Report

Reuse of the surplus heat from data centers through different end users

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SUMMARY

It is estimated that 95 to 98% from the electrical supply to a data center (DC) is converted to heat, and most of this heat is not utilized efficiently. This report investigates the possibilities of reusing the surplus heat from DCs by diverse end users. The specific end users were selected to enforce a more efficient usage of the energy resources and surplus heat in Norway, in addition to a sustainable and secure food production. The first end-user case included three generations of district heating (DH) systems. The lower the supply heating water temperature is set, the better the surplus heat is utilized; that is, the lower is the required input of electricity for upgrading the heat. The second study explored connecting three seafood farm types of shrimp, lobster, and trout with different temperature requirements to the DC's surplus heat. The third study included combining greenhouses and biogas plants as end users. Combining a group of diverse end users may be a good solution to overcome any mismatch between the surplus heat from DCs and the thermal demands of end users.

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1 Introduction and background

The increasing demand for data processing, data storage systems, and digital telecommunications, coupled with the simultaneous advances in computer and electronic technology, has resulted in a dramatic growth rate in the data center (DC) industry [1]. Meanwhile, energy statistics indicate that data centers are responsible for 1.3% of the world's energy consumption [2]. The energy demand of data centers is projected to increase to 3,000 TWh by 2030, as illustrated in Figure 1 [3]. In Norway, the growth in data center establishments has been significant in the recent years.
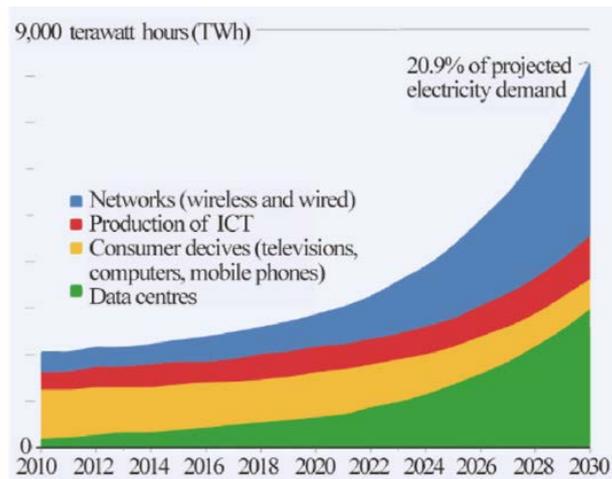

Figure 1. Trends of ICT electricity usage expectations

The energy consumption of DCs is mainly due to computing and communication, cooling, data storage, lighting, power conversion, and electronics (see Figure 2). The computer and communication system takes the biggest share, accounting typically for about 50% of the total energy consumption. The cooling system and the remaining part (including lighting and the power system) account for about 40% and 10%, respectively, of the total energy consumption [4].
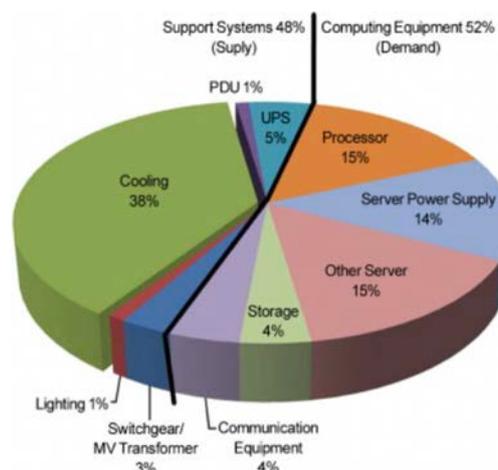

Figure 2. Typical electrical components in a data center [5]

Nearly all the electrical power input into DCs is dissipated as heat. For that, the world is facing an urgent need to improve not only the DC energy efficiency, but also methods to utilize the surplus heat. This report evaluates the potential of DC surplus heat utilization for three different purposes: district heating (DH), seafood farms, and greenhouses and biogas plants.

2 Cooling technologies of data centers

The cooling of DCs covers cooling down the servers, removing the heat from the server room, as well as disposing of the heat to the ambient or to potential end users. At each stage, different cooling media, technologies, and challenges related to energy efficiency are present. On the other hand, cooling technology is vital in determining the power usage effectiveness (PUE) of DCs and the surplus heat quality. The PUE is defined as the ratio of the total amount of energy used by a DC facility to the energy delivered to the IT computing equipment, i.e.,

$$PUE = \frac{Total\ DC\ facility\ energy\ consumption}{IT\ equipment\ energy\ consumption}\ .$$

Another key metric that is relevant regarding surplus heat utilization is the energy recovery factor (ERF), which is defined as the ratio between the recovered waste heat energy from the DC and the total amount of energy used by the DC facility [6], i.e.,

$$ERF = \frac{Recovered\ waste\ heat\ energy}{Total\ DC\ facility\ energy\ consumption}\ .$$

This section demonstrates some of the cooling technologies of DCs.

2.1 Air cooling system

Most of the existing DCs are cooled through air cooling, this being the least costly cooling method. In air cooled DCs, server racks are typically arranged into cold and hot aisles as shown in Figure 3. In cold aisles, the front sides of the server racks face each other, and this aisle provides cool intake air to each server. In hot aisles, the rear sides of the racks line the aisles, and the hot exhaust air exits each server here.

Traditional DCs with air-based cooling systems have low waste heat temperatures with return temperatures in the range 20-40 °C and limited potential for reuse [6]. Air is not an ideal heat transfer medium due to low heat transfer coefficients, resulting in large heat transfer areas and thereby limiting the rack density. Modern, high-efficient DCs for applications such as edge computing require high rack density, in which case cooling with air may not be sufficient [7]. In this case liquid or two-phase cooling technologies are required, discussed in the following sections. Apart from promoting the use of alternative cooling technologies, higher rack density would also reduce the data center footprint.
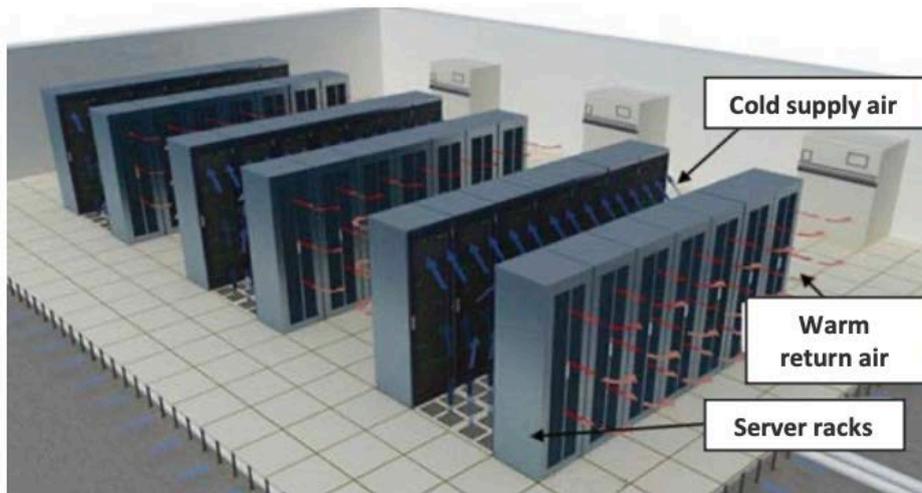
Figure 3. Server rack arrangement in an air-cooled data center [8]

