is represented by MLC indicator in Fig. 5-17. MLC indicator for “100 % ATES” case reaches very low values around 0.15 which means that DC in average needs for the operation of 1 kW server only cooling power of 0.15 kW.

The case where DC uses cold water from ATES only when ATES policy allows, yields in a different amount of heat inserted by DC into ATES, which was already shown in Fig. 5-5. After simulating “100 % ATES” variant the amount of heat inserted into ATES increased, which is shown in Fig. 5-18.

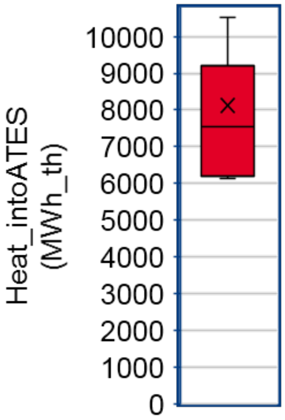

Figure 5-18 Heat inserted into ATES by DC without “ATES policy”.

As was already mentioned in 3.2.2, in the reference year TU/e consumed almost 3 million of cubic meters of natural gas.

Thus, in accordance with TU/e carbon policy [24], it is assumed that gas consumption on campus will decrease in next years.

It is assumed that 80 % of gas is used for heating, though exact data is not available to support this information. In 2015, 2 880 000 m^3 of gas was used. 80 % of that gives 2 300 000 m^3 and according to the caloric value of gas, it is assumed that 1 m^3 of gas can provide 10 kWh of heat.

Hence, it can be deducted that in the reference year 2015 the heating energy due to gas combustion was 23 000 MWh (refer to Fig. 2-10).

It is estimated that in near future the use of gas for heating reaches half the value and this missing half will be replaced by energy from ATES. This situation of potentially future ATES is shown in Fig. 5-18.

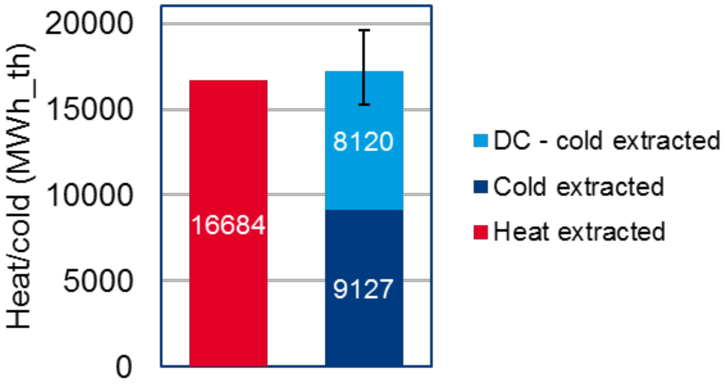

Figure 5-18 The theoretical use of ATES system in future after connection of DC into the system.

Fig. 5-19 describes heating demand of future campus where almost exactly half of the heat (29 %) provided by ATES would come from DC as waste heat. To put Fig. 5-19 into context with Fig. 5-18, this 29 % in Fig. 5-19 corresponds to the light blue bar in Fig. 5-18.

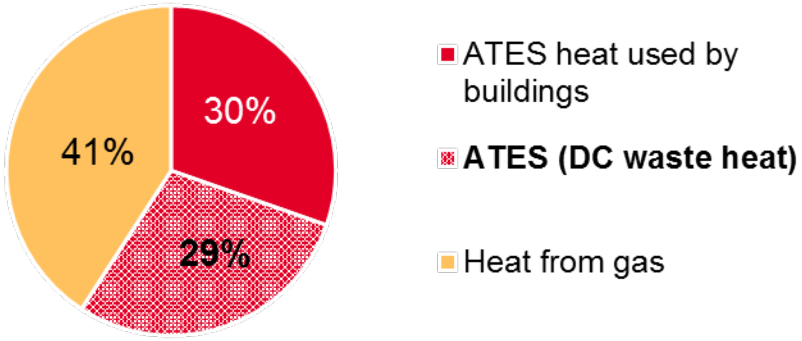

Figure 5-19 Sources of heat within future scenario TU/e campus.

