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The role of data centres in the future Danish energy system

Stefan Petrović,[1*] Alessandro Colangelo,[2] Olexandr Balyk,[1] Chiara Delmastro,[2] Maurizio Gargiulo,[3] Mikkel Bosack Simonsen,[1] Kenneth Karlsson[1]

[1] Department of Management Engineering, Technical University of Denmark, Kongens Lyngby, Denmark

[2] DENERG: Energy Department, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Turin, Italy

[3] E4SMA, Via Livorno 60, 10144 Turin, Italy

[*]Corresponding author: e-mail stpet@dtu.dk

Abstract

Data centres (DCs) are expected to satisfy the rising demand for internet services. Denmark alone is expected to host several large-scale DCs, whose demand for electricity in 2040 may reach 33% of 2017 national electricity consumption. Understanding the operation and interactions of DCs with energy systems is key to understanding their impacts on installed capacities, costs and emissions. The present paper makes three contributions in this regard. First, we introduce a thermodynamic model that relates the power consumption of DCs to their production of excess heat (EH). Second, the results are scaled up to represent DCs in a national energy-system model for the analysis of different scenarios. Third, scenarios are generated and analysed to quantify the impact of DCs on the Danish energy system until 2050. The results show that DCs might have significant impacts on Denmark's power and district heating (DH) sectors. First, the power demand from DCs translates into an additional 3-6 GW of offshore wind capacity. Second, EH from DCs is beneficial to the whole energy system, the entire quantity of EH being utilized in four out of five scenarios. EH recovery from DCs is economically beneficial, providing from 4% to 27% of Denmark's DH after 2040.

Keywords: Power demand, excess heat, carbon budget, district heating, TIMES-DK, energy-system analysis

Abbreviations

DC	Data centre	PV	Photovoltaic
DH	District heating	CB	Carbon budget
EH	Excess heat	FP	Frozen Policy
IT	Information Technology	PSO	Public service obligation
CHP	Combined Heat and Power	HP	Heat pump
DKE	East Denmark	O&M	Operation and Maintenance
DKW	West Denmark	COP	Coefficient of Performance

1 Introduction

The electricity demand generated by global data centres (DCs) has been estimated at around 194 TWh, corresponding roughly to 1% of global final demand for electricity in 2014 [1]. However, this demand is expected to double every five years due to increasing digitalization [2]. DCs work around the clock and are highly energy-intensive, requiring energy to power both information technology (IT) equipment (servers, network ports, storage disks) and the supporting infrastructure (mainly cooling systems). The annual power consumption of DCs is therefore influenced by several factors, which can be summarized in terms of the quality and operating conditions of their IT equipment and cooling systems. Most current research focuses either on energy-efficient design or on exploring ways of reducing energy demand. A wide variety of models for abstracting the total power consumption of single facilities has therefore become available in the literature, as shown below.

The power demand generated by DCs is highly variable. Early benchmark studies calculated the power densities of different facilities at values of from 54 to 1000 W/m^2 [3]. More recently, Avgerinou et al. [4] showed that the average size of a DC in Europe is around 2 MW, while a comprehensive study by COWI [5] predicts that in the future DCs in Denmark will each require up to 150 MW per facility. In addition, it has been estimated that on average up to half of the total energy consumption of DCs may be attributable to cooling [6,7], even though the most recent large-scale facilities are able to reduce their overheads for non-computing purposes to between 12% and 10% [8,9] of the total power demand.

Consequently, the power demand of DCs is dependent on external weather conditions and therefore on their geographical location. An effective way to reduce their power consumption is to locate them in cold regions in order to exploit external air for cooling purposes (so-called “free-cooling” strategies) instead of using energy-intensive chiller plants. In this context, north European countries such as Denmark occupy a strategic position for the construction of new DCs. Most more recent research has sought to identify efficient cooling strategies, as they are essential if the energy demand of DCs is to be reduced. For instance, Ham et al. [10] created a model for a modular DC in Seoul with the purpose of capturing the interaction between the servers’ heat dissipation and the cooling system’s operating conditions in different configurations. Similarly, Depoorter et al. [11] created a model for coupling the server’s power consumption and heat dissipation with a specific free-cooling strategy in a sample facility located in various European cities. Gozcu et al. [12] instead simulated the annual power consumption of four different free-cooling strategies in several places around the world, but did so by disregarding the modelling of the heat dissipated by the information technology (IT) equipment by assuming it to be equal to the absorbed power. A further methodology was presented by Pelley et al. [13], who proposed a parametric model for abstracting the total power demand of a DC and then analysed different efficiency scenarios involving both optimal cooling and IT equipment management. Besides these facility-oriented approaches, there have been attempts to estimate the overall electricity consumption of DCs in specific countries. Koomey [14] was the first to combine data on the shipping of IT equipment to the US and the rest of the world with a model for calculating the equipment’s average power consumption, which enabled estimates of the overall annual electricity demand of DCs in the US and worldwide. Later, Koomey [15] updated these results and estimated annual electricity demand of

DCs in other regions of the world (Western Europe, Japan, Asia Pacific). This methodology has also been applied by Stobbe et al. [16] in Germany and Shehabi et al. [17] in the U.S.

Data about the shipping of IT equipment are not easy to obtain, and their projections are limited to a maximum five years ahead, thus making long-term analyses difficult. Moreover, except for the efforts made by Depoorter et al. [11] to investigate the power production mix at the locations chosen for their simulations, little attention has been paid to assessing the impact of DC's increasing energy demand on regional energy systems. A larger diffusion of DCs may influence the mix of power-generating technologies deployed in an energy system.

Denmark represents a relevant location for DCs, as it has a relatively cold climate, developed DH grids and a large share of renewables. The cold climate provides cheaper cooling, developed DH grids make it possible to exploit EH, while a larger share of renewables in Denmark's energy mix is often desired by the owners of DCs in order to maintain a positive public image.[1] Denmark has also seized this economic opportunity by facilitating investments in DCs, as demonstrated by the gradual abolition of the Public Service Obligation (PSO) tax on electricity consumption [19]. However, this choice may result in a significant burden for the Danish energy system and may affect its transition towards carbon neutrality. In 2015 electricity demand in the Danish IT sector amounted to 0.5% of national electricity consumption [20]. Energinet [21] and COWI [5] estimate that this will increase from 8% to 33% when the potential development of DCs up to 2040 is considered. On the other hand, excess heat (EH) from DCs may represent an interesting alternative source for DH production [22].

Most of the research on DCs focuses either on facility-oriented approaches (energy-efficient design, efficient cooling strategies) or on overall electricity consumption by DCs for wider geographical regions. We have not identified any research analysing DCs from an energy-system perspective. Within energy-system models, DCs are usually covered by aggregated sectoral demand projections. In this paper we have therefore analysed the long-term double role of data centres within the Danish energy system, that is, as electricity consumers and as providers of EH for DH. However, the methods we present are general and can be applied to any national energy system worldwide, while the results could be relevant for countries with colder climates and at least partly developed DH grids. The novelty of this work lies in its combination of two modelling approaches to analyse the broader relationship between the deployment of DCs and long-term energy-system strategies in terms of the required investments, energy production and emissions. The methodology has three steps: (i) a thermodynamic model that relates the power consumption of DCs to their EH production, (ii) explicit representation of DCs in a national energy system model, and (iii) scenario analysis to quantify the impact of DCs on Denmark's future energy system until 2050.

The paper is structured as follows. Section 2 briefly describes the main characteristics of the TIMES-DK model, the thermodynamic model of DCs and an innovative methodology for introducing the DCs within TIMES-DK. Section 3 describes the scenarios being analysed. Section 4 presents the results of the energy-system analyses. The results of the sensitivity analysis are presented in Section 5. The results are discussed in Section 6. Finally, conclusions are drawn in Section 7.

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[1] In their respective sustainability reports, Google, Facebook and Apple clearly state their willingness to buy renewable energy in order to reduce their environmental impact [8,9,18].

2 Methodology

This section describes a methodology for incorporating DCs into an energy-system model, in this application into TIMES-DK, a bottom-up engineering model of the Danish energy system [23]. Besides the general advantages of technologically rich bottom-up models, the main reasons for choosing TIMES-DK is that it has been developed by several of the authors of the present paper, while the other authors have extensive experience in using other models from the TIMES family. Furthermore, the model covers all the sectors of the Danish energy system, so it has the right properties for understanding the impact of DCs on the broader Danish energy system. In the framework of an energy system, DCs are located on the demand side, as a part of industrial sector (Figure 1). This choice is driven by the fact that they consume substantial amounts of electricity per facility but may also produce heat for DH networks.

