Energy 281 (2023) 128112

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Impacts of flexible-cooling and waste-heat recovery from data centres on energy systems: A Danish case study

Juan Jerez Monsalves *, Claire Bergaentzlé, Dogan Keles

Technical University of Denmark, Department of Management, Kongens Lyngby, Denmark

ARTICLE INFO

Handling editor: Dr G Chicco

Keywords:
Energy system modelling
Data centres
Flexibility
Waste heat recovery
District heating

ABSTRACT

The fast development of large data centres increases energy demand, pressuring energy systems and potentially hindering progress towards climate targets. Nevertheless, data centres are also a potential sector-coupling interface supporting the energy transition through demand flexibility in electricity markets and waste-heat recovery for district heating systems. In this respect, this paper quantifies the economic and environmental benefits of integrating large data centres into highly renewable energy systems, using Denmark as a case study and focusing on the transition until 2035. The Balmorel energy system model optimises the investments and operation of the energy system along with the data centre's portfolio of flexible-cooling and waste-heat equipment. The results illustrate that waste-heat recovery displaces conventional heat pumps in district heating, indirectly reducing investments in photovoltaic capacity while increasing electricity exports. Integration reduces Danish energy system costs by 5.1% and carbon emissions by 1.4% throughout this period. More importantly, this study highlights the significance of optimal integration, which saves up to 63% of costs and 180% of emissions that non-integrated data centres would otherwise incur. While these figures depend on local conditions, they emphasise the high costs to society of non-integration and the need for appropriate policies to support such integration.

1. Introduction

Data centres house the information technology (IT) equipment that supports the digitalisation of our society, and the industry is rapidly growing to keep pace with it. The International Energy Agency has estimated that data centres used between 220 and 320 TWh of electricity in 2021, i.e., 0.9%–1.3% of the global final electricity demand, and were responsible for about 300 Mtons of $CO_{2\text{-eq}}$ in 2020 [1]. Even though data centre workloads rose approximately 10-fold between 2010 and 2020, their energy use remained stable [2], thanks to energy efficiency improvements in IT equipment [3]. However, it is uncertain how long these efficiency gains can compensate for growing demand. Additionally, data centres are a source of low-temperature waste heat, which is released to the environment but might be a valuable resource since data centres tend to develop in colder climates [4]. In this context, it has become necessary to evaluate the potential for improving the sustainability of data centres, not only from a facility perspective, but also through closer integration with the energy system through measures such as waste-heat recovery and demand flexibility.

Data centres are energy-intensive facilities, as electricity is required to operate their IT equipment and to keep them operating at a stable temperature through cooling. The importance of energy costs and economies of scale has led to the development of geographic clusters of large-scale data centres in locations with the most favourable conditions in terms of climate and electricity supply quality, pressuring local energy systems [5]. In the last years, Denmark has seen the deployment of large data centres because of its renewable and reliable electricity supply, favourable connectivity infrastructure, and cold climate that reduces cooling needs [6]. The Danish Energy Agency estimates that electricity demand from data centres in Denmark will increase from 0.2 TWh_{el} to 9.6 TWh_{el} between 2019 and 2035. Fig. 1 shows the historical and projected use of electricity by sector type in Denmark, with data centres consuming approximately 16% of national demand towards 2035, even in a context of strong electrification of the heating and transport sectors [7].

Despite the challenge of increased energy demand, data centres can support the energy transition through closer integration with the energy system by becoming an interface between the electricity and heating

* Corresponding author.
E-mail address: jujmo@dtu.dk (J. Jerez Monsalves).

https://doi.org/10.1016/j.energy.2023.128112
Received 11 March 2023; Received in revised form 20 May 2023; Accepted 11 June 2023
Available online 30 June 2023