Carbon emissions:

In considered future campus scenario, the connection DC – ATES would be very beneficial for both sides. This claim is supported through calculating the reduction of carbon footprint (refer to Table 5-1, where the first four lines represent the emission reduction). The main reduction is aimed at a reduction in gas consumption. The reduction in emissions is shown by minus, the increase is shown by plus.

Table 5-1 Future campus shown through carbon emissions.

Type	Description	Value (unit)	Emissions (tons of CO_2)
−	Gas consumption	11 516 MWh_{th}	**2 170**
	No ATES CT needed	?	?
	No balancing the ATES through extra heat source needed	8 000 MWh_{th}	?
	DC cooling system connected to ATES against CCS	1 167 MWh_{el}	**630**
+	DC cooling system?	955 MWh_{el}	**516**

6 Discussion

The simulation results demonstrate the benefit of co-operation of DC and ATES system.

The waste heat utilization potential of the conventional air-cooled system was studied. The co-operation of the DC system with ATES was found as a feasible solution for utilization of low-grade waste heat. Usually, for DCs with air-based cooling, there is only a poor range of waste heat possibilities. Mainly space heating for the building nearby can be provided by DC requiring complex piping system. However, due to ATES, even mid-sized DC with air-based cooling can mean the significant source of heat for buildings across the campus as ATES in substance solves the mismatch in time between heat produced by DC and heating demand by buildings.

While current situation in campus does not request balancing out the ATES by waste heat from DC, in future campus scenario might circumstances change.

6.1 Actual situation: Reduction of DC electricity demand and carbon emissions due to connection of DC cooling system into ATES considering the ATES policy

In chapter 5.1, the conventional DC cooling system using WSE is compared with a cooling system connected to ATES. The use of ATES for cooling of DC is allowed according to ATES policy. Thus, ATES is used only to substitute the use of electricity demanding chillers in the conventional cooling system.

Because of ATES policy, the obtained results are characterized by increasing cooling demand with increasing temperature of air in DC. By comparison of DC with CCS and ATES connection for the same temperature of air, the benefit in annual cooling electricity demand by ATES connection in 13 °C case is around 1 700 MWh (60 % of electricity demand for cooling would be reduced). In 25 °C case, the benefit is only 300 MWh by comparing mean values. It means that for DC working with average IT load about [2]475 kW (where total electricity demand is in average 9 700 MWh for CCS and 8 500 MWh for DC connected to ATES) has a significant beneficial influence how much the co-operation with ATES is allowed. Thus, it is clear that if once the DC is connected to ATES, the DC management puts

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[2] Average of values 420 kW and 530 kW (refer to 3.2.1)

enormous effort to use the ATES as much as possible. However, it depends on the agreement of ATES site. These links between DC and ATES managers are beyond the scope of this work. Certain ATES policy was applied only to give to the work a real outline.

By change of cooling approach from CCS to ATES, the benefit in carbon footprint reduction was calculated. The value about 630 tons of CO_2 was obtained which roughly corresponds to energy used for the annual operation of TU/e sports center or educational building called Matrix, which is described in Fig. 5-13.

6.2 Future scenario: Benefits of using the DC waste heat for space heating in university campus through the ATES system

By assumption of a future scenario, promising results were obtained. Although, these results make sense only after an understanding of all assumptions that were made. In accordance with TU/e carbon politics, and also the politics of the whole Netherlands, the assumption of reducing the consumption of natural gas for heating opens the gates for DC waste heat utilization. Thus, DC could be used for heating the buildings in campus through ATES and simultaneously balance out this storage system. That would result in a win-win situation with carbon and energy reduction on side of DC and energy and carbon reduction on side of the TU/e campus, furthermore with balanced ATES.