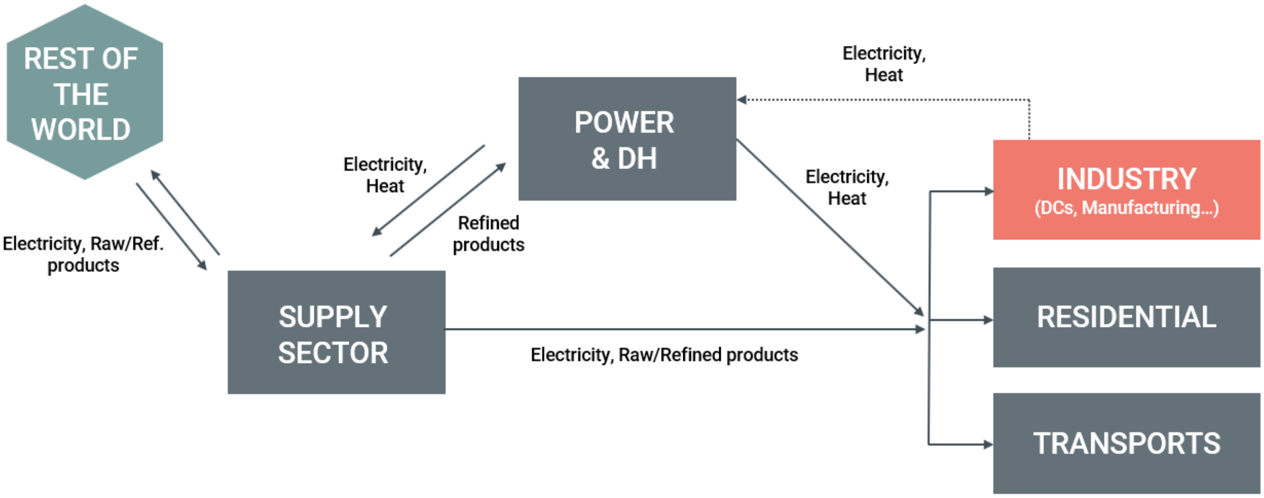

Figure 1. DCs on the demand side of the energy system.

In addition to the TIMES-DK model of the Danish energy system, a thermodynamic model is used in this study to identify the key features of DCs for subsequent implementation in TIMES-DK. Lastly, a scenario analysis is developed covering several development paths for DCs in Denmark.

Section 2.1 gives a brief description of TIMES-DK, while Sections 2.2 and 2.3 focus on the modelling of DCs. The scenarios we have analysed and their basic assumptions are presented in Section 3.

2.1 TIMES-DK

As already noted, to analyse the role of DCs in the future Danish energy system, we have applied the TIMES-DK model. A short description of this model is based on a model's description article [23] and recent applications [24–26] analysing the competition between heat savings, district heating expansion and individual heating options in the Danish energy system until 2050. [26] proposes a new methodology for endogenous modal shifts in TIMES energy-system models in which travel time budgets and infrastructure requirements regulate the shift. TIMES-DK, as a member of the family of TIMES energy-system optimization models [27,28], assumes the role of the central energy planner who makes decisions on behalf of the average consumer with full information and perfect rationality in order to maximize the system's economic utility. It is a multi-regional model covering the entire Danish energy system, from the extraction, import and export of primary energy commodities in the supply sector through the conversion sectors to fulfil the energy-service demands of the end-use sectors. The model is represented by five sectors, namely supply, power and DH, industry, residential and transport. It is geographically aggregated into the regions of East (DKE) and West (DKW) Denmark, with technological and economic projections until 2050. The two regions are connected with power transmission lines to each other and to neighbouring countries, the latter being represented by projections of power transmission capacities and electricity prices.

DH producers in Denmark, as in the model, are characterized as Central or Decentral, as are the DH areas supplied by these producers. Central DH areas are located in the bigger cities and have higher installed capacities, more consumers and higher grid efficiency compared to Decentral areas.

The time horizon covers the years 2010–2050 and is sub-divided into shorter periods of varying durations, usually of five years. Every year comprises 32 non-sequential time slices representing four seasons (to represent changes in heating demand), weekly variations (working/non-working days, to represent the difference in demand patterns) and four categories critical for the power system:

A) “high wind production, low power demand”,
B) “high power demand, low wind production”,
C) “no photovoltaics (PV) production” and
D) “other”.

The definition of the time slices ensures that the model invests in sufficient back-up capacity to ensure supply at any time.

2.2 DC modelling

Ways of estimating the electricity demand of DCs have been adopted from a reference study [5]. To assess the temporal profiles of electricity demand and EH, as well as EH temperature levels, we apply a dedicated thermodynamic model of DCs. This section describes the thermodynamic model for cooling systems of DCs and its major assumptions, as well as its significant inputs and outputs.

The working principle of DCs is simple from an energy-system perspective. The IT equipment extracts electricity from the grid and releases heat, which is then removed from the facility through the cooling system. External weather conditions and the IT equipment's workload profile influence the overall electricity consumption. The former affects both the amount of outdoor air flowing through the fans (when free-cooling strategies are adopted) and the COP of chiller plants, while the latter directly influences the power withdrawal and heat dissipation of the IT equipment. A schematic view of the adopted concept is presented in Figure 2, based on [11].

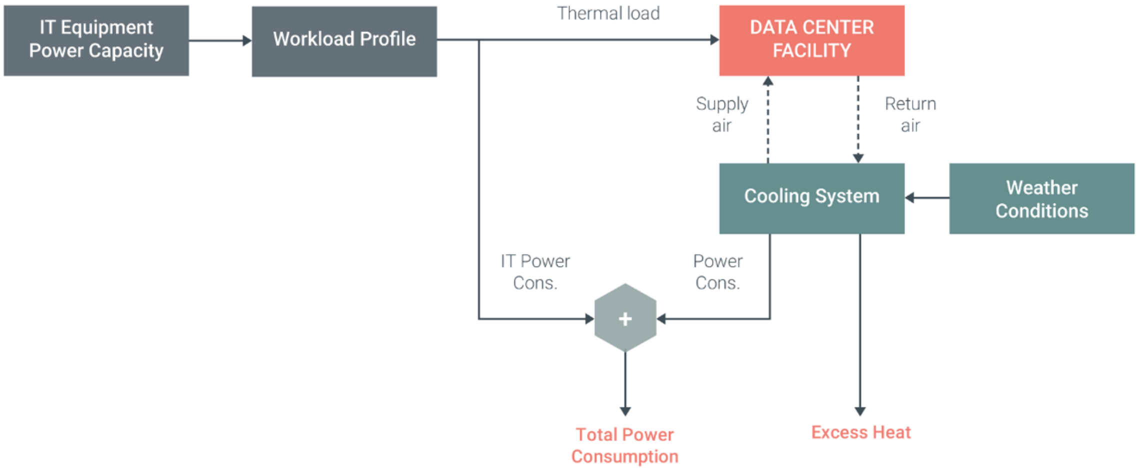

Figure 2. Schematic representation of DCs power consumption and EH production.

Depending on their purpose, DCs may have different dimensions and configurations. However, a modular structure is quite common, as it improves the overall efficiency [29]. Therefore, this study considers a single submodule (data hall) for abstracting the behaviour of the entire DC.

Another assumption concerns the IT equipment of the data hall. IT equipment is not divided into components, but is represented as a single entity characterized by the overall power demand. This choice is due to the well-known uncertainties in the configuration of data halls. Nevertheless, modelling the IT equipment as a single entity is still relevant, particularly in respect of its interaction with the cooling system. Another important assumption regards estimating the thermal load, which is considered equal to the amount of power consumed by the IT equipment, as suggested in [11,30]. This hypothesis also suggests that a thorough description of the IT equipment is unnecessary for this study. In addition, as the facility's internal heat production is predominant, heat transfer through the building envelope is disregarded [11]. Finally, since the majority of future DCs will be designed to provide internet services to European customers, variable daily workload profiles are assumed, as indicated in [31].

To summarize, the assumptions regarding the thermodynamic model of DCs are listed below:

- Perfect scalability: the behaviour of a single data hall is representative of a whole large DC;
- The IT equipment is treated as a unique entity and is not divided into components;
- All the power consumed by the IT equipment is converted into heat;
- Heat losses through the building envelope are negligible compared to internal heat production;
- Variable daily workload profiles responding to web requests are assumed [31].

The thermodynamic model provides the electricity demand of DCs and available EH (as a fraction of DCs' electricity demand) to TIMES-DK. The outputs from the model are characterized by hourly resolutions and are aggregated at the time-slice level before being fed to TIMES-DK. The thermodynamic model allows hourly variations in the power consumed by the cooling system and the available EH to be estimated during a reference year depending on the workload profile and the external weather conditions. It is based on previous work [11,30,31] and well-known thermodynamic equations. The procedure for estimating power consumption and EH production is summarized below.

The temperature increase in the cooling air flowing through the IT equipment is fixed at 15°C [11]. The hourly heat load is calculated by combining the size of the sample data hall (4 MW, adopted from [32]) and the assumed workload profile. Consequently, the airflow to be recirculated inside the data hall and the power consumption of the dedicated fans are calculated. This airflow can be cooled to the supply conditions (20°C [31]) in two ways depending on external temperature. Outdoor air temperatures below 17°C [11] are sufficient for indirect cooling of the air inside the data hall through a heat exchanger ("free-cooling" mode). In this case, a consistent flow of external air is extracted, and the power consumption of its dedicated fans is calculated. As the power consumption is proportional to the volume of processed air, it is minimal at small amounts of external air, i.e. at lower temperatures. Conversely, when the outdoor air temperature is above 17°C, a chiller cools the air inside the data hall using a constant flow rate of external air as a thermal sink. Its power consumption is calculated assuming a variable COP, as in [11]. The available EH is obtained assuming that the exhaust flow of outdoor air at an average yearly temperature of 31 °C can be cooled to 20°C before being rejected into the environment. Finally, the rejected heat is upgraded to supply DH through heat pumps. It is assumed that the DH supply temperature will fall from 80°C in 2015 to 60°C in 2050 [33]. As a result, the COP of HPs is assumed to improve from 4.4 in 2015 to 7.4 in 2050 [33]. The results of the thermodynamic model for a reference year are reported in Figures 3 and 4.