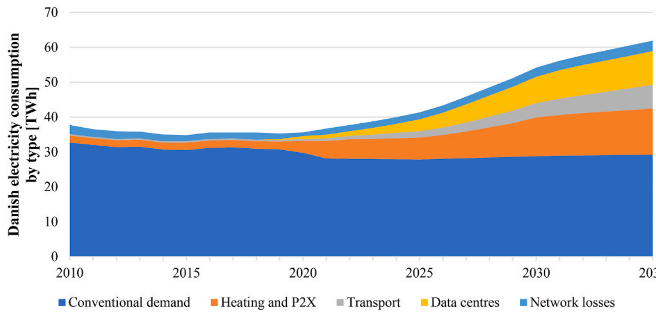

Fig. 1. Historic (up to 2020) and projected electricity use by type in Denmark [7].

sectors. On the one hand, they can modulate their electricity consumption from their IT equipment, backup batteries, or cooling systems. By providing demand-response, data centres could contribute to matching energy demand to the available supply of variable renewable electricity, benefitting from lower energy prices and carbon footprint. On the other hand, the low-temperature waste heat released by their IT equipment can be recovered for use in nearby buildings or injected into existing district heating networks, thereby substituting other fossil heat sources. Consequently, data centres can actively mitigate their energy-use impacts, opening opportunities for system flexibility, energy efficiency, and decarbonisation.

The Danish district heating sector supplies 65% of households and 37% of the total national residential energy demand [8]. Approximately 400 networks operate nationwide, with their portfolios managed under a least-cost and non-profit principle [9]. Co-generation plants, fuelled predominantly by municipal waste and biomass, have dominated these networks, and 68% of the total supply comes from renewable sources [8]. Denmark aims at sourcing 90% of its district heating supply from non-fossil fuels by 2030 [10], in which waste heat may play an important role. Utilising waste heat reduces the dependency on other fuels, potentially fossil-based or imported, thereby leading to reduced costs and emissions, as well as increased energy efficiency and security.

This paper quantifies the economic and environmental gains from data centre's cooling-based flexibility and waste-heat recovery in energy systems with significant data centre demand, high penetration of variable renewable sources, and well-established district heating networks. Therefore, Denmark has been chosen as a study case. These gains are evaluated for different levels of integration regarding their effects on the system-wide energy mix, costs, and emissions. In this study, "integrated data centres" refers to those facilities investing in cooling storage and waste-heat recovery technologies.

This work extends the current state-of-the-art by assessing, for the first time, the enhanced benefits these two strategies bring to the energy system by transforming data centres into a sector-coupling interface between the electricity and heating sectors. Three fundamental questions related to data centre integration and its potential impact on the energy sector are answered:

- What are the systemic effects of varying levels of integration in terms of substitution effects and sector coupling interactions?
- How does widespread integration support the system's long-term transition regarding supply costs and emissions reduction?
- To what extent is integration effective in mitigating the energy supply costs and emissions associated with this industry's traditional, non-integrated operation?

This study is structured as follows. Section 2 presents related work on data centre integration. Section 3 introduces the modelling tool and scope. Section 4 presents the data used in this analysis. Sections 5 and 6 describe and discuss the results. Section 7 summarises the main findings, limitations, and implications.

2. Literature review

The literature on the relationship between data centres, energy, and carbon footprint has expanded rapidly. Review studies have examined it from several perspectives, such as evaluation metrics focused on sustainability [11], thermal management [12], and energy efficiency evaluation [13–15]; workload management strategies [16,17]; design and optimisation of rack layouts [18,19], air management and ventilation [20], thermal storage [21], and cooling systems [22–24]; use of renewable electricity through renewable-sourced Power Purchasing Agreements (PPA) [15] or on-site generation [23]; and carbon footprint mitigation [25,26].

Research has shown that operational emissions largely dominate data centres' life-cycle carbon footprint [27], and the facility's location primarily determines its magnitude based on cooling requirements and local electricity carbon intensity [28]. Even though using low-carbon electricity reduces carbon footprint, a low energy efficiency performance still hinders decarbonisation because inefficient data centres tie up renewable generation that could otherwise be used elsewhere [27]. For this reason, the evaluation of their emissions but be addressed holistically, considering the composition of the electricity supply, cooling system operation, and possibilities for integration.