2.2 Liquid cooling system

Liquid cooling technology uses liquid as a heat transfer medium to cool servers. Liquid cooling can be done at different levels, from immersion cooling, where the server is immersed into a dielectric fluid, into cold plates or other types of heat exchangers attached at the central processing unit (CPU). Liquid cooling is especially suitable for DCs and transmission base stations (TBSs) with a high-power density, or edge computing, as mentioned previously. The main advantage of liquid cooling is the higher heat transfer coefficient than air cooling, hence leading to a reduced temperature difference between the CPU and the coolant. This allows for more heat to be recovered from the DC and TBS for reuse [9]. Thus, typical operation temperatures for water-cooled systems are in the range 20-65 °C [1]. Figure 4 illustrates a water-cooling system where the heat sink is an evaporative cooling unit, i.e., the cooling tower, which dissipates the DC cooling load into the ambient conditions. Figure 5 shows the principle for liquid immersion cooling.
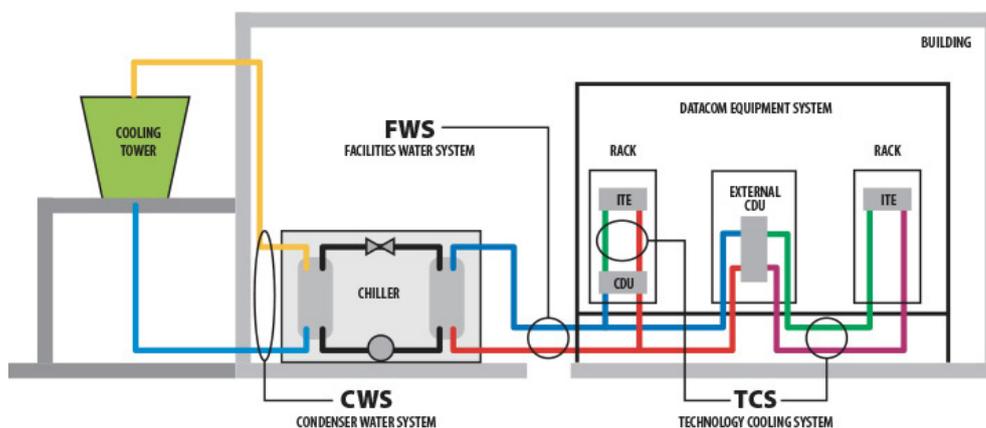


Figure 4. Liquid cooling system [10]
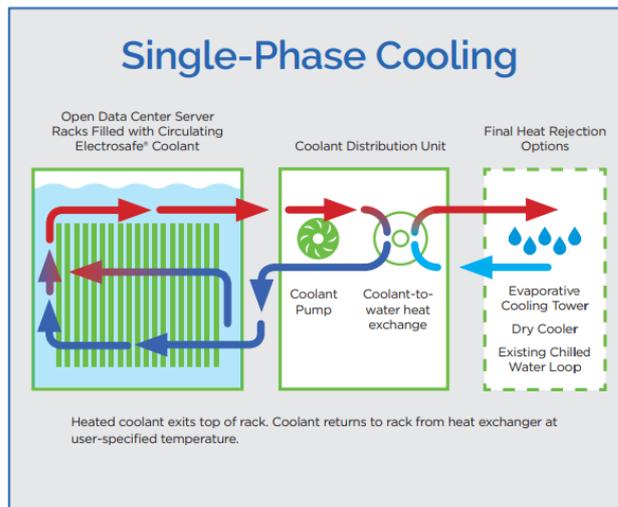
Figure 5. The principle for liquid immersion cooling [11]

2.3 Two-phase cooling

Two-phase cooling refers to using a liquid-vapor phase change of circulating coolant for cooling, utilizing the large latent heat of vaporization [12]. An example of a two-phase cooling system is a heat pipe. The heat pipe unit consists of a hollow tube filled with a structured material to create the capillary forces on the working fluid. This design allows for thermodynamic processes of evaporation and condensation between the servers, refrigerant and ambient air to occur using thermosyphon phenomena and natural cooling sources. The principle of operation of the heat pipe is shown in Figure 6. Cooling energy savings could range between 15 to 18% by implementing heat pipes [13].
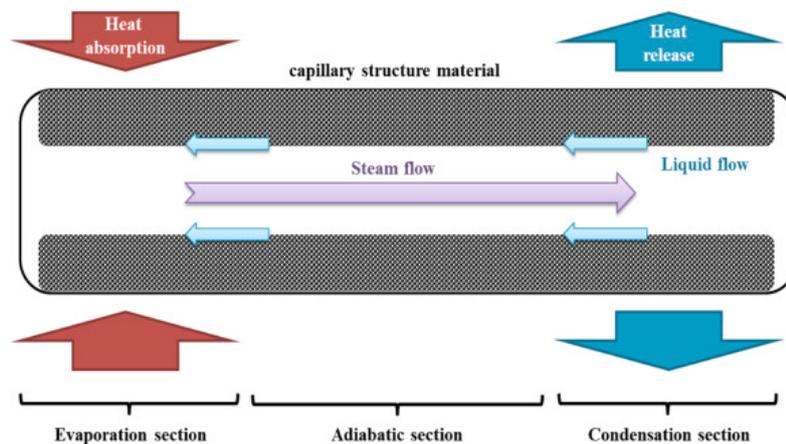
Figure 6. Structural and principle of heat pipe cooling example [12]