Suitability of nonlimited co-operation of DC and ATES system is described in Fig. 5-17 by low MLC values which refer to the efficient cooling system. While for the variant with CCS the average MLC was 0.47, for the variant with ATES under ATES policy that average value reached 0.29 and for the variant with continual use of ATES for cooling the average value reached 0.18 which in comparison with ongoing DCs represents very low value.

From the perspective of the whole campus, it was investigated that under considered assumptions the DC would cover 29 % of campus heating demand and due to natural gas reduction would be significantly decreased emissions from gas (refer to Table 5-1).

Besides, another savings would be reached as ATES cooling towers would not be needed because the ATES system would be balanced out. Purely theoretically, the interesting situation would arise if in that future scenario there was no heat inserted into the ATES by DC. Then ATES would need some extra heat to balance out the system, and the system providing that heat would, of course, request energy, respectively would increase carbon footprint.

7 Conclusion

In this thesis, an analysis of chosen waste heat utilization approach in a mid-sized data center located in a university campus was carried out. The influence of DC cooling approach on the potential of waste heat was discussed. Harvesting the heat from air-cooled and liquid-cooled DCs was reviewed with emphasis on advantages and drawbacks of both technologies. In the practical part of the work, the convenience of co-operation of DC and sessional thermal storage was assessed and compared with DC with the conventional cooling system. In order to assess these two cases, the numerical models of these systems were developed using building energy simulation. Specifically, the numerical model was created in simulation tools TRNSYS and CONTAM. The model can represent dynamic behavior of the DC energy performance. The numerical model of DC is used to assess the potential of the waste heat utilization for university campus with ATES. The evaluation is performed for the current and future situation in the campus. Furthermore, the uncertainty of the DC performance, caused by undecided DC management is evaluated. Various operational scenarios are defined and tested. The detailed analysis of the simulation results provides comprehensive materials to answer the research questions. The research aimed to quantify the waste heat utilization and reduction of CO_2 emission. According to this study, from 6 to 10 GWh of waste heat per year can be reused for given case-study. Using the values of carbon emissions in chapter 3.2.2, the co-operation of DC and ATES can reduce the CO_2 emission in the range of 970 to 1190 tons per year (emissions released by the DC alone are not included).

The project showed that the co-operation of DC and ATES can be very convenient and that even mid-sized DC working with average IT load around 500 kW can in the future represent a strong heat supplier within the campus, balance out the ATES and significantly decrease TU/e carbon footprint. However, for the actual situation, the collaboration between DC and ATES would be more convenient for the DC side than for the campus side. But there might exist a win-win situation between DC and ATES side under certain ATES policy condition which was slightly investigated. Nevertheless, this should be more assessed by future work.

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9 Appendix

Table A-1 Design parameters.

Component	TRNSYS Type	Parameter (unit)	Value
CRAC – Heat exchanger	91	Temp. dif. of air (K)	10
CRAC - Fan	3c	Fan flow rate (kg/s)	100
		Fan power (kW)	100
		Conversion coefficient (-)	1
		Fluid specific heat (kJ/kg.K)	1.01
Pump (refer to Fig. 3-6)	3d	Flow rate (kg/s)	50
		Power (kW)	4
		Conversion coefficient (-)	0.05
		Fluid specific heat (kJ/kg.K)	4.19
CT pump	3d	Flow rate (kg/s)	113
		Power (kW)	8
		Conversion coefficient (-)	0.05
[3]Closed Circuit CT	510	Design air flow rate (kg/s)	150
		[4] Rated fan power (kW)	150
		Number of power coefficients (-)	4
		Power coeff. 1 (-)	0.2
		Power coeff. 4 (-)	0.8
Chiller	666	Rated capacity (kW)	1300
x	x	Simulation time step (min)	5

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[3] The pattern for design of Closed Circuit CT was data from: https://www.baltimoreaircoil.eu

[4] The number of coefficients that are provided in the relationship between fan power (power law) and fraction of design flow rate.