Besides energy efficiency, recent research shows data centres benefiting from demand flexibility and waste-heat recovery. Focusing on the flexibility aspect first, existing studies are usually focused on providing demand response services by manipulating workloads or utilising backup batteries [29]. Data centres are distinct flexible consumers due to their large load, multi-scale demand response (from second to hours), and potential for spatial power shifting between networked facilities [30]. However, participation in flexibility programs is weak, facing challenges in coordinating it with the business-critical nature of IT equipment operation. Another branch of research approaches flexibility in data centres from their cooling systems through the utilisation of thermal storage, which allows flexible operation without compromising the servers' operating conditions [21] shows thermal storage improving reliability and demonstrating high economic benefits under variable electricity pricing [31] also demonstrates that combined management of thermal storage and workload scheduling can reduce peak cooling load. Generally, extending flexibility applications to cooling systems opens the possibility of diversifying flexibility services, as illustrated in Ref. [32]. Here, the authors developed a methodology to schedule servers, chillers and cooling storage, trading flexibility and ancillary services in smart grids while proposing potential business cases [33].

Regarding waste-heat recovery, data centres produce large amounts of waste heat as a by-product of their operations, as the electricity consumed by the IT equipment is ultimately dissipated as heat. This heat must be removed to maintain stable operating conditions, and its temperature depends on the techniques and design of the data centre's cooling system [22]. The link between data centres and district heating via waste-heat recovery has so far mainly focused on technical implementations [34] demonstrate an air-cooled data centre case in Barcelona, Spain, in which positive results are only obtained if waste heat is recovered from within the server room and not if taken from the discharge of existing chillers. The benefits of waste-heat recovery projects may be further improved by internalising the environmental benefits due to the displacement of other heat sources; [35] show an increase of up to 75% from avoided emissions in northern China. Additional techno-economic studies use feasibility analysis and inform on waste-heat recovery's key success factors, such as location, load profile, pricing structure [36] and data centre size [37].

In both cases, flexibility and waste-heat recovery, existing literature indicate that efficiency and economic improvements exist but are dependent on the specific characteristics of the facility. However, while these studies address these private benefits for data centre operators from a facility-level scope, they ignore the systemic conditions that permit them and how they evolve. For instance, the potential for data centre integration may depend on other cost developments, competition from other technologies, local saturation, or infrastructure expansion.

Yet, research demonstrates that stronger couplings between electricity systems and key economic sectors, such as transportation [38,39], industries [40,41], or hydrogen [42–44] and synthetic fuel production [45,46], are major milestones in the pathway to a 100% renewable system [47–49]. Sector coupling opens up opportunities for systemic flexibility [50–52], like the relatively recent vehicle-to-grid capabilities [53,54]. The synergy effects at the electricity-heat interface are well-documented in the Nordics [55–58], as extensive co-generation and district heating infrastructure permits to accommodate large fluctuations in VRE generation through flexible operation and storage. Analogously, similar effects are expected from integrating data centres into the electricity and heating sectors, given their significant use of electricity and waste-heat production. However, few studies have yet been conducted to identify and evaluate the broader gains expected from converting data centres into sector-coupling interfaces, systemic impacts, and their contribution to decarbonisation.

At the interface between electricity grids and data centres, [59] show that load regulation in data centres can alleviate power flow violations and support grid stability, disregarding the gains at the wholesale market and subsequent generation dispatch. On a more systemic approach, [60] demonstrates that widespread data centre flexibility can support the transition of the Irish electricity system towards 2030 by reducing variable renewable curtailment, carbon emissions, and stability margins. At the district heating/data centre interface, [61] estimate that data centres' waste heat could reduce district heating operation costs by up to 7.3% in Espoo, Finland, and offers a suitable baseload production [62]. Both analyses are based on one-year models without considering the long-term evolution of the district heating system. Among past research, [63]'s study stands out by optimising the Danish energy system, including the electricity and district heating systems, along with data centres able to invest in waste-heat recovery equipment on a long-term perspective (2010–2050) using the Times-DK model. The results show that, while 3–6 GW of offshore wind capacity is required to support data centres' electricity consumption, their waste heat is completely tapped in all but one scenario, expanding the supply share of district heating from 50% to 70%. However, the analysis assumed data centres as passive electricity users, incapable of flexible behaviour, therefore neglecting the value chain of decarbonisation of electricity for cooling that results in further low-carbon district heating generation.