Another approach for two-phase cooling is two-phase immersion cooling, illustrated in Figure 7. In this approach, servers are sealed in a bath of fluorocarbon-based coolant with a low boiling point, which evaporates with the heat given from the servers [9]. Heat is the rejected into water-cooled condenser coils, where the coolant condenses. Two-phase immersion cooling is very efficient and can give high temperatures for the surplus heat (above 60 °C, depending on the boiling point of the coolant). A disadvantage is the use of fluorocarbon-based coolants.
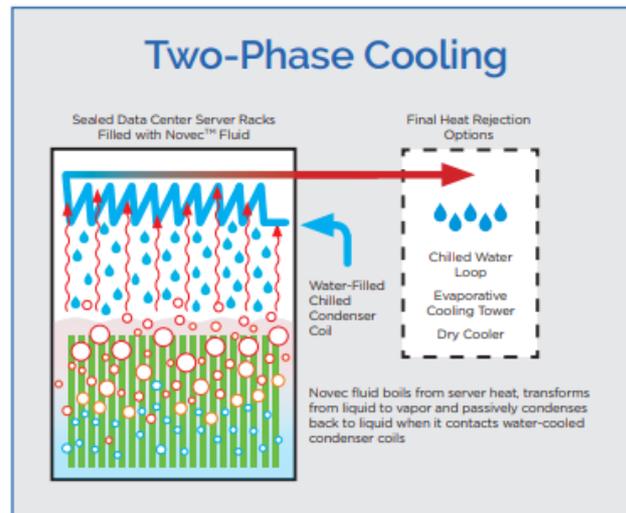
Figure 7. Two-phase immersion cooling [11]

2.4 Free cooling

Free cooling refers to using ambient air or a nearby water source to cool the DC's servers, thus bypassing mechanical active components [14]. Free cooling can be accomplished through a direct connection between the cold source, e.g., air or water, or indirectly through a heat exchanger. An example of the waterside direct free cooling is shown below.

The waterside free cooling takes cold water from a nearby water source to cool down a DC and can also be subdivided into two categories of direct or indirect cooling. The waterside direct free cooling uses natural cold water to directly cool the indoor air in the DC, as shown in Figure 8. This approach is geographically limited since the DC needs to be located close to or nearby the cold-water source [14].
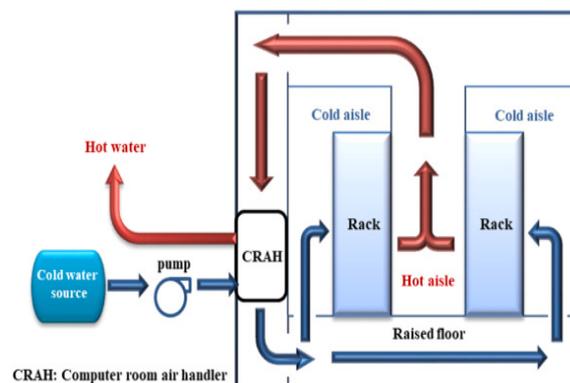
Figure 8. Schematic diagram of a waterside direct free cooling system [14]

2.5 Cooling assisted by thermal energy storage (TES)

TES-assisted cooling is usually used in conjunction with other cooling technologies and has become an effective way to resolve energy supply-demand mismatches during operation [15]. A water cooling system with a TES tank is shown in Figure 9, where in the case the water temperature is below 12 °C the nearby lake water is used as the natural cooling source. If the water temperature increases to higher levels, the water-cooled chiller can work with the lake water or the chiller operates independently. In this case, the chilled

water is supplied to the DC through cold storage, while the TES provides cold energy during a power outage for increased security.
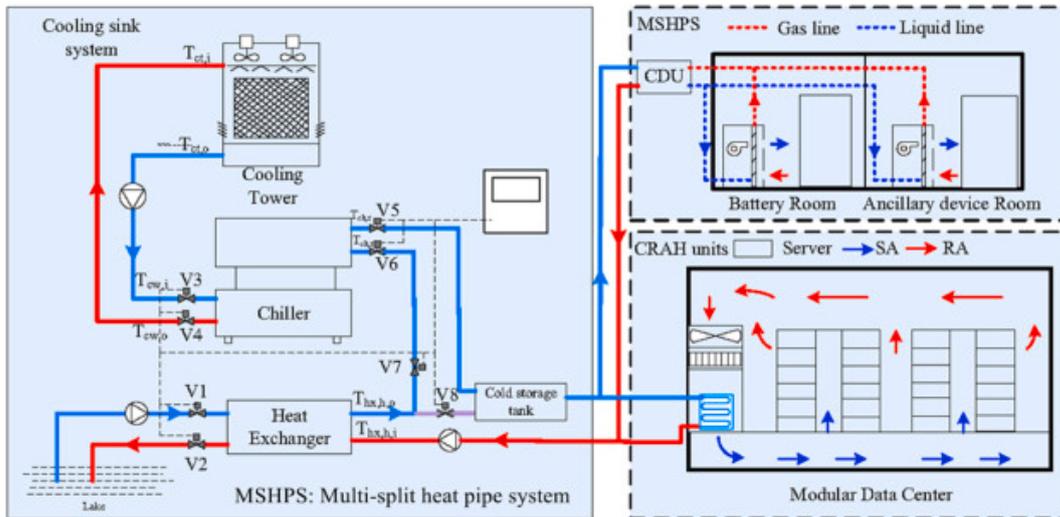
Figure 9. Schematic diagram of the lake water assisted cooling plant in the data center [16]

2.6 Summary of DC cooling technologies

In the end, among different cooling technologies, the liquid cooling system has the most optimal PUE range of 1.1 - 1.2 and energy-saving cooling efficiency in the range 45 - 50%, as shown in Figure 10. Accordingly, this study will focus on DC's liquid cooling systems and how to capture and connect its surplus heat to different end users.
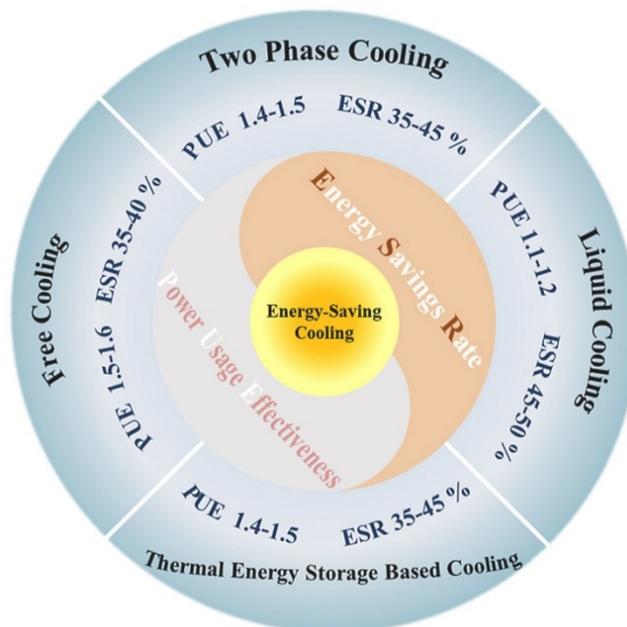
Figure 10. DC cooling technologies and corresponding PUEs and energy saving rates (ESR) [17]

3 Surplus heat recovery management

No matter how energy efficient a DC is in terms of its PUE, all the power is eventually converted to heat and is largely unused today. Accordingly, the Norwegian Government in 2021 proposed introducing a requirement to assess the possibility for utilization of surplus heat when building new or upgrading facilities with high energy consumption – known as Article 14.5 in the Energy Act (Norwegian Ministry of Local Government and Modernisation, 2021). Data centers were explicitly mentioned in this proposal.