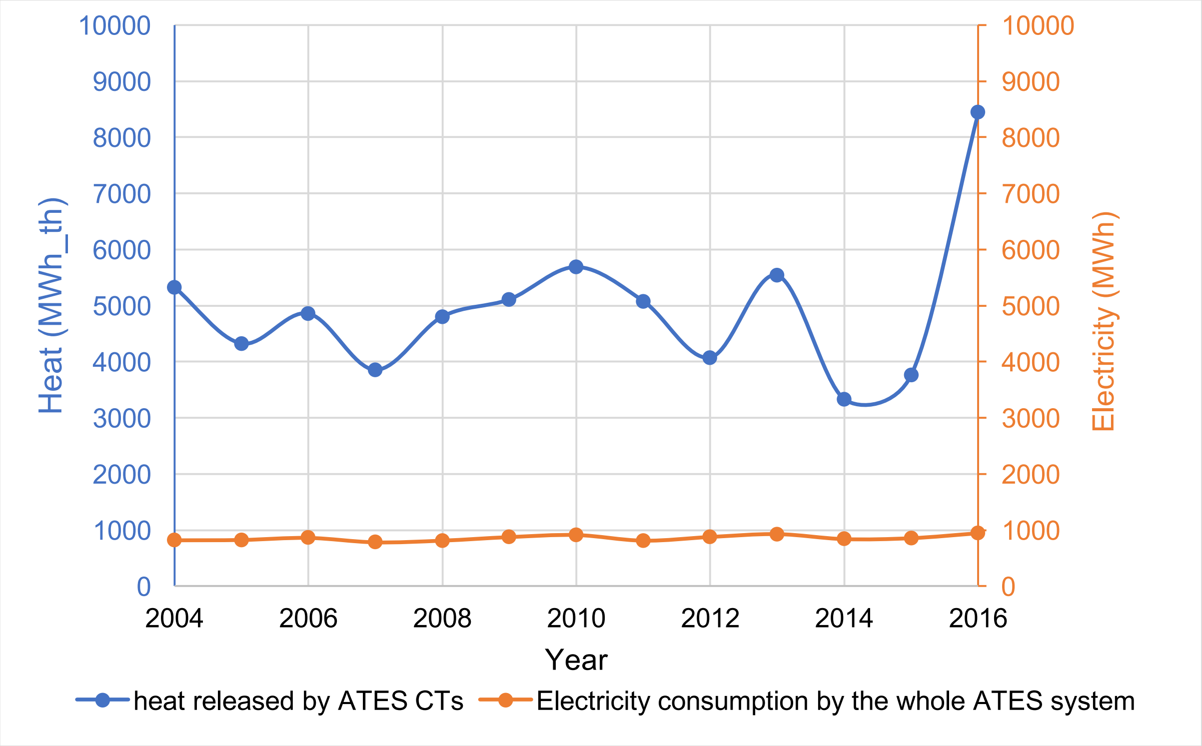

Figure A-1 Relationship between Heat released by ATES CTs and Electricity consumption of the whole ATES system.