To our knowledge, no past studies conduct a systemic analysis on the effects of data centre's full flexible integration into both the electricity and district heating sectors, considering it a sector coupling interface. Yet, this holistic analysis is crucial to evaluate its long-term economic and environmental benefits for society within an energy system in transition.

2.1. Contribution to the literature

The main contribution of this paper lies in determining the systemic and long-term implications of data centre integration based on combined upstream electricity flexibility and downstream waste-heat utilisation considering cross-sector interactions. This analysis includes key parameters of the energy system, such as demand and cost evolution, competition from other flexibility and waste-heat sources, infrastructure expansion, and electrification of different energy sectors. It also highlights how integrated data centres are a tool for effective decarbonisation, supporting the case for policy development targeted at this sector. Methodologically, this paper contributes by developing a framework for simultaneous optimisation of the energy system and cooling portfolio for data centres. In summary, this analysis extends the state-of-the-art by:

- Assessing the emissions impact of data centres holistically, based on their national energy consumption, cooling portfolio, and energy supply.
- Evaluating the effective potential for data centre integration by considering the evolving systemic conditions enabling or hindering it.
- Analysing data centre integration in the context of providing an additional interface for sector coupling between electricity and district heating sectors.

3. Methodology

This study takes a modelling approach by using Balmorel to determine the optimal development of the Danish energy system; we extend Balmorel to allow for the optimisation of integrated data centres.

3.1. Balmorel energy system model

Balmorel is a deterministic partial-equilibrium optimisation model for large-scale energy systems that minimises the cost of supplying the demand of several energy carriers, initially electricity and district heat, from a socioeconomic perspective. These demands are inelastic and exogenously defined over space and time. The total system costs, as expressed in Equation (1), are minimised by finding the optimal set of investment decisions and operational scheduling of generation and transmission assets.

$$\min \mathrm{C}^{\mathrm{sys}} = \sum_{\mathrm{Y}} \left[\sum_{\mathrm{G}} \left\{ \mathrm{C}^{\mathrm{capex}}_{\mathrm{Y,G}} + \sum_{\mathrm{T}} \left(\mathrm{C}^{\mathrm{opex}}_{\mathrm{Y,G,T}} + \mathrm{C}^{\mathrm{ems}}_{\mathrm{Y,G,T}} + \mathrm{C}^{\mathrm{fuel}}_{\mathrm{Y,G,T}} \right) \right\} + \sum_{\mathrm{X}} \left\{ \mathrm{C}^{\mathrm{capex}}_{\mathrm{Y,X}} + \sum_{\mathrm{T}} \mathrm{C}^{\mathrm{opex}}_{\mathrm{Y,T,X}} \right\} \right] \tag{1}$$

The objective function minimises the total system costs ($\mathrm{C}^{\mathrm{sys}}$) over the years included in the analysis (Y). All generators (G) have expenses associated with annualised capital investments ($\mathrm{C}^{\mathrm{capex}}$), operation ($\mathrm{C}^{\mathrm{opex}}$), fuel use ($\mathrm{C}^{\mathrm{fuel}}$) and emissions ($\mathrm{C}^{\mathrm{ems}}$). Transmission assets (X) incur in capital and operational expenses. This function is subject to constraints regarding technical aspects, physical limitations, and policy considerations. Such constraints include energy balances, renewable potential, and emission costs.

First published in 2001, Balmorel has progressively been developed and validated through collaboration between various research institutions and consultancies across different countries, evolving with the needs of the energy system. Balmorel's core model structure is illustrated in Fig. 2, along with its various types of generators, demands and fuels. Further details on the formulation, development, capabilities, and applications of Balmorel are described by Wiese et al. [64].