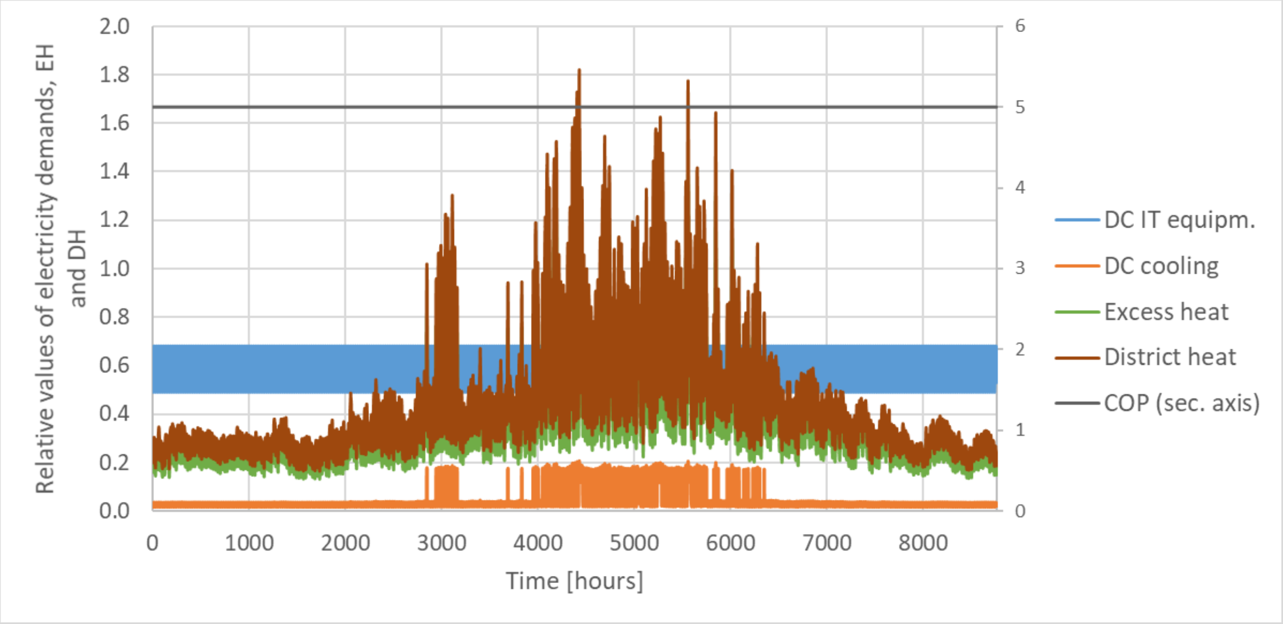

Figure 3. Electricity demand of IT equipment, cooling equipment, EH and DH relative to the maximum potential hourly electricity consumption of the IT equipment.

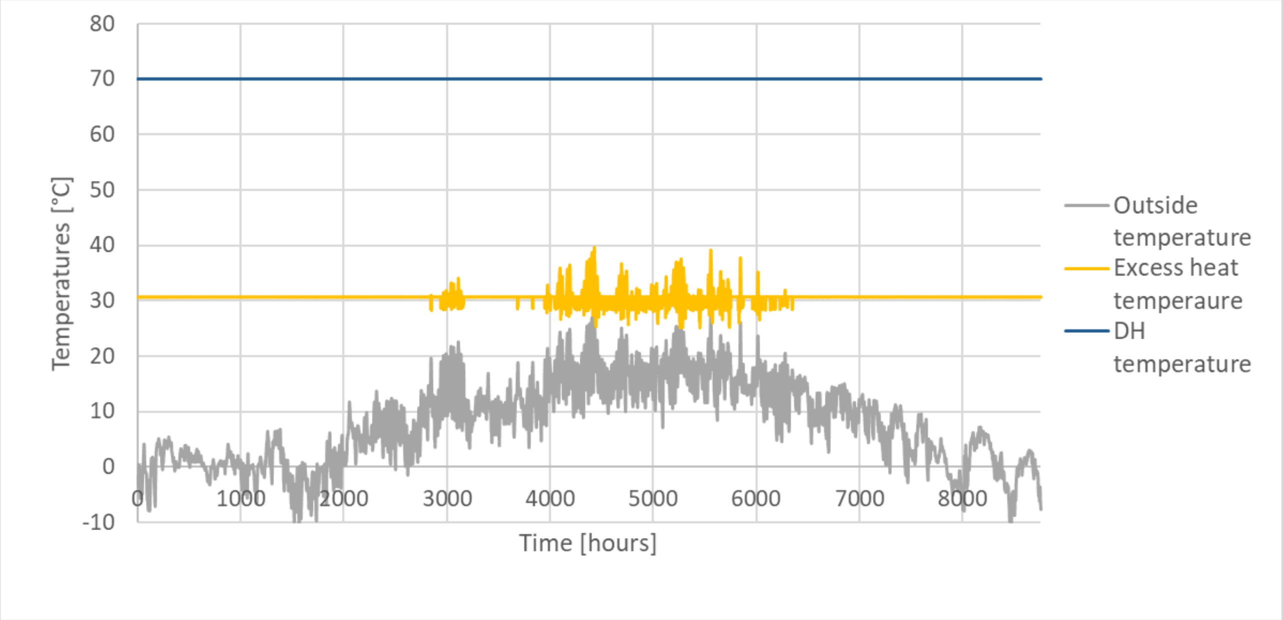

Figure 4. Outdoor, EH and DH temperatures in the reference year.

2.3 Data centres in TIMES-DK

In TIMES-DK, the DCs are treated as a demand technology, that is, they demand electricity from the power grid to run IT equipment and cooling systems. The electricity demand of the IT equipment is defined exogenously, while the demand of the cooling system is expressed as a fraction of that demand. The projection of the IT equipment's electricity demand until 2040 is derived from [5]. Furthermore, low-temperature (25-40 °C) EH, another output of DCs, can be injected into the DH network if investments are made in heat exchangers and HPs. Industrial EH was already part of the TIMES-DK model, its lowest temperature being 40°C [34]. Figure 5 represents the DCs and their connections with the rest of TIMES-DK.

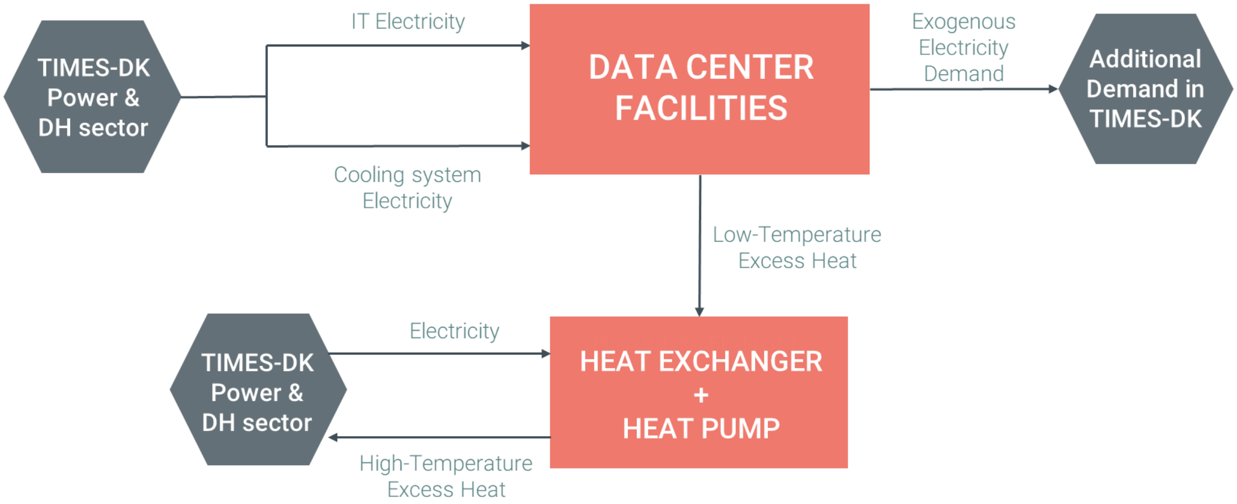

Figure 5. Schematic representation of DCs in the TIMES-DK Reference Energy System.

The DCs are not characterized by economic parameters, as these facilities are exogenously introduced into the energy system. This is because for business purposes DCs are considered to be outside the system boundary. Heat exchangers and HPs are described by techno-economic parameters [33] in order to understand whether EH recovery from DCs is convenient from an energy-system perspective. Taxes are not associated with the EH that is injected in the DH grid since governmental policies have not foreseen this so far.

To capture the interaction of DCs with the Danish energy system, electricity demand and EH production (estimated by the thermodynamic model) are included in TIMES-DK at the time-slice level. The time-sliced electricity demand of IT equipment depends on both the assumed hourly workload profile and the length of the time-slice. The electricity consumption of the cooling systems and EH production are affected by the external weather conditions. The electricity consumption of the cooling systems spikes at about 20% of the IT equipment's power consumption in the summer months, when the chiller is mostly operative. EH production is also at its maximum in the summer because exhaust temperatures and cooling airflows are higher relative to the other months.