Capturing and reusing the resultant DC surplus heat is the major focus of this section. As the surplus heat is captured through the coolant stream flow for most heat recovery techniques, the quantity and quality of surplus heat strongly depend on the type and specification of the thermal management system. As shown in Table 1, the amount of surplus heat increases with a higher the capacity of the DC.

Table 1. Approximated surplus heat for two different capacities of DCs [18], [19]

DC	Small 5MW	Large 10MW
Excess heat capacity	4.85 MW	9.7 MW
Excess heat energy per year	42.5 GWh/year	85 GWh/year

The main goal of this subsection is to demonstrate the possibilities, technical configurations, know-how, and challenges of utilizing the excess heat of liquid-cooled DCs towards three different end users (see Figure 11):

- District heating networks
- Seafood farms
- Greenhouses and biogas plants
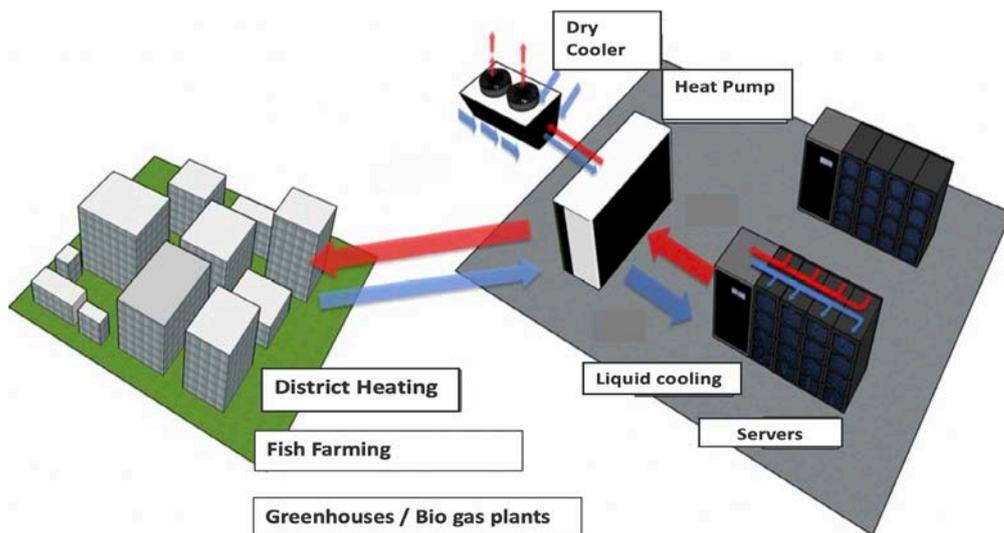
Figure 11. DC Surplus heat and three end users

3.1 Required infrastructure

In general, connecting the DC's surplus heat to diverse end users requires two high-level components:
- **Heat pumps**
- **Substation**

A heat pump is a device that can provide heating and/or cooling energy to a space or a system. Utilizing a heat pump depends mainly on the heating requirement of the end user and whether a heating upgrade is required or not.

The main function of a substation is to link the surplus heat of the DC with the end user. Usually, it consists of a heat exchanger and a modulated circulation pump. The pump is controlled to maintain the supply water temperature as per the requirement of each end user. It is also important to take into account some parameters that influence the heat transfer/exchange between the surplus heat source, i.e., the DC, and the end user, when designing the substation. Such parameters could be:
- heat exchanger effectiveness
- thermal losses from/to the surplus heat source and the substation

It is important to highlight that **combining the two components** mainly depends on the thermal demands of the end user, i.e., a heat pump is required only if the quality of the surplus heat is not high enough to meet the thermal demand of the end user. However, the substation will always be required to connect both sides of the surplus heat, i.e., the source and the sink (end user).

3.2 District heating network

DH networks are an efficient solution designed to meet the thermal demands of cities and/or clusters of buildings. The development of the supply temperature in DH network favors increased utilization of renewable heat and surplus heat sources, as shown in Figure 12. Thus, the temperature of the carrier has declined from > 100 °C for the first generation (1stG) down to < 60 °C for the 4thG. In the literature, 5th generation DH is also discussed, often referring to systems taking advantage of the synergy of combined heating and cooling in areas of mixed purpose buildings, and with supply temperatures below 40 °C [20].

In Norway, most existing DH networks are a mixture of 2nd and 3rd generation systems, although 4th generation systems are becoming relevant in new developments. Thus, this subsection discusses the possibilities of utilizing DC surplus heat in 2nd to 4th generation DH systems.
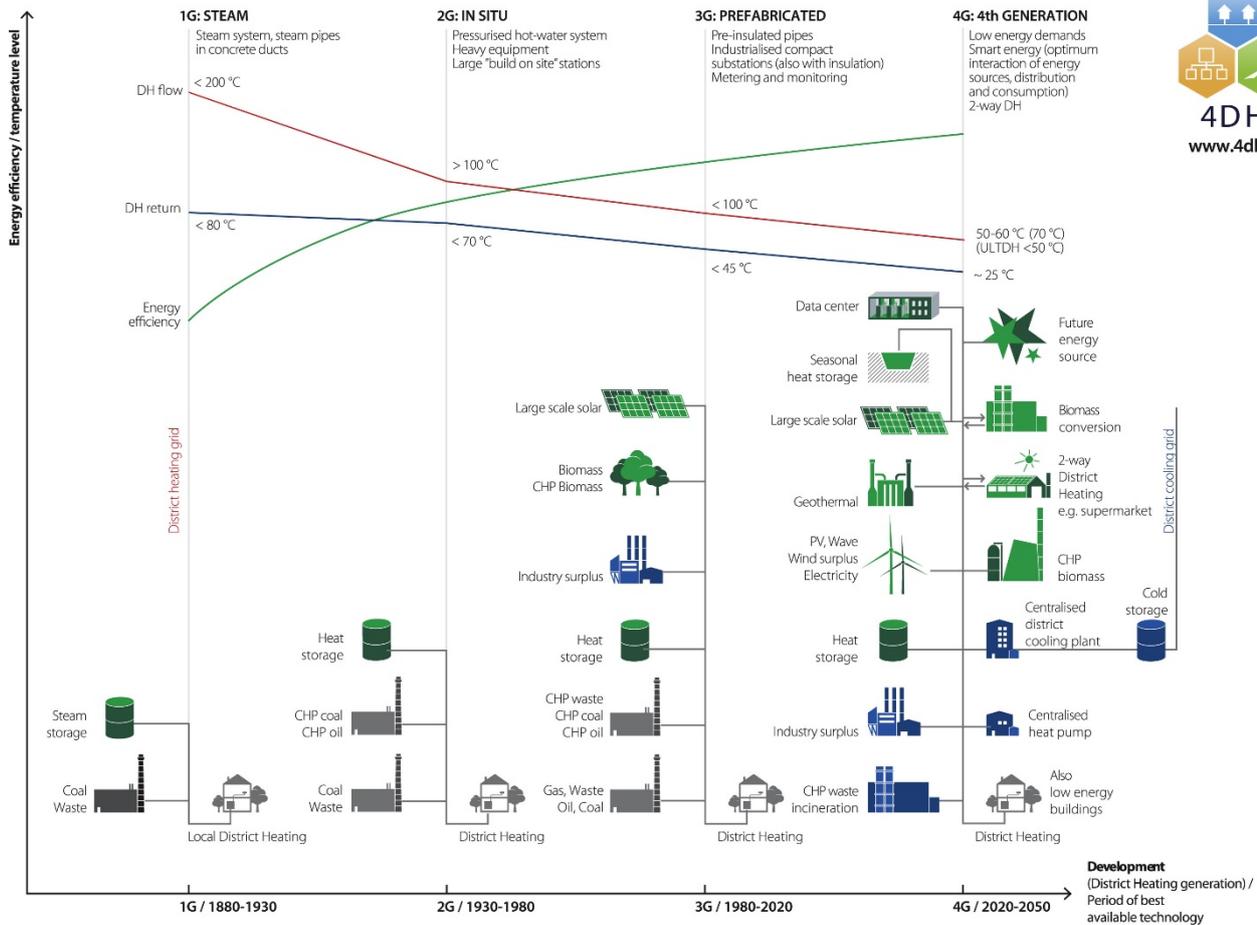
Figure 12. From the 1st to the 4th generation of DH [20]