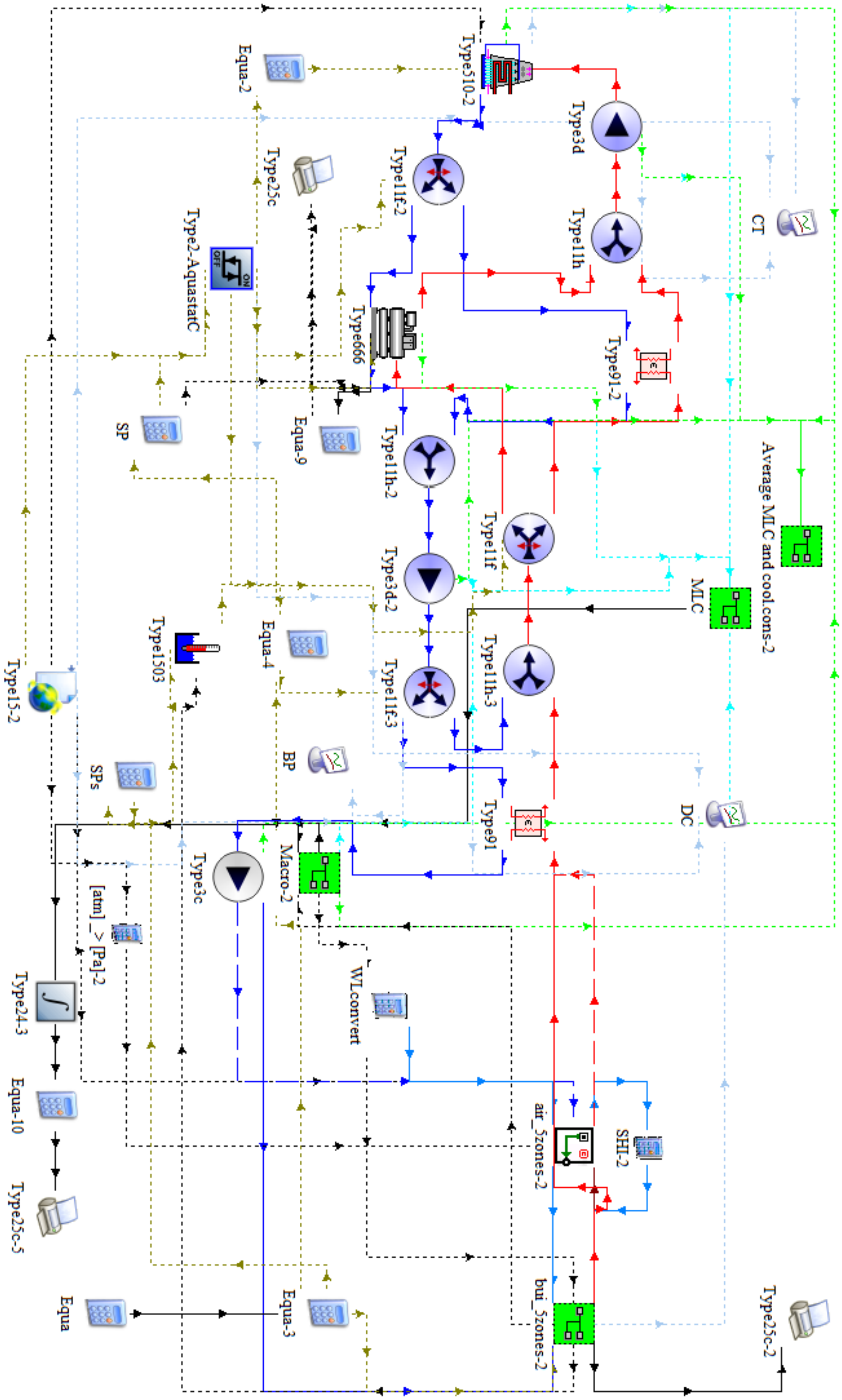

Figure A-2 TRNSYS model of DC cooled by conventional cooling system.