3 Analysed scenarios

Two scenarios have been compared in the present analysis:

1. The Frozen Policy (FP) scenario represents the expected development of the energy system, assuming that no new policies are introduced from today. Since, with regard to national energy and climate policy, as well as subsidies, tariffs and taxes, the FP scenario assumes that policies will be frozen, it does not necessarily represent a "best guess" of how things will develop. The scenario assumes that specific projects that have already been launched will be completed, such as the conversion of power plants from coal to biomass.
2. The Carbon Budget (CB) scenario assumes with 66% confidence that the development of Denmark's energy system will be constrained by a carbon budget corresponding to a global temperature rise of 2^{o}C. The carbon budget is based on population ('equity') and emissions ('inertia') and has been adopted from [35]. We have chosen the CB scenario over the current Danish goal of being fossil fuel-free by 2050 for two reasons. First, the CB scenario is aligned with the Paris agreement, whereas the Danish 2050 target is not. Second, the CB scenario shows the importance of achieving emissions reductions sooner rather than later, i.e. while still on the pathway to 2050, while Denmark's 2050 target focuses only on the year 2050. Subsidies, tariffs and taxes are also included in this scenario.

The results of the FP scenario suggest the optimal investment in and operation of Denmark's energy system until 2050 under existing (frozen) policies, which are allowed to expire, i.e. they are included until the date of their expiry. The role of DCs is obtained alongside the optimal solution. The comparison between the scenarios shows how the role of the DCs will change from a moderately ambitious scenario (FP) to a strict carbon budget (CB) scenario. In both scenarios the electricity demand of the DCs is based on the "linear growth" scenario taken from [5]. The number of DCs grows linearly until 2040, when there will be nine DCs in Denmark.

The background to the "linear growth" scenario is that the basic framework conditions for DCs in Denmark continue to develop in favour of the establishment of DCs in terms of political environment, cost level, ease of doing business, energy supply, etc. In this scenario, Denmark maintains a relatively high share of Europe's DCs. In addition, it is assumed that data rates grow faster than DC efficiency, alternative data storage facilities and processing technologies.

Since the number of DCs and consequently their electricity demand and available EH are uncertain, we have adopted three "sensitivity" scenarios characterized by different developments of DCs in Denmark [5]:

- LowDC. Although global and European market share of new DCs is maintained, Denmark's market share falls to zero. After the establishment of two DCs by 2020, no more DCs will be set up. This kind of development could result from Denmark becoming attractive relative to other European countries because of its international fibre connections, smoother treatment from the authorities and sustainable energy supply or general upgrading of the power supply, with greater security of supply as a result.
- DisDC. Disruptive development and efficiency improvements in the DC market. Five DCs will be established by 2027, after which no more will be set up. The power consumption of the DCs decreases because the efficiency of the servers increases. The disruption scenario describes a situation in which technological advances in data storage and distribution develop faster than the number of DCs. Therefore, in this scenario, it is assumed that power consumption per module falls to one third in 2023-2027. This development can be expected, but the speed of technological development is difficult to predict.
- HighDC. High (exponential) growth in the number of DCs and continued high Danish market share are assumed. The number of DCs rises during the period of the analysis until 2040, when there are 22 DCs in Denmark. The HighDC scenario is based on the assumption that the basic framework conditions for DCs in Denmark continue to develop in favour of their establishment with regard to political environment, cost level, ease of doing business, energy supply etc.

4 Results

Electricity and DH production, together with their associated production costs, are presented in sections 4.1 and 4.2 respectively, CO_2 emissions in section 4.3, and the costs of power and DH systems in section 4.4.

4.1 Electricity production

The development of electricity production in the CB and FP scenarios until 2050 are presented in Figure 6. The scenarios are very similar, the only significant difference being electricity production from offshore wind at the end of the analysed period. First, the similarity between the scenarios comes from the declining costs of renewable energy technologies. Second, favourable renewable energy policies in the FP scenario and the cumulative carbon budget in the CB scenario have similar effects. On the other hand, the cumulative carbon budget in the CB scenario acts as a very strict constraint close to 2050.

At the beginning of the analysed period, over 75% of electricity is produced from CHPs, over 60% from coal-based CHPs, while the rest is produced from natural gas and biomass CHPs. The ban on coal use after 2030 and the assumption of increasing natural gas costs limits the choice of CHPs in the FP scenario, as does the cumulative carbon budget in the CB scenario. The remaining choices are biomass and waste CHPs. Investments in biomass CHPs are made at the beginning of the analysed period and stay active up to 2035, i.e. they serve as a transitional option. Due to the introduced constraint that all the available waste produced by society needs to be burned, production from CHPs remains constant over the analysed period.

The share of wind in electricity production grows from 23% in the base year up to 80% in 2030 and remains constant thereafter. Onshore wind is dominant until 2020 due to the lower costs compared to offshore wind. Increasing domestic electricity demand and relatively high electricity prices in the neighbouring countries, at least in some time slices, require other producers than just onshore wind. Offshore wind turns out to be the most affordable technology to fill in the gap, therefore it becomes the dominant source of electricity from 2025. The contribution of large-scale PVs becomes visible from 2025, while almost the entire potential (1500 MW in DKE and 1500 MW in DKW) is utilized after 2040. The main reasons for the high shares of wind and PVs are the renewable energy constraints and the assumed decreasing investment costs of these technologies. Denmark will become a net importer of electricity between 2015 and 2045, imports accounting for between 6% and 9% of electricity production.

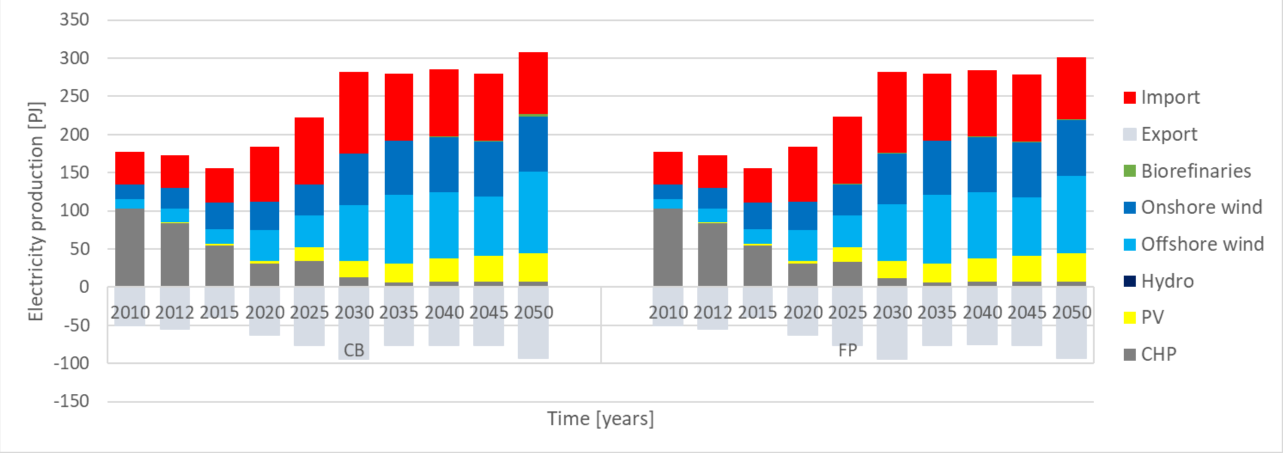

Figure 6. Electricity production mix.

The trend in marginal electricity costs is presented in Figure 7. These costs fall between 2010 and 2015 due to the assumed decrease in electricity costs in neighbouring countries (Norway and Sweden). The rise in costs between 2015 and 2025 is due to similar rises in all the neighbouring countries and to the decommissioning mainly of coal but partly also natural gas CHPs. Despite the increase in wind capacity, there is still a lack of capacity in some time slices, which causes the increase in average prices. After 2025 the production mix stays the same, which results in a constant electricity price.

Figure 7. Marginal electricity costs.

4.2 District heating production

The development of DH production in the CB and FP scenarios until 2050 are presented in Figure 8. As with electricity production, there is a small difference between the scenarios due to the similar impacts of cumulative carbon budgets and favourable policies for renewable energy in the CB and FP scenarios respectively.

In both scenarios, DH production changes from boilers and CHPs to large-scale HPs, EH, solar heating and waste CHPs. The only significant difference between the scenarios appears in 2050. In the FP scenario, 41% of DH is produced from large-scale HPs, while the rest is split nearly equally between CHPs, solar heating, EH from DCs and EH from biorefineries; EH from production industries contributes 4%. In the CB scenario, the share of DH from biorefineries in 2050 increases to 27%, mainly displacing large-scale HPs and EH from DCs.

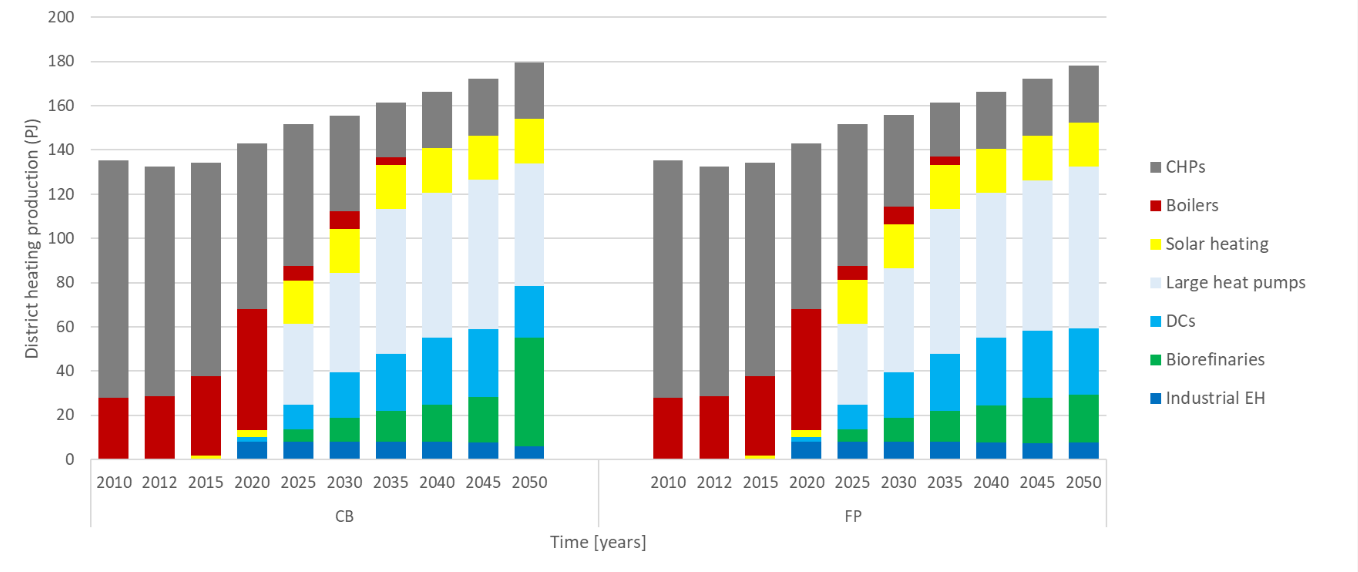

Figure 8. DH production.