3.2.1 2nd generation DH

The higher the end-user temperature requirements, the more complex the coupling system between the DC's surplus heat and the end user becomes. In this case, the district heating network operates with supply/return conditions of up to 120°C/90°C in the coldest periods.

A high-temperature heat pump (HTHP) system is required to connect the DC to the high-temperature DH network. HTHPs delivering temperatures at above 120 °C are not fully commercialized yet and will thus entail high investment and operation costs. A potential HTHP technology for this application is to use two refrigerants, butane and propane, in a cascade system where butane flows at the higher loop while propane is at the lower loop, illustrated in Figure 13. The DC cooling loop delivers heat to the evaporator of the propane heat pump ('4' in Figure 13), while the condenser of the propane heat pump delivers heat to the DH network ('2'). The dry cooler component, indicated by '6' in Figure 13, is used for heat dissipation when the district heating supply is not required or as a backup cooling system.

Cascade heat pump, in general, has some level of complexity compared to a single-stage heat pump. It requires a certain level of experience, a skilled supplier, and technical competencies to assemble the whole unit components correctly and synchronize the control and sequence of operating efficiently. SINTEF has contributed to developing the cascade propane-butane heat pump systems and can provide the required technical support to integrate it into different applications and end users successfully [21], [22].
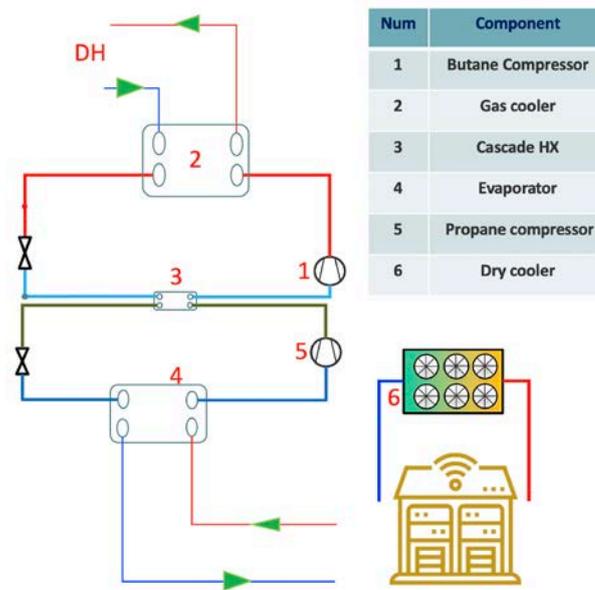
Figure 13. High-temperature (2nd generation) DH and data center surplus heat.

3.2.2 3rd generation DH

3rd generation DH networks are operated with typical supply/return conditions of 80-90°C/60°C. In this case, a single-stage heat pump system is sufficient to upgrade the DC's surplus heat (Figure 14). This will reduce both the investment costs and the electric input, thus the operational costs, significantly, compared to a two-stage system. For the heat pump technology, ammonia or butane could be applied as a clean yet energy-efficient refrigerant.
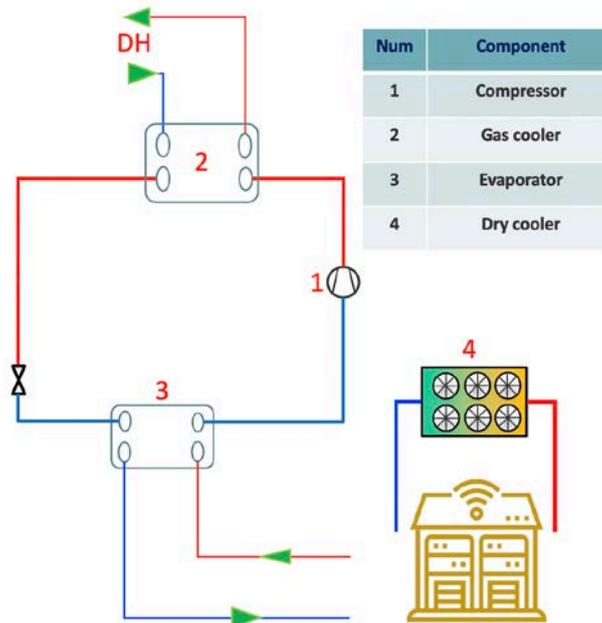
Figure 14. Data center surplus heat integration into 3rd generation DH

3.2.3 4th generation DH

In Norway, the application of 4th generation, low-temperature DH, is limited by the temperature regulations for domestic hot water (DHW) production. To hinder the growth of *Legionella,* temperatures at minimum of 60°C are required at the tapping point, and minimum 70 °C in hot water tanks [23]. Thus, the supply temperature in a DH network covering both space heating (SH) and DHW demand is limited to minimum 65 °C. However, if local booster units are applied for DHW production, supply temperatures down to 40 °C may be sufficient for buildings with floor heating [24].