Balmorel can be modularly extended to provide enhanced modelling capabilities and include new energy carriers or sectors. In this study, we developed an extension representing the cooling systems within data centres that jointly optimises them, along with the broader energy system, based on a portfolio of flexible-cooling and waste-heat technologies. Therefore, the investment and dispatch decisions of the data

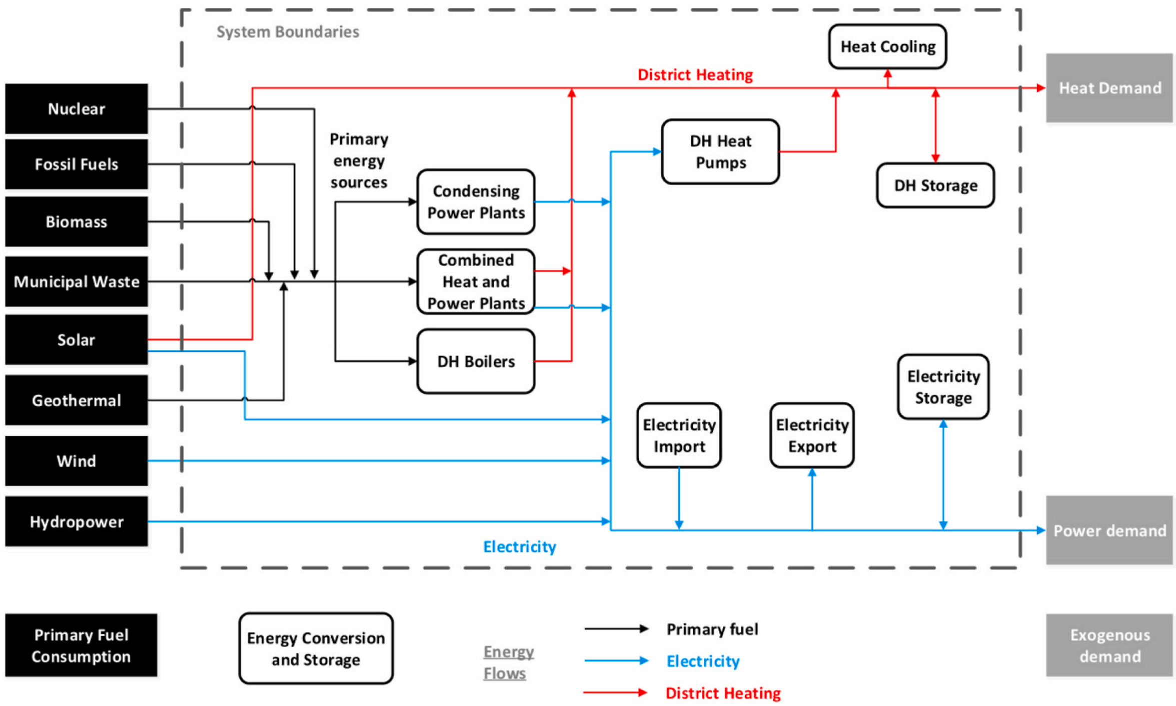

Fig. 2. Balmorel's core structure [64].

centre's cooling systems are made to minimise the total energy system cost. This detailed representation of data centres in Balmorel can be adapted to model different portfolios, types of data centres, geographic scales, and other industries with similar energy use, such as supermarkets.

3.2. Data centre modelling

This section broadly describes how data centres are modelled in Balmorel; more details of its implementation and formulation can be found in Ref. [65], while the model code is available in Ref. [66]. Data centres require electricity to operate their hardware and to produce cooling to keep it functioning at stable temperatures. The cooling load is considered equal to the electricity demand of the IT hardware, as all the electricity consumed is assumed to be dissipated as waste heat that needs to be removed [63]. These electricity and cooling demands are exogenously defined at each location and timestep. The cooling system of an integrated data centre is depicted in Fig. 3, detailing the technologies included in this analysis and their relationships with the broader energy system. These technologies are defined by parameters such as efficiencies, capital expenses, and operational expenses, fixed and variable, as described in Section 4.2.

Fig. 4 illustrates the internal representation of data centres in this extended Balmorel version. It includes all possible modelled technologies, energy flows and connections with other spatial elements of the core model. It should be noted that the extension supports absorption chillers (G_{ABS}), which have not been considered for this analysis.