The relative values related to DH production are presented in Figure 9. DH competes with energy-efficiency measures in industries and households and individual heating supply options. Because of the competition, DH production grows linearly throughout the analysed period, meaning that the share of DH in total heat supply also grows. The entire EH potential from DCs is utilized from 2020 in Decentral areas in both scenarios, while in Central areas this share drops in 2050 in the CB scenario. The reason for the drop is the increase in high-temperature EH from biorefineries, which is a result of increased biofuel production. EH from industries, DCs and biorefineries grows until 2045 in both scenarios, reaching 35% of total DH production. In the CB scenario, another jump occurs in 2050 because of the increased production of biofuels.

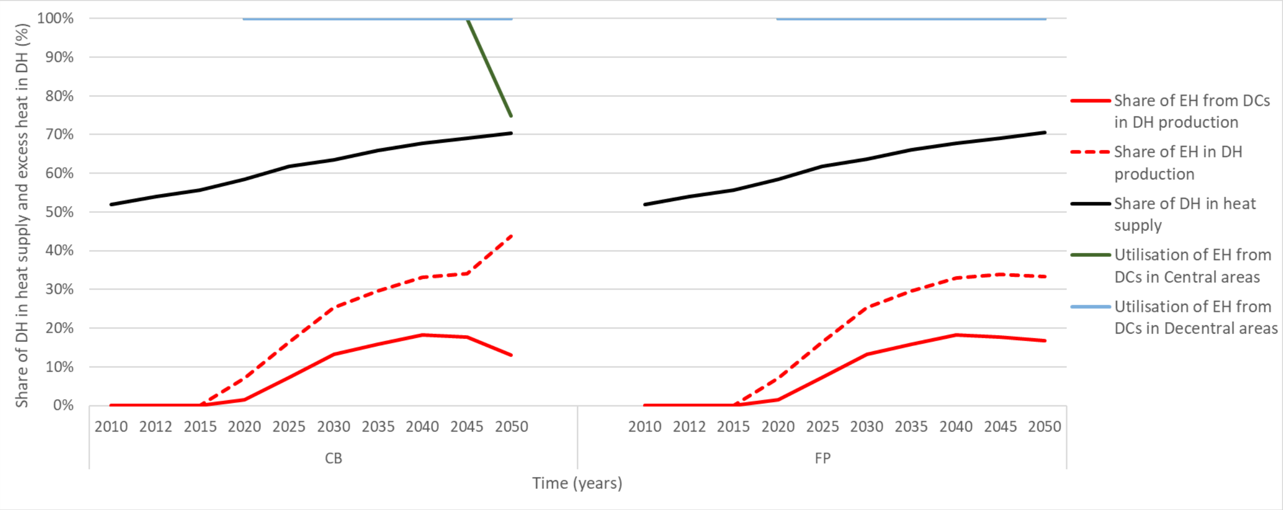

Figure 9. Shares related to DH production.

The development of marginal DH costs is presented in Figure 10, in which HETC and HETD denote Central and Decentral DH respectively. The increase in DH costs between 2010 and 2020 and between 2025 and 2030 is due to the decommissioning of coal and natural gas CHPs. Investments in large-scale HPs and solar heating plants cause the drop in 2025. After 2030, the share of EH grows in both scenarios, which pushes down the marginal DH cost. The biggest difference between the two scenarios is the significant drop in Central DH costs in 2050. The marginal production source in DKE is high-temperature industrial EH, while in DKW it is large-scale HPs.

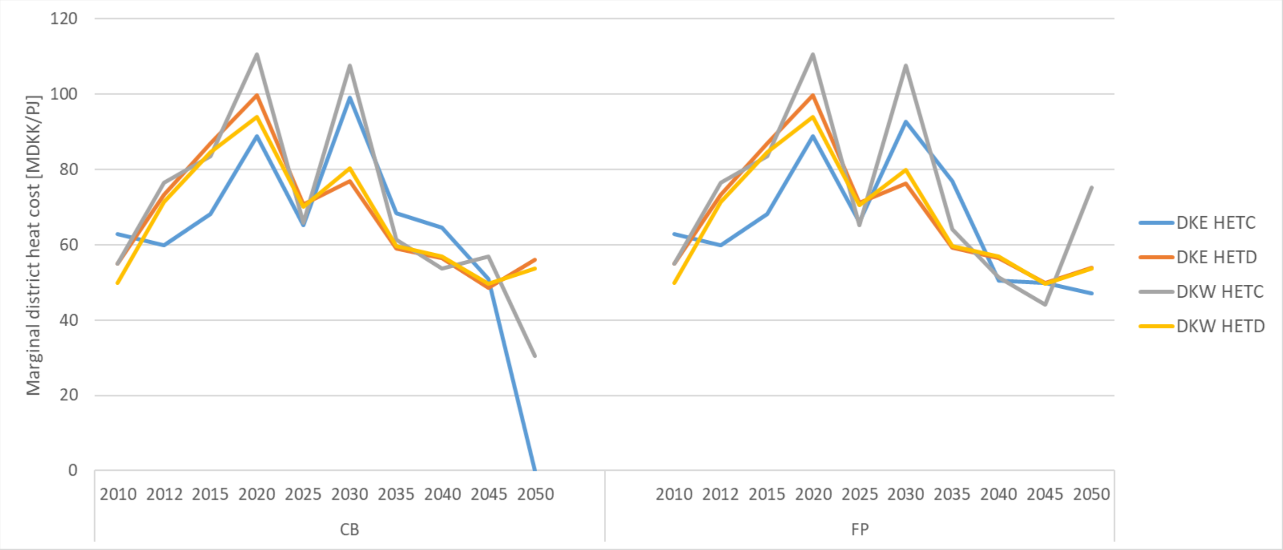

Figure 10. Marginal DH costs.

4.3 CO_2 emissions

CO_2 emissions from different sectors of the Danish energy system until 2050 are presented in Figure 11. The trend until 2045 is very similar in the two scenarios. Power and the DH sector have the highest sectoral CO_2 emissions in the base year, being responsible for 44% of total CO_2 emissions. As presented in sections 4.1 and 4.2, power production switches to offshore and onshore wind and PVs, while DH production switches to different forms of EH and large-scale HPs. This reduces the sector's CO_2 emissions by over 95%. The only remaining emissions in the power and DH sector in 2050 come from waste CHPs.

The industrial sector achieves decarbonization through efficiency improvements, increased connection to DH and electrification, while decarbonization of the transport sector is achieved through the use of biofuels and extensive use of electric vehicles. The production of biofuels results in biogenic emissions. The residential sector is decarbonized through increased connection to DH, heat savings and use of individual air-to-air heat pumps. The emissions from burning waste and imports of electricity are not included in the carbon budget.

The difference between the scenarios appears in 2045 and 2050. The nature of economic optimization is such that the model aims to postpone investment for as long as possible, i.e. to use up the carbon budget as soon as possible. This is the main reason for the steep reduction in CO_2 emissions between 2045 and 2050 in the CB scenario. Due to the imposed growth constraints, the energy system needs to react sooner than 2050. That creates the difference between the scenarios in 2045. The residential and power and DH sectors are decarbonized even under current policies, while industries and transport continue using fossil fuels in the FP scenario.