Figure 15 shows possible configurations for the heat central and a customer substation in these two alternatives: 40 °C (LT) and 70 °C (MT) supply temperature. In the LT case, a heat pump for upgrading the surplus heat is not necessary, but local booster heat pumps are needed at the buildings for DHW production. Such a solution will probably have higher investment costs; however, a big advantage of the LT solution is lower peak power demand during the cold periods, as no heat pump is applied for covering the SH demands; that is, the heat pump electricity input is independent of the outdoor temperature [24].
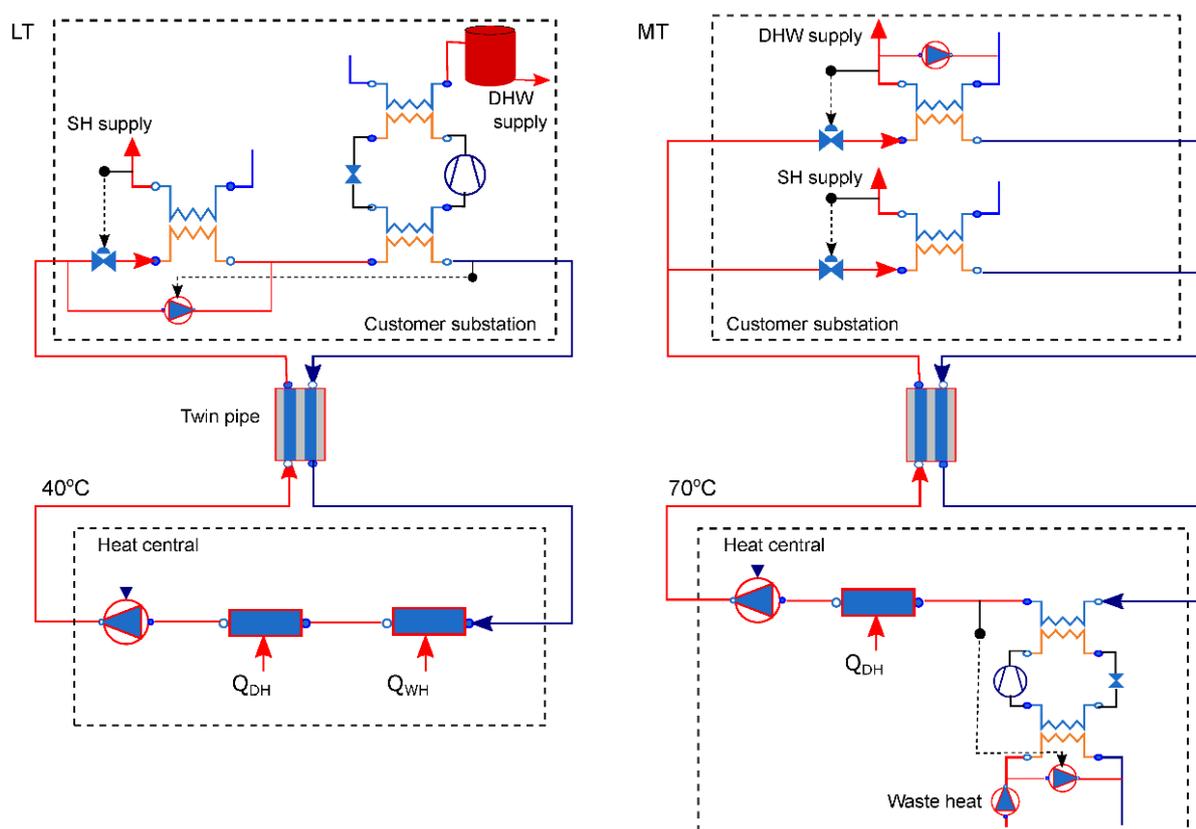

Figure 15. Possible configurations for a 4th generation DH network with surplus heat utilization**,** with two supply temperature alternatives: low (LT, 40°C) or medium (MT, 70°C) [24]. Q_{WH}: heat input from waste heat source. Q_{DH}: auxiliary heat supply from a high-temperature DH network.

3.3 Seafood farms

As the need for securing food production increases, more affordable and advanced energy-efficient production solutions are required. Utilizing the surplus heat from a DC at seafood farming is considered an excellent and sustainable end user for multiple reasons:

- Continuous low-grade heating demand all year which fits well with the all-year operation of the DC.
- Upgrading the temperature with a dedicated heat pump is not required, as the water temperature of seafood farms ranges between 12 to 30 °C. This range is considered very efficient for the direct cooling of the data servers, and, accordingly, direct surplus heat connection to the seafood farms.
- Seafood farms are often constructed near a reservoir or the sea which could be deployed as a free cooling system for a nearby DC.

Table 2 shows typical water temperatures for different types of seafood farming.

Table 2. Seafood farms water temperature

Seafood type	Water Temperature ˚C
Shrimps	29-30
Lobster	20-21
Trout	12-14

- **Normal operation**

The DC cooling will utilize the sea/lake water side to cool the servers, as shown in Figure 16. The seawater/ lake is connected to the DC servers for free cooling. The hot water leaving the servers is connected to each seafood farm via a substation of a heat exchanger and a modulating pump. The pump is controlled to maintain the supply temperature as per the design value.

| Num	Component
1	DC Pump
2	HX
3	Pump seafood circuit
4	Pump sea water
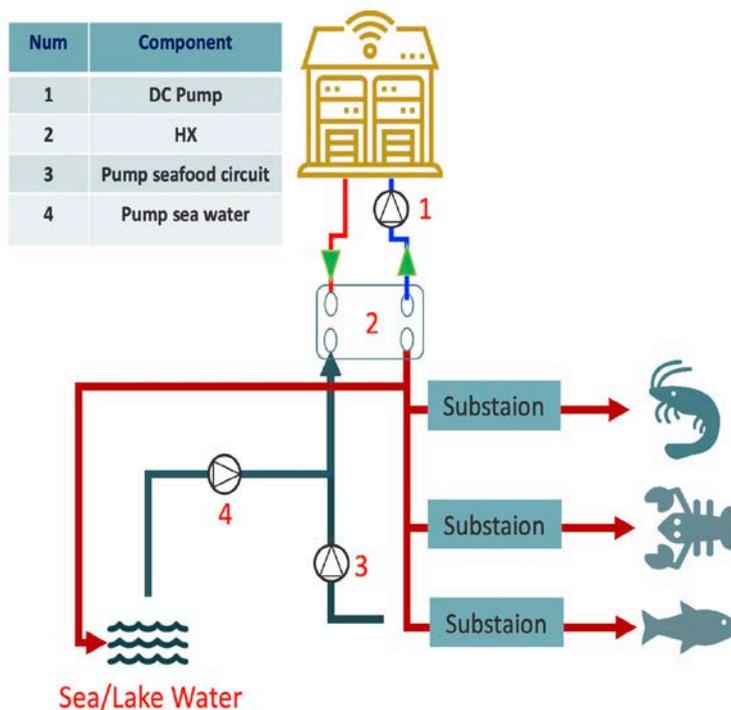
Figure 16. Seafood farms and DC surplus heat

- **Backup cooling**

Since the DC cooling system depends on the sustainable sea/lake as the free cooling source, a backup cooling system might not be required. However, a dry cooler could also be implemented for a higher security level.