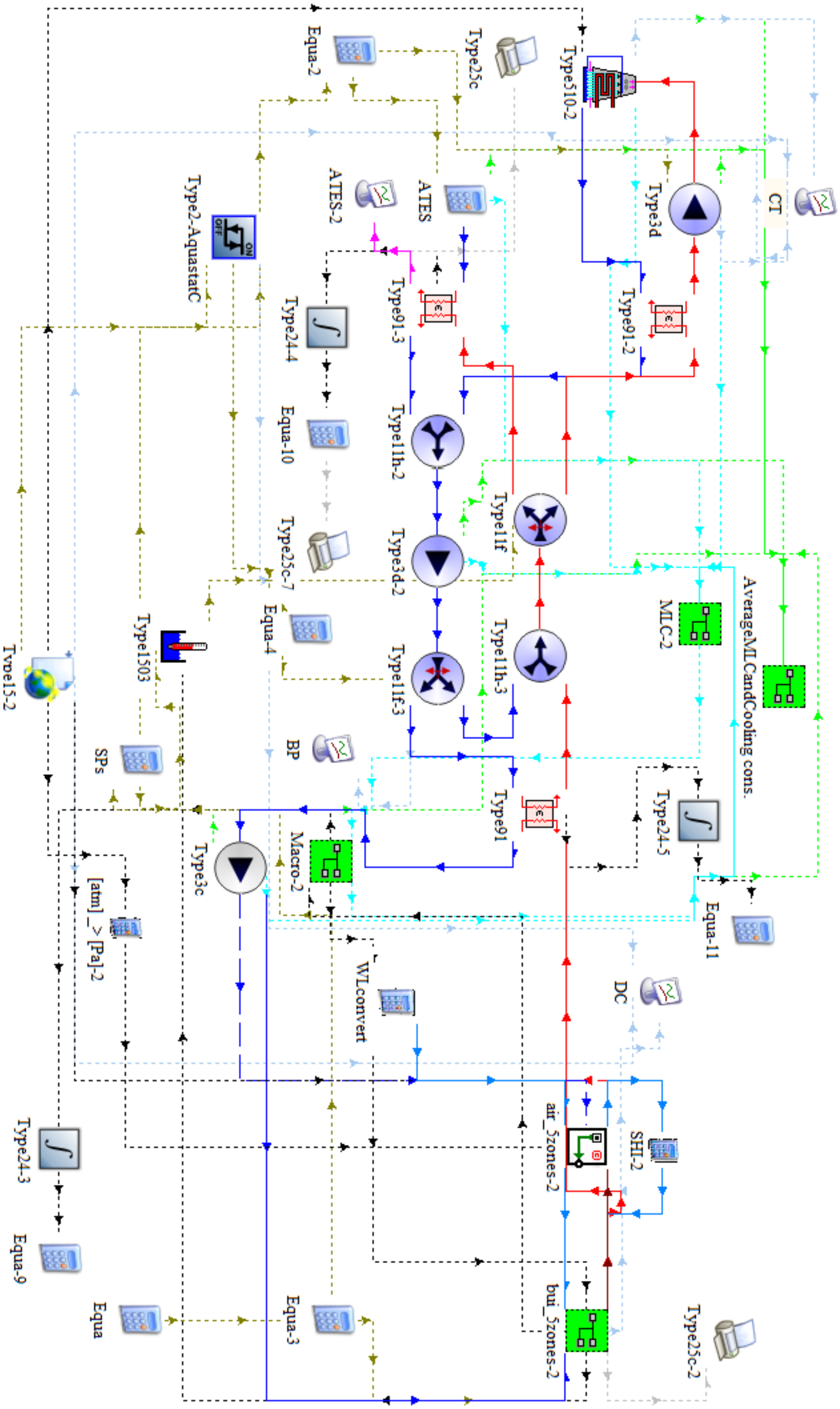

Figure A-3 TRNSYS model of DC cooled by system connected to ATES.