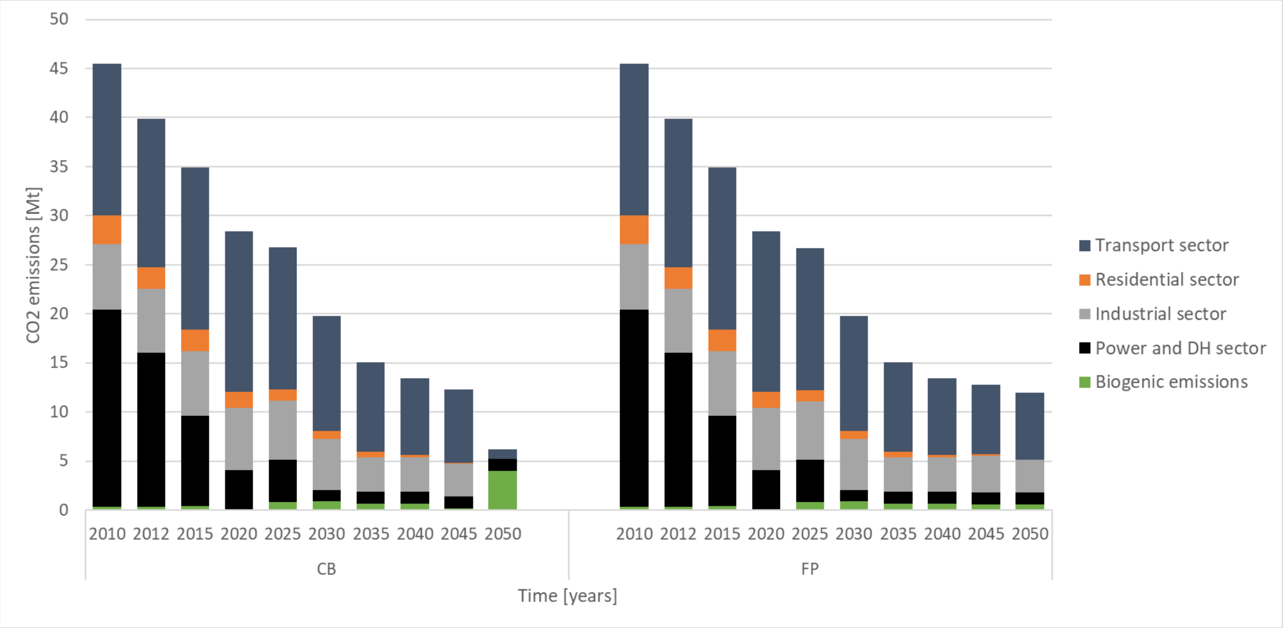

Figure 11. CO_2 emissions.

4.4 Costs of power and district heating system

The total undiscounted costs of power and DH system over the analysed period are 0.2% higher in the CB than the FP scenario, as shown in Figure 12, which contains two important messages. First, the composition of the costs in both scenarios are very similar. Due to the significant switch from fossil fuels to renewable energy, investments strongly predominate over fuel costs. The investment costs are caused by the investments in waste CHPs, PVs, wind and large-scale HPs and amount to around 63%.

Fixed O&M costs are around 23% and are stable over the analysed period. The transition from coal, natural gas and biomass CHPs to wind and PVs reduces the variable O&M costs, which amount to 11% of the total undiscounted costs of power and DH systems over the analysed period.

Second, in both scenarios characterized by increasing demand for electricity, the additional costs of staying within the carbon budget (CB scenario) are almost negligible.

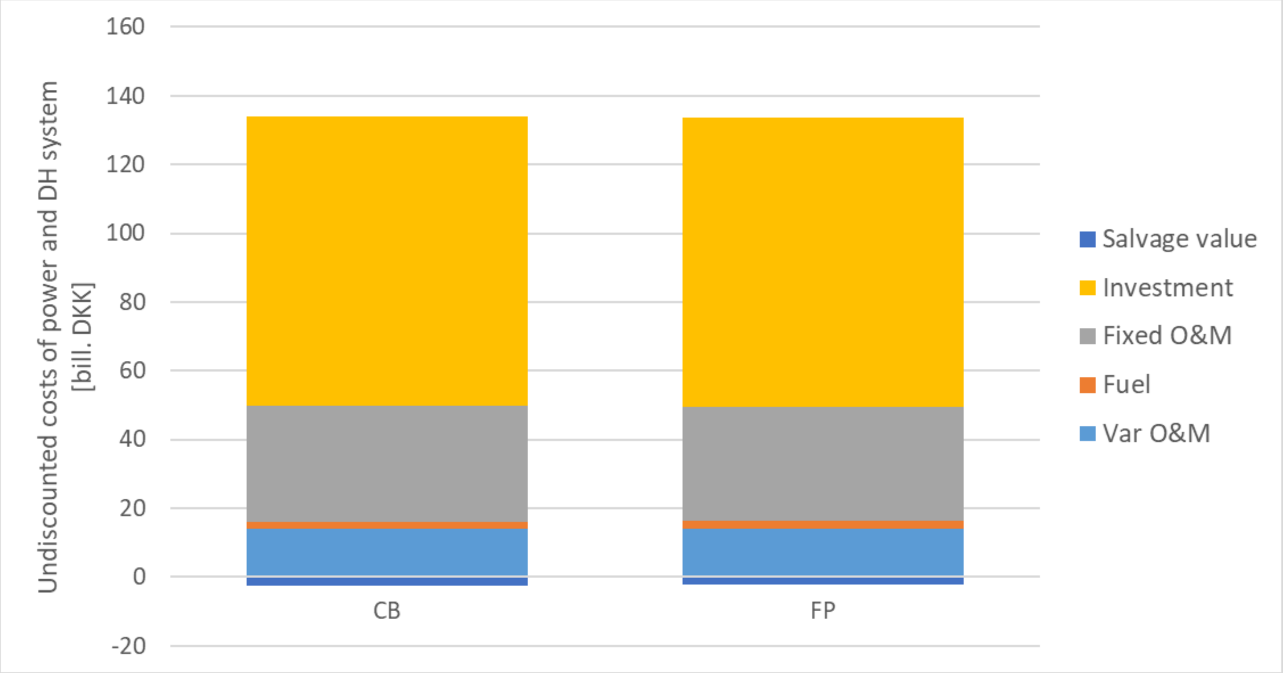

Figure 12. Sum of undiscounted costs of P&H system over the analysed period.

5 Results of sensitivity analysis

The effect of DCs on Denmark's future energy system is very similar in both scenarios: the increased electricity demand is mainly supplied from wind power, while EH accelerates the decarbonization of the DH system. The aim of the sensitivity analysis is to quantify the effect of different penetrations of DCs on Denmark's future energy system. For each of the three sensitivity scenarios, the following most significant variables are compared with their values in the FP scenario:

- Average utilisation and share of EH from DCs in total DH production over the analysed period
- Total DH production over the analysed period and average DH share in total heat production
- Average electricity prices and DH prices throughout the analysed period
- Total electricity production, total electricity production from wind power and total electricity production from offshore wind power over the analysed period
- Total CO_2 emissions from power and DH system and total CO_2 emissions over the analysed period
- Total costs of power and DH system over the analysed period and total system costs

The sensitivity analysis confirms the results presented in Section 4. The whole of the available EH from DCs is utilized in the FP scenario, which is used as the basis for the sensitivity analysis. There is less EH from DCs in the DisDC and LowDC scenarios. Therefore, the share of EH from DCs in DH production does not go over 4.7% and 6% respectively. Since all this heat is beneficial to the whole energy system, and assuming other conditions do not change, the utilization of EH from DCs stays at 100%. The HighDC scenario leads in the opposite direction: the EH from DCs is not fully utilised, while the average share of EH from DCs in DH production grows by 20%. The EH from DCs is beneficial to the energy system, but it cannot be fully exploited due to competition from large-scale HPs, the only real competition in the field of DH production. DH production from high-temperature industrial EH and EH from bio-refineries, solar DH and waste CHPs do not change between the scenarios.

DH production and the share of DH in the total heat supply do not change compared to the FP and CB scenarios. This means that the DCs do not disturb the competition between DH production and DH expansion on one side, efficiency improvements in industries and households on the other and individual heat supply on the third side.

The effect of DCs on electricity and DH costs is not great. Despite the increase in electricity demand of over 50 PJ or around 24% in 2050 in the HighDC scenario, electricity prices do not change significantly. This is because Denmark is a "transit" country: domestic production alone does not determine electricity prices in Denmark, as the cost of imports and exports must also be taken into account. EH from DCs is cheap heat and thus lowers average DH costs. That explains the moderate decrease in DH costs in the HighDC scenario. In the remaining sensitivity scenarios, the use of large-scale HPs reduces DH costs.

The electricity demand of DCs in the HighDC scenario is around 80% higher than in the FP scenario. However, even in this scenario DCs are not the major part of the power demand. Therefore, the HighDC scenario is characterized by increased power production by 12%, which is supplied from increased production from offshore wind (28%) and slightly decreased imports and exports (2%). The electricity demand from DCs is lower in the LowDC and DisDC scenarios. The lower demand is translated into decreased production from offshore wind by 9%. None of the sensitivity scenarios affects power production from onshore wind.

The power and DH sector is fully decarbonized from 2025 in all scenarios. Power demand and EH from DCs are very similar in the DisDC and FP scenarios up to 2025, which results in negligible differences in CO_2 emissions. In the HighDC scenario, fossil-fuel sources supply some of the increased demand for power up to 2025, which results in 0.2% higher CO_2 emissions compared to the FP scenario. Surprisingly, CO_2 emissions increase in the LowDC scenario as well. On one hand, the lower number of DCs reduces the demand for electricity. On the other hand, as the reduced electricity demand does not put enough pressure on the existing capacity, this decelerates investments in large-scale PVs and thus increases the carbon content of electricity. Due to the small change in CO_2 emissions from the power and DH sector in the sensitivity scenarios and rapid decarbonization, the effect on total CO_2 emissions is zero.

The electricity demand is higher in the HighDC than the FP scenario. The additional 3GW from offshore wind turbines (200-350 turbines) supply that demand, which results in 13% higher costs for the power and DH system; reduced electricity demand in the LowDC and DisDC scenarios results in 5% and 4% lower costs for the power and DH system respectively. Since the power and DH system is not the dominant sector of the energy system, the objective function falls within +/- 0.2% in the sensitivity scenarios.