The central equation in Balmorel representing data centres is their cooling balance, shown in Equation (2), where cooling production (χ_{G}^{cold}), which includes storage discharge, minus the charging of storage ($\gamma_{G_{sto}}^{cold}$) equals demand (D^{cold}) at each timestep.

$$\sum_{G}\chi_{T,G}^{cold} - \sum_{G_{sto}}\gamma_{T,G_{sto}}^{cold} = D_{T}^{cold} \tag{2}$$

Another important equation added to Balmorel relates the heat ($\chi_{T,G}^{heat}$) and cooling ($\chi_{T,G}^{cold}$) production of heat pumps through their heat-to-cold ratio ($\alpha_{T,G}$), as shown in Equation (3).

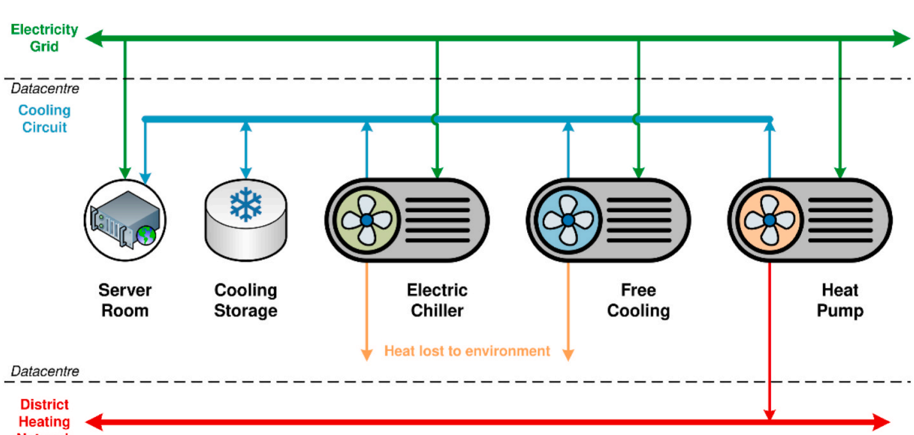

Fig. 3. Representation of the cooling system of an integrated data centre.

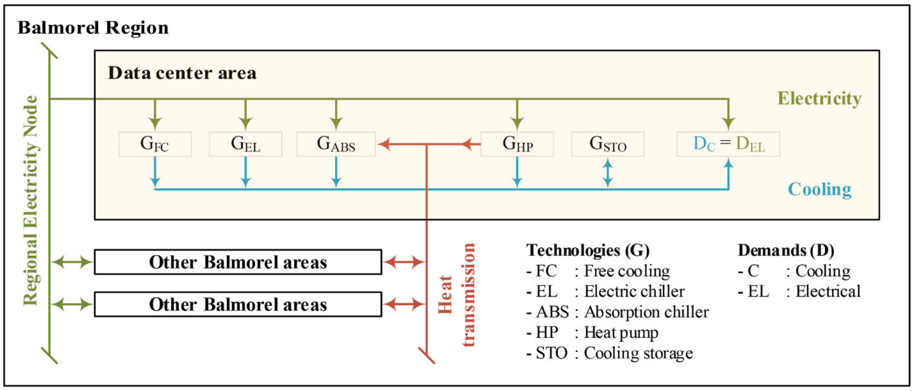

Fig. 4. Schematic implementation of an integrated data centre within Balmorel [65].

$$\chi^{heat}_{T,G_{hp}} = \alpha_{T,G_{hp}} \cdot \chi^{cold}_{T,G_{hp}} \tag{3}$$

The availability of free cooling to cover demand depends on the weather conditions at each timestep. Therefore, the production of free cooling technologies is represented by the availability parameter β_T as shown in Equation (4).

$$\sum_{G_{fc}} \chi^{cold}_{T,G_{fc}} \leq \beta_T \cdot D^{cold}_T \tag{4}$$

The characteristics of each technology are described below:

- **Free cooling:** Heat naturally flows outdoors whenever the outdoor temperature is lower than the server rooms', but its operation is possible only during specific periods. Minor costs and electricity use is required for fans and auxiliary equipment. It is assumed that its cooling production only covers instantaneous demand and cannot be stored.
- **Electric Chillers:** These devices cool a space by extracting heat from it and rejecting the heat outdoors after raising its temperature above the environment's. They operate through an electrically driven vapour compression cycle (shown in Figure C-1 in the appendix), in which a refrigerant circulates absorbing heat from the cooled space and releasing it outdoors as it undergoes changes in pressure and phase. Electric chillers are commonly used in data centres to meet cooling requirements when free cooling is unavailable, albeit at increased costs and energy use.
- **Heat Pumps:** These devices work similarly to electric chillers, albeit primarily designed to extract heat from the environment and generate useful heat at higher temperatures. When the heat source is a confined space, such as a server room, heat pumps effectively function as both heating and cooling systems. In this study, useful heat is injected into the district heating network, and due to the larger temperature gap, heat pumps consume higher electricity than electric chillers. The model determines whether to invest in the heat pump, connect it to the district heating network, and the capacity of this connection.
- **Cooling storages:** Thermal storages are defined based on their techno-economic parameters. They provide flexibility by decoupling cooling production and consumption.

3.3. Modelling scope

3.3.1. Sectorial scope

The following four main sectors of the energy system have been included in this analysis, based on the work of Gea-Bermúdez et al. [67]:

- Electricity: This sector is the backbone of the energy system, linking all other sectors included in this analysis. In contrast to Ref. [67], offshore hubs like those planned in the North Sea are not considered, as it is deemed that their development will not be significant within the temporal horizon of this analysis.
- Heating: This sector comprises three subsectors: district heating networks, individual users with private heating systems, and industries. District heating networks are aggregated based on their size to simplify the optimisation problem, whereas industries are aggregated by the heat temperature level.
- Hydrogen: This sector is an extension of the Balmorel core model and covers the conventional demand for hydrogen from industry and the future demand to produce synthetic fuels for heavy transport, shipping, and aviation. The industrial H_2 demand is based on scenario 1.5TECH of the European Commission's report *"A Clean Planet for All"* [68] and is assumed constant over time. The H_2 demand for synthetic fuels is based on [69], starting in 2030 and reaching up to 5.6 TWh in 2035.
- Integrated data centres: This sector includes two types of data centres: large-scale facilities associated with international corporations (e.g., Google, Apple, Meta) and extensive co-location facilities renting rack space or processing power to third parties. Estimations for their electricity demand are described in Section 4.1. Small data centres supporting the internal operations of single companies, often located inside their premises, are not included in this analysis.

3.3.2. Temporal scope

The optimisation period includes every year from 2023 to 2035. We consider this period to capture most of the data centre growth [70] and to avoid long-term uncertainties arising from data traffic, as technological and business developments make projecting data centre energy demand extremely difficult in the longer term.

Each year is optimised independently and consecutively in this study. The model makes investment decisions at the beginning of each year based on perfect foresight for that year and including investments made in previous ones, but without any information about future ones. The intra-year resolution is reduced to 192 timesteps to lessen the computational load and keep solving times manageable. Each year comprises eight 3-h timesteps per day, three days per week (two weekdays and one weekend day), and eight representative weeks. This selection process is intended to reflect seasonal patterns in energy consumption and the availability of renewable resources. Furthermore, the reduced time series data are scaled as described in Ref. [71], based on probability integral transformations, to align their statistical properties to those of the full-resolution time series.

3.3.3. Spatial scope

The scope of interest of this analysis covers Denmark. Norway, Sweden, and Germany are included in the model to account for their influence on cross-border electricity transmission to/from Denmark. Each country is subdivided into several regions based on electricity transmission constraints, as shown in Fig. 5. Denmark is divided into two

Fig. 5. Geographic modelling scope and intranational electricity transmission regions.

regions: east and west Denmark.