- **Reuse of surplus heat percentage**

The reuse of surplus heat in the seafood farms case study could be estimated to 90 to 98% for the whole year operation.

3.4 Greenhouses and biogas plants

Greenhouses and biogas plants require heating throughout the year. The former's need is mainly for indoor temperature regulation while the latter needs for controlling the temperature of the biogas reactor and might require heating for sludge/digestate (residual product after biogas production) drying as well, depending on the type of the downstream process. Their heat demand varies depending on the climate conditions such as the temperature and precipitation, as well as the process conditions and the scale such as the reactor size and the greenhouse area. Integration of greenhouses and biogas systems have been investigated and applied in full-scale plants [25], [26]. The purpose of the integration is to increase the energy efficiency of the integrated system by utilizing surplus/low grade heat generated in the biogas powered combined heat-and-power (CHP) unit in the greenhouse, as well as using the carbon dioxide (mainly a mixture of methane and carbon dioxide) generated from the biogas production to enhance the plant growth in the greenhouses. Use of surplus heat from DC can thus be done separately in greenhouses and biogas plants as well as integrated system of these two.

a) Greenhouses

Greenhouses are complex systems whose size, shape and construction material, and their thermal systems can vary largely [27]. Energy costs, of which heating is a major component, and lighting account for about 30-40% of the total production costs of Norwegian greenhouse production [28], [29]. Table 3 summarizes the temperature required for diverse crops.

Table 3. Crops air temperature

Crop	Temperature ˚C
Tomato	19-22
Cucumber	20-25
Avocado	23-29
Flowers	15

Multiple considerations need to be examined regarding the heating of greenhouses and the control of their indoor climate. First, assuming an operation temperature of 50-60 °C of the water-cooled system of the DC servers, a hot water delivery at 45-50 ˚C is expected for the greenhouse. This is the return temperature of the coolant distribution unit (CDU), serving as the middle-man and exchanging heat between the liquid coolant and the hot water pipes [6]. For heating of the greenhouse, the direct use of the DC surplus heat at 45-50 ˚C is feasible and will normally, dependent on the piping system, cover 70 to 90% of the total power requirement. This implies, however, that an upgrade or back-up system is needed to cover the intermittent peak load demands. In this regard, an upgrade to a heat pump system that can deliver 70-80 ˚C is a viable

solution to deliver sufficient heat in colder periods of the year. Other possibilities are to use gas or electric boilers to cover the peak loads.

In general terms, the needed amount of pipes is higher for pipe temperatures at 45-50 °C compared to 70-80 ˚C. This must be especially considered in a greenhouse since the plants need sunlight and higher amounts of pipes cast more shadows in the greenhouse. With a pipe temperature at 45-50 °C, there is also higher investment costs due to the increased need for pipe lengths and higher surface area for heat transfer. To visualize this, we apply the heat transfer formula

$$Q = hA\Delta T,$$

where Q [W] is the transferred heat, h [W/m$^2\cdot$K] is the heat transfer coefficient, A [m^2] is the surface area where the heat transfer takes place, and ΔT [K] is the temperature difference between the hot and cold side. Assuming a hot water delivery to the greenhouse at 45 °C and 75 °C for two different cases, and a 10 K temperature drop in the greenhouse pipes, the average pipe temperature becomes 40 °C and 70 °C, respectively. Assuming also a greenhouse air temperature of 25 °C in this example, we obtain a temperature difference ΔT = 15 K and ΔT = 45 K, respectively, for the two cases. This shows that the surface area A, i.e., the amount of hot water pipes in the greenhouse, must be 3 times higher when the hot water delivery is at 45 °C compared to 75 °C in order to transfer the same amount of heat Q to the greenhouse.

Another concern for greenhouses in Norway is the need to melt the snow on the greenhouse roofs after snowfalls. Snow on the greenhouse roofs will block the sunlight and can be detrimental not just to the greenhouse crop but can also destroy the greenhouse itself. Although the need for snow melting is smaller in Rogaland than at many other locations in Norway, there is a periodic need for this, and it is crucial to get rid of the snow as quickly as possible when snow falls occur. In new and modern greenhouses, high-temperature pipes at 70-80 ˚C are often installed just beneath the greenhouse roof precisely to be able to melt the falling snow. Such pipes have smaller diameters than those used for temperatures at 45-50 °C, i.e., they have a larger relative surface (compared to their diameter) and therefore let more sunlight through. Additional piping for 45-50 ˚C can then be limited to the ground level of the greenhouse where the piping does not block the sunlight.

Overall, a high-temperature piping system at 70-80 °C is recommended, at least as part of the heating system in a greenhouse, to normalize the air temperature over the entire greenhouse and secure a homogenous temperature as possible everywhere [30]-[32]. An upgrade of DC surplus heat at 45-50 °C to 70-80 °C, using heat pumps, is a flexible and efficient solution that safeguards against extreme weather conditions such as very cold weather and snowfalls.

In addition, heat pumps can be reversed and be used to provide cooling to the greenhouse when this is needed. Since greenhouses are highly efficient collectors of solar energy, the maximum cooling load in a greenhouse is generally much higher than the corresponding heating load in southern parts of Norway [33]. An integrated heat pump system for greenhouses therefore can provide both heating and cooling as needed to control the indoor greenhouse climate.

b) Biogas plants

Biogas is produced through anaerobic digestion that is biological degradation of organic material in the absence of oxygen. Biogas is a mixture of mainly CO_2 and methane (CH_4) with trace amounts of hydrogen sulphide (H_2S) and water. Upon gas upgrading, CH_4 can be obtained with high purity (>99 vol.%) that has the same properties as fossil natural gas. When it is produced from renewable sources, the biogas is considered carbon neutral. Municipal solid waste, water treatment sludge, manure, agricultural wastes, and crops are

the main feedstocks used for biogas production. Biogas can be utilized in the same ways as that of fossil natural gas such as heat and power generation using gas turbines or running vehicles. The former has an advantage of lower noise and emissions when used in buses, for example as discussed in [34].

Biogas plants require heat for temperature control of anaerobic digestion process that varies between and 25 °C and 65 °C depending on the type of the feedstock, reactor type and other process parameters [35]. The biogas production rate declines in cold weather in winter due to deviation from the optimal temperature when the production is done in a landfill where the system is in more contact with the outer environment instead of a closed reactor. Biogas production has a co-product called digestate or sludge that is remaining in the reactor after the feedstock is exhausted during anaerobic digestion. Digestate can be used as fertilizer or solid enhancer due to its rich nutrients content. This can be done directly or after further treatment in the downstream process which often consists of dewatering and/or drying with additional use of polymers for stabilization. In case of thermal drying of the digestate, the biogas plant heat requirement is higher. Thus, the temperature of the drying air can vary from 100 to 180 °C [36]. Therefore, heat requirement of biogas plants has seasonal variations due to the changing ambient conditions.