Table 1. Summary of sensitivity analysis

Change of results relative to FP scenario	Sensitivity scenarios		
	DisDC	HighDC	LowDC
DC use	0%	-5%	0%
Share of EH from DCs in DH production	-69%	20%	-66%
DH production	0%	0%	0%
DH share of heat production	0%	0%	0%
Electricity cost	-5%	6%	-3%
DH cost	-1%	-2%	-1%
Electricity production	-5%	12%	-4%
Electricity imports	9%	-2%	9%
Electricity exports	6%	-2%	4%
Onshore wind production	0%	0%	0%
Offshore wind production	-9%	28%	-9%
Power and heat CO_2 emissions	0.0%	0.2%	0.6%
Total CO_2 emissions	0%	0%	0%
Power and DH system costs	-5%	13%	-4%
Objective function	-0.2%	0.2%	-0.2%

6 Discussion

The results show that DCs will significantly affect the power and DH sector in Denmark. The additional electricity demand will be supplied from additional offshore wind turbines: an additional 3 GWs in the CB and FP scenarios and another 3 GWs in the HighDC scenario. EH from DCs is beneficial to the DH sector. However, many assumptions influence the present analysis; they are discussed in this section.

The location of DCs is important for their role in the future energy system, especially the exploitation of EH for DH. Based on [5] we have assumed that all DCs are located within DH areas of DKW. The locations of existing transformer stations and already planned DCs, together with lower electricity prices, justify this assumption. The further assumption that DCs will be located within DH areas is optimal for the energy system, i.e. it minimizes the costs of EH utilisation for DH. However, the owners of DCs could choose locations based on other criteria. This analysis should be included in future work.

The EH from DCs is treated as free of charge in the present analysis. In reality, the costs of EH might be subject to negotiations between the EH emitter and the DH company. If EH is not free, taxes imposed by the Danish government come into play. In the case of the DCs, it is reasonable to assume that the large international companies will be willing to give the EH away free in order to build up their image as good businesses. On the other hand, exploiting EH for DH might reduce the need for cooling and thus reduce the cooling costs. This would negatively affect the costs of EH from DCs.

However, the costs and taxes imposed on EH are not the only obstacles associated with the exploitation of EH for DH purposes. [34,36] have analysed the use of industrial EH for DH, concluding that not even well-designed taxes and policies guarantee that DH companies would be willing to accept industrial EH due to the risk of the industrial facilities that produce EH closing or relocating. The same message is applicable to EH from DCs. This suggests a need for the business models for the utilization of EH from DCs to be analysed.

The present paper presents the results that are optimal for the whole energy system. Even though the analysis includes all taxes and subsidies, it cannot guarantee performance from a business-economic perspective. Such analyses, as well as those of specific business cases, must be left for future research.

In the present analysis, Denmark's future energy system is exposed to stable policies (in the FP and sensitivity scenarios) or targets (in the CB scenario). Due to political changes, policies tend to change every couple of years. For long-term infrastructure projects such as DH and electricity supply, stable policies are surely desirable. However, it would go beyond the scope of this research to quantify how harmful "policy shocks" might be.

Lastly, the variations in air temperature variation adopted in the present analysis are those of the Danish Reference Year (DRY) from 2001-2010 [37]. Climate change creates an increase in outdoor temperatures. Higher air temperatures will reduce the efficiency of cooling equipment in DCs but also increase the efficiency of the HPs that use the EH from DCs for DH purposes. In addition, the change in daily temperature peaks will change the operating patterns of the cooling equipment. Additional analysis is needed to evaluate how significant these effects are for the whole energy system.

7 Conclusion

The present paper presents a comprehensive methodology, based on both a thermodynamic model and a broader energy system analysis, to assess the possible impacts of four different DC deployment options in Denmark's future energy system.

The principal effects of the deployment of DCs are mostly reflected in the additional power required by the system, up to 3-6 GW (30-60% of base-year generating capacity), and in the potential to exploit DCs' excess heat to supply DH. The approach presented here allows the cost-optimal solutions for deploying DCs and simultaneously limiting their associated overall carbon footprint to be estimated. As a result, offshore wind turbines emerge as suitable options to cover additional the capacity needs of new DCs in Denmark. Offshore wind is favoured due to the imposed policy constraints, decreasing investment costs and limited onshore wind potential. The second key outcome is the potential to fully exploit the EH from DCs, which has proved beneficial to the energy system in almost all scenarios. The only exception is HighDC, in which the EH cannot be fully exploited due to the competition from large-scale HPs. Therefore, the DH system can accept between 44 and 88 PJ of EH from DCs. After 2040, EH from DCs contributes around 20% of DH production in the CB and FP scenarios. In the sensitivity scenarios, these values vary between 4% and 27% after 2040.

In addition, DCs are not expected to affect electricity and DH prices significantly. An exponential growth in the number of DCs, such as that assumed in the HighDC scenario, might increase the electricity price by 6%, while the low implementation of DCs might reduce the electricity price by 3%-5%. The price variation is justified by the fact that Denmark is surrounded by "energetically large" countries (Germany, Norway, Sweden), which significantly influence domestic electricity prices. On the other hand, the DH price might drop between 1% and 2% over the analysed period, thanks to heat-recovery strategies. Although the present analysis refers specifically to Denmark, these results could be relevant for other countries with cold climates and with DH grids in place. The methodology can be replicated in other countries to assess the energy strategies for DC deployment. Additional analyses will be devoted to a better understanding of how additional efficiency measures, such as the use of alternative cooling systems (e.g. exploiting rainwater) or improved operational management strategies, and increased air temperatures might affect new capacity needs and the related costs and emissions.

8 Acknowledgment

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9 Appendix: thermodynamic model

Table 2. Key assumptions of the thermodynamic model.

Nomenclature	Units	Value	Description
$\boldsymbol{c_p}$	MJ/(kg*K)	0.001	Specific heat of air
$\boldsymbol{\rho}$	kg/m^3	1.2	Air density
$\boldsymbol{\dot{Q}_{IT,max}}$	MW	4	Maximum power consumed by IT equipment [32]
$\boldsymbol{\Delta T_{IT}}$	°C	15	Temperature increase across IT equipment [11]
$\boldsymbol{T_{DC,sup}}$	°C	20	Data centre supply temperature [31]
$\boldsymbol{\Delta T_{PP}}$	°C	3	Minimum allowed temperature difference in heat exchanger [31]
$\boldsymbol{T_{OA,max}}$	°C	17	Maximum outdoor temperature for free cooling ($T_{OA,max} = T_{DC,sup} - \Delta T_{PP}$) [31]
BP	-	10%	Airflow by-pass [31]
$\boldsymbol{\eta_{fan}}$	-	75%	Fan efficiency (including motor) [31]
$\boldsymbol{\dot{V}_{DC,max}}$	m^3/s	246	Maximum recirculated airflow inside data hall (calculated, see eq.3)
$\boldsymbol{\dot{V}_{OA,max}}$	m^3/s	246	Maximum external airflow (assumed equal to $V_{DC,max}$)
$\boldsymbol{\Delta p_{fan,OA,max}}$	Pa	350	Pressure drop over economizer fan [31] (confirmed also by [30])
$\boldsymbol{\Delta p_{fan,IASE,max}}$	Pa	400	Additional pressure drop for moving DC air through HX [31]
$\boldsymbol{\Delta p_{fan,CRAH,max}}$	Pa	700	Pressure drop for recirculating air inside data hall [31]
$\boldsymbol{T_{air,rejected}}$	°C	20	Assumed air outlet temperature after heat recovery

A vapour compression air-cooled chiller associated with an indirect airside economizer (IASE) is assumed for cooling system configuration [12]. Depending on the outdoor air temperature, two cooling modes can be performed: "free cooling" through IASE, or chiller mode. A scheme is presented in Figure 13 and Figure 14.

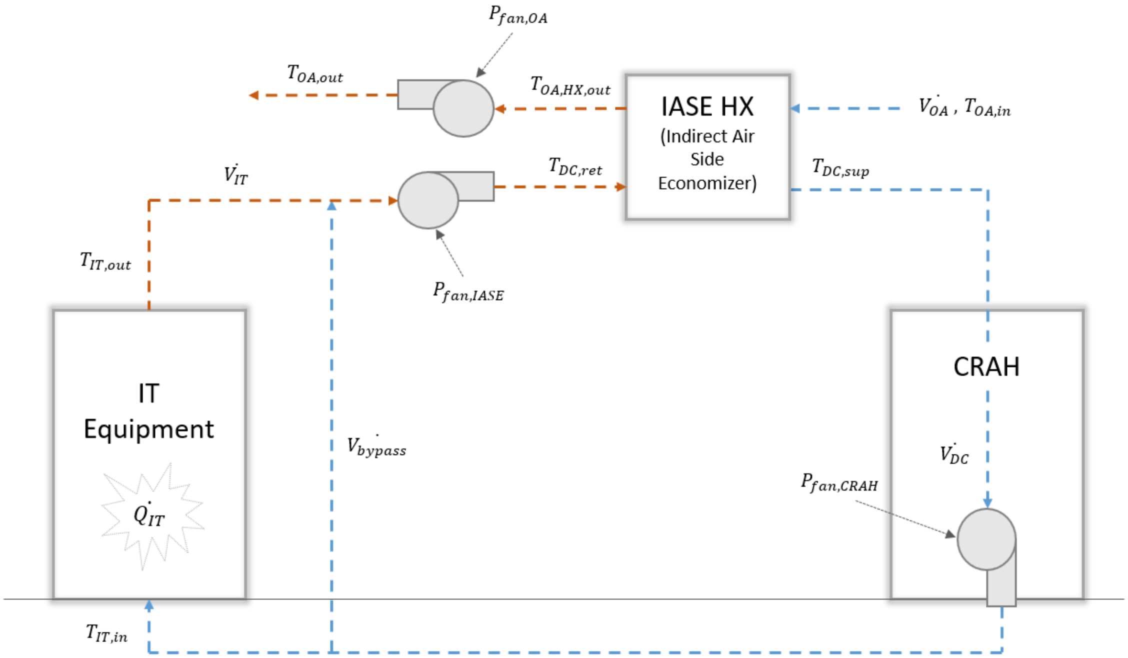

Figure 13. Scheme adopted for free cooling mode.