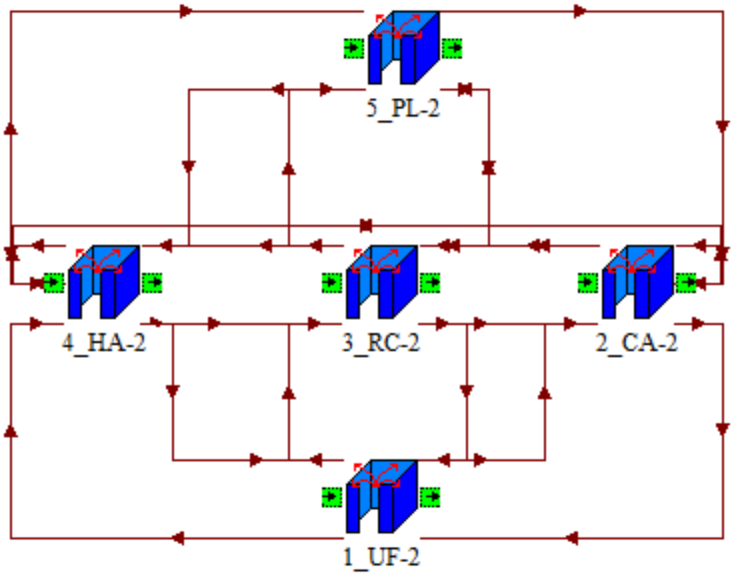

Figure A-4 Five-zonal model of DC room in TRNSYS.

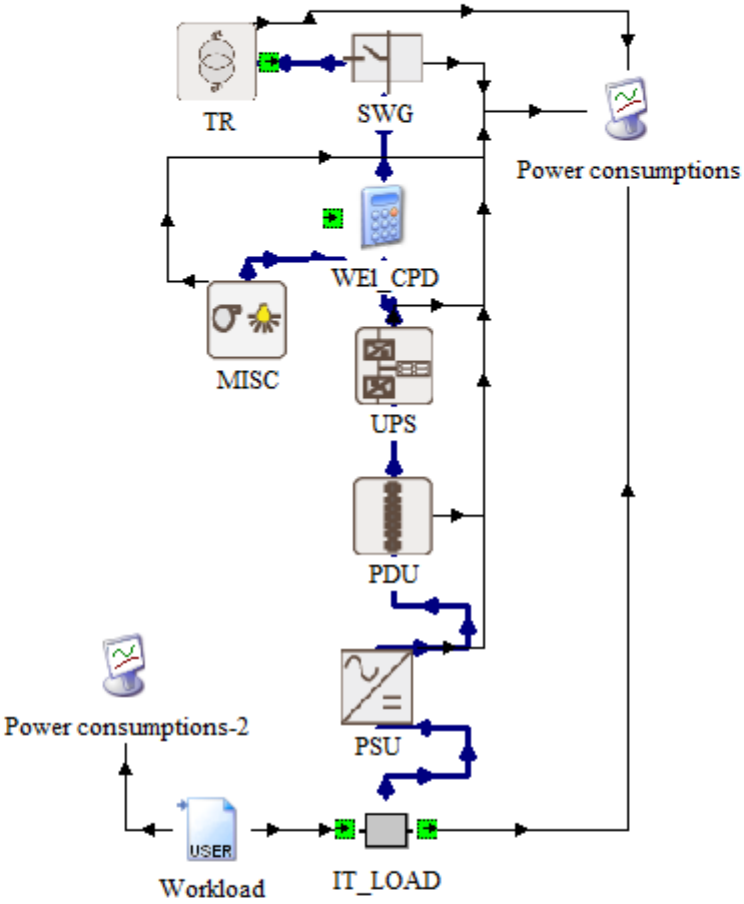

Figure A-5 Elements of electricity delivery site in TRNSYS.

Table A-2 Capacitance (CAP) and heat loss coefficient overview.

Total heat loss coefficient (W/K)				
UF	50			
HA	67			
CA	67			
PL	50			
High CAP	**Capacitance of zone (kJ/K)**	Volume of concrete (m^3)	Mass of steel (kg)	Volume of air (m^3)
UF	85100	38	0	486
HA	17000	5	10200	602
CA	17000	5	10200	602
RC	39000	0	81600	228
PL	85000	38	0	486
Total	**243100**			
Low CAP	**Capacitance of zone (kJ/K)**	Volume of concrete (m^3)	Mass of steel (kg)	Volume of air (m^3)
UF	3000	1	0	486
HA	8000	1	10200	602
CA	8000	1	10200	602
RC	39000	0	81600	228
PL	3000	1	0	486
Total	**61000**			