- **Normal operation**

A heat pump is required to upgrade the surplus heat to higher temperatures that suit the nature of the greenhouse and biogas plant heating system. However, integrating a thermal energy storage tank in the case of the greenhouse end user, as shown in Figure 17, could enhance the energy performance of the system, especially during the night hours operation where outside temperature is lower, thus heat demand is higher.

Connecting the DC surplus heat to both end users is executed using a single-stage heat pump which acts as an upgrader. The DC servers are connected to the chilled water leaving the heat pump evaporator. At the same time, the condenser/gas cooler is connected to both the greenhouse hot water tank and the biogas plant through a substation.

- **Backup cooling system**

A combined greenhouse and biogas plant increases the energy efficiency of the integrated system and has the advantage of providing CO_2 for the greenhouse plants. To level out any mismatch between the continuous yearly operation and the seasonal heating demands of a greenhouse/biogas plant, dry coolers can also be considered as a backup cooling system.
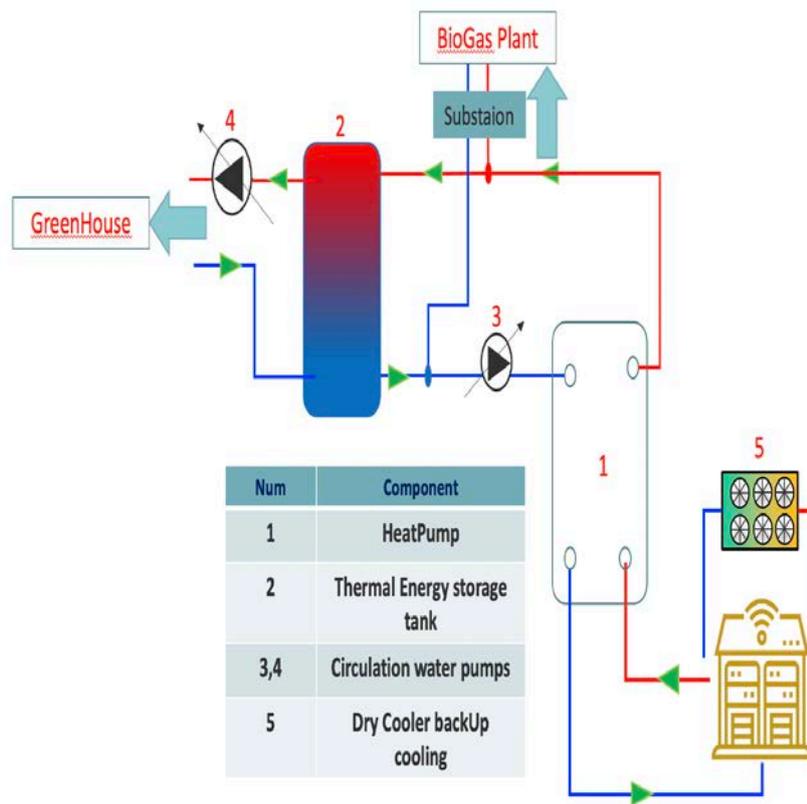
Figure 17. Greenhouse/biogas plant and DC's surplus heat

- **Reuse of surplus heat percentage**

Reuse of surplus heat could reach 75 to 80% for the whole year of operation after combing the two end users, depending on the capability of the biogas plant to handle the extra heat during the summer season.

4 Summary and recommendations

The importance of connecting the surplus heat of DCs to different end users is becoming more and more of a necessity due to its environmental, economic, and societal positive impacts. Achieving an efficient connection is governed by the type of end user and its location, yearly heating demand profile, and temperature requirements.

Choosing the most appropriate cooling technology is an important step in improving the possibilities for surplus heat utilization. In this respect, liquid cooling enables significantly higher surplus heat temperatures compared to air cooling and should be preferred in applications where surplus heat utilization is relevant.

Table 4 summarizes different end-user groups and the conditions for utilization of DC surplus heat. The required input of electricity increases with increasing temperature requirement, and so does the investment costs for heat upgrading equipment. The lowest total costs are obtained for end users that do not require heat upgrade with a heat pump. These end users include seafood farming, biomass fermentation, and possibly low-temperature (4th generation) district heating and greenhouses.

Table 4. DC surplus heat utilization possibilities

End user	Temperature requirement		Conditions for utilization
District heating	2nd generation	>100 °C	Requires upgrading with high-temperature heat pump.
	3rd generation	80-90 °C	Requires upgrading (1-stage heat pump)
	4th generation	40-70 °C	May be possible without upgrading but will require boosters for hot water production.
Seafood Farming	14-30 °C		No heat upgrade required
Greenhouse	45-50 ˚C in normal operation		Heat upgrade not required for normal operation but will require boilers or heat pumps to cover peak loads
	70-80 ˚C to cover extremes		
Bio-Gas plant:			
o Fermentation	25 – 65 °C		May be possible without heat upgrade
o Sludge dryer	100-180 °C		Heat upgrading required

To optimize the integration between DC operators and different end users, the following recommendations are made:

1) Combining a group of diverse end users may be the preferred solution to overcome any mismatch between the surplus heat from DCs and the thermal demands of end users.
2) Utilizing DC surplus heat towards heating of buildings through DH is a socio-economically beneficial solution as it reduces the use of other (fossil or electric) heat sources. To improve the possibilities for such symbiotic solutions, DCs should, where possible, be placed nearby densely populated areas.
3) Seafood farming has the lowest temperature requirement and a continuous heat demand, matching well with the continuous cooling demand DCs. Seafood farming can therefore be considered as a most suitable end user option for DC excess heat that do not require very high investment costs.
4) For greenhouses, a high-temperature piping system at 70-80 °C is recommended to safeguard against cold weather conditions and snowfalls. An upgrade of DC surplus heat at 45-50 °C using heat pumps is a renewable and energy-efficient solution. Heat pumps can also be reversed and provide cooling to greenhouses.
5) The type of DC cooling system has a strong impact on the quality of the surplus heat and the DC energy consumption. High rack density of DCs may require liquid cooling which gives higher surplus heat temperatures and reduces the area footprint of the data center.

Nomenclature

COP	Coefficient of performance
CPU	Central processing unit
CDU	Cooling distribution unit
DC	Data center
DH	District heating
PUE	Power usage effectiveness
TES	Thermal energy storage
TBS	Telecommunication base station

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