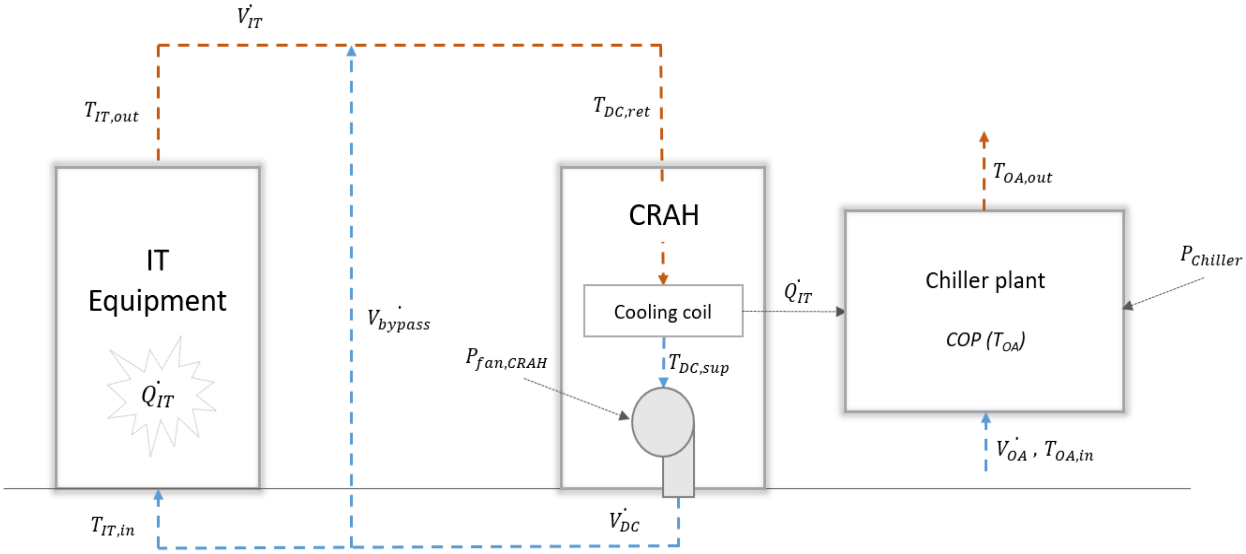

Figure 14. Scheme adopted when the cooling is produced by a chiller plant.

The amount of air recirculating through the IT equipment ($\dot{V}_{IT}$) is calculated by imposing a temperature rise of 15°C [11] and assuming the heat dissipated by the IT equipment ($\dot{Q}_{IT}$) according to the variable workload profile adopted [31]:

$$\dot{V}_{IT} = \frac{\dot{Q}_{IT}}{\rho c_P \Delta T_{IT}} \tag{1}$$

The airflow supplied to the data hall should not be the exact amount required to cool the equipment due to by-pass effects [12,31]. Therefore, the total airflow recirculating inside the data hall is expressed by eq.(2):

$$\dot{V}_{DC} = \dot{V}_{IT} + \dot{V}_{bypass} = \frac{\dot{V}_{IT}}{1 - BP} \tag{2}$$

The supply of air is always recirculated inside the data hall by the fans of the CRAH (Computer Room Air Handler) units. Their power demand is calculated according to eq.(3):

$$P_{fan,CRAH} = P_{fan,CRAH,max} * \left(\frac{\dot{V}_{DC}}{\dot{V}_{DC,max}}\right)^{2,5} \tag{3}$$

where:

$$P_{fan,CRAH,max} = \frac{\dot{V}_{DC,max} \Delta p_{CRAH,max}}{\eta_{fan}}$$

$$\dot{V}_{DC,max} = \frac{Q_{IT,max}}{\rho c_p \Delta T_{IT}} * \frac{1}{1 - BP} \cong 246\ m^3/s$$

The exponent is set to 2.5 to account for variations in fan efficiency with the airflow [31].

9.1.1 Free-cooling mode

Two temperatures are set across the economizer heat exchanger: the data hall supply temperature ($T_{DC,sup}$), and the outdoor air temperature at the IASE exit ($T_{OA,HX,out}$). $T_{DC,sup}$ is equal to 20°C [31], while $T_{OA,HX,out}$ is assumed to be 3°C lower than the return air temperature ($T_{DC,ret}$), expressed by eq.(4).

$T_{DC,ret}$ is obtained by assuming an adiabatic mixing between the by-pass airflow and the IT airflow and adding the heat dissipation of the fan.

$$T_{DC,ret} = \left[(1 - BP) * T_{IT,out} + BP * T_{IT,in}\right] * \frac{(1 - \eta_{fan}) P_{fan,IASE}}{\dot{V}_{DC} * \rho * c_p} \tag{4}$$

Subsequently, the airflow withdrawn from the external environment ($\dot{V}_{OA}$) is calculated by eq.(5):

$$\dot{V}_{OA} = \dot{V}_{DC} \frac{\left(T_{DC,ret} - T_{DC,sup}\right)}{\left(T_{OA,HX,out} - T_{OA,in}\right)} \tag{5}$$

The power consumption of the two additional fans ($P_{fan,IASE}$ and $P_{fan,OA}$) is then calculated using the same reasoning of eq.(3), but taking into account the respective airflows and different values for the maximum pressure drops (see **Errore. L'origine riferimento non è stata trovata.**) and assuming that the maximum outdoor airflow ($\dot{V}_{OA,max}$) coincides with ($\dot{V}_{DC,max}$), since they are processed by the same heat exchanger.

In free-cooling mode the power consumption of the cooling system is thus indicated by eq.(6):

$$P_{cooling\ system} = P_{fan,CRAH} + P_{fan,IASE} + P_{fan,OA} \tag{6}$$

9.1.2 Cooling from a chiller

The chiller plant is modelled through an overall COP that is dependent on external temperatures (Table 3) [11]. Its variation at different loads is disregarded here for the sake of simplicity. A linear interpolation of the data in Table 3 was then used.

Table 3. Dependence of chiller efficiency on external temperatures [11].

Outdoor T [°C]	**0**	**5**	**10**	**15**	**20**	**25**	**30**	**35**	**41**
COP	5.82	5.49	5.13	4.74	4.34	3.93	3.52	3.12	2.66

The power consumption of the chiller plant is expressed by eq.(7):

$$P_{chiller} = \frac{\dot{Q}_{IT}}{COP} \tag{7}$$

Inside the data hall, instead, the economizer is by-passed and the additional pressure drops of the free-cooling mode are disregarded.

In conclusion, when the chiller plant is activated, the power consumption of the cooling system is expressed by eq.(8).

$$P_{cooling\ system} = P_{fan,CRAH} + P_{chiller} \tag{8}$$

9.1.3 Available excess heat

The excess heat is generated by the cooling down of $\dot{V}_{OA}$ in an intermediate heat exchanger between the data hall and the heat pump to upgrade its temperature (Figure 5). The logarithmic temperature of the excess heat source ($T_{lm,source}$) is assumed to be 20°C [33]. The average heated outdoor air temperature from the data hall ($\overline{T_{OA,out}}$) is 31°C. The design temperature difference in the intermediate heat exchanger between the data hall and the heat pump is assumed to be 5°C. To satisfy this constraint and the assumed value of $T_{lm,source}$ in eq.(9), the design temperature range of the heat pump source is 26-15°C ($T_{source,in}$ and $T_{source,out}$). Consequently, the air stream coming from the data hall ($\dot{V}_{OA}$) and supplying the intermediate heat exchanger is assumed to be cooled down to 20°C ($T_{air,rejected}$).

$$T_{lm,source} = \frac{T_{source,in} - T_{source,out}}{\ln\left(\frac{T_{source,in}}{T_{source,out}}\right)} \tag{9}$$

Therefore, the excess heat available at the heat exchanger (which coincides with the excess heat available at the heat pump) is calculated according to eq.(10):

$$Q_{HX} = \dot{V}_{air} * \rho * c_p * (T_{OA,out} - T_{air,rejected}) \tag{10}$$

Where:

	Free-cooling mode	**Cooling with chiller**
$\dot{V}_{air}$	$\dot{V}_{OA}$	$V_{OA,max}$ (fixed by hypothesis)
$T_{OA,out}$	$T_{OA,out} \cong T_{DC,ret} - \Delta T_{pp}$	$T_{OA,out} = T_{OA,in} + \frac{Q_{IT} + P_{chiller}}{V_{OA,max}\rho c_p}$
$T_{air,rejected}$	20 °C	20 °C

9.1.4 Validation

The results obtained from our thermodynamic model were compared with measured data.

The average annual power usage effectiveness (PUE) reported by Facebook’s and Google’s data centres in 2018 was 1.11 [8,9], while the average annual overhead of the cooling system calculated using our model with respect to the power consumption of IT equipment corresponds to 12%. Although the PUE does not only take account of the overhead of the cooling system with respect to IT energy consumption, the components of the cooling system are its major contributors [38]. Therefore, we suggest that the outcome of our thermodynamic model fairly represents the behaviour of today’s most efficient DCs.

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