4. Data

The complete data set used for this Balmorel analysis is available at [72]. This section summarises the data characterising data centres, their portfolio, and their connection to district heating networks. Data for the other sectors of the energy system, as well as technology, fuel, and carbon costs, are taken from Refs. [51,67,73]. Carbon emissions are calculated based on fuel consumption and its respective emissions factor. This analysis applies a cost to carbon [74], but no carbon budget or any other limitation is implemented. Selected technology, fuel, and emissions data are presented in the appendix.

4.1. Data centre energy demand

Data centre electricity demand is based on forecasts prepared by the Danish Energy Agency [70], which consider large projects currently in operation, construction, or at a prospective stage. That report presents three scenarios based on the estimated probability of completion of future projects, resulting in a range of approximately ±30% by 2035. This analysis assumes that data centres will follow the "medium demand" scenario shown in Fig. 6,while the other demand scenarios are considered through a sensitivity analysis.

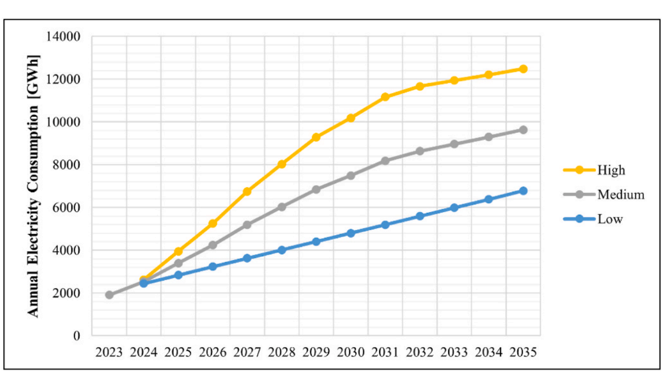

Fig. 6. Data centre electricity demand forecasts [70].

Table 1
Techno-economic parameters of cooling technologies in data centres.

	Free Cooling	Electric Chiller	Heat Pump	Thermal Storage	References
Investment costs [Million €/MW]	0	1.24	1.24	0.03	[76,77]
Fixed operation costs [€/MW]	0	2000	2000	8.43	[76,77]
Variable operation costs [€/MWh]	0	2.69	2.69	0.00	[76,77]
Cooling efficiency [MW_{th}/MW_{el}]	23.1	5.2	3.7	0.98	[75–78]
Heating efficiency [MW_{th}/MW_{el}]	–	–	4.7	–	[76]
Lifetime [y]	25	25	25	40	[76,77]
Hours to load/ unload [MWh/ MW]	–	–	–	6	[77]

4.2. Cooling technologies

The costs and efficiencies of cooling technologies in data centres are summarised in Table 1. Investment and operating costs of free cooling are assumed to be zero, as that equipment (e.g., dry-coolers, pumps, fans) is shared with electric chillers and heat pumps and already included in their costs. Costs from electricity use are accounted for through its cooling efficiency [75].

Temperatures in the datacentre water cooling loop are assumed to be 15 °C (supply)–20 °C (return). The heat pump's efficiency is calculated using these source temperatures, along with a constant sink temperature on the district heating side of 70 °C (supply)–35 °C (return), following the methodology outlined in Ref. [76]. The chiller's efficiency and the availability of free cooling are calculated based on the national-average hourly temperature from 2011 to 2019 [79]. The efficiency of the electric chiller follows the outdoor temperature, according to the relationship outlined in Ref. [78]. The availability of free cooling ranges from 100% at temperatures lower than 10 °C, to 0% at temperatures higher than 15 °C, as 5 °C are reserved for the heat exchange process with the environment. Fig. 7 shows the hourly availability of free cooling, which reaches an annual value of 67%.

4.3. District heating

As large data centres are usually located on the outskirts of cities due to better land availability, this analysis assumes investments in district heating transmission pipes of 12 km from the district heating network to the data centre facilities. This reflects the case of Apple's data centre in Viborg, Denmark. Table 2 summarises the costs of district heating connection.

4.4. Integration scenarios

Three integration scenarios have been set up based on varying levels of data centre integration: with the electricity sector through flexible cooling, with the district heating sector through waste-heat recovery, and with full integration through a combination of both. A fourth scenario, which does not consider integration, serves as a benchmark. These scenarios aim to assess the advantages of coupling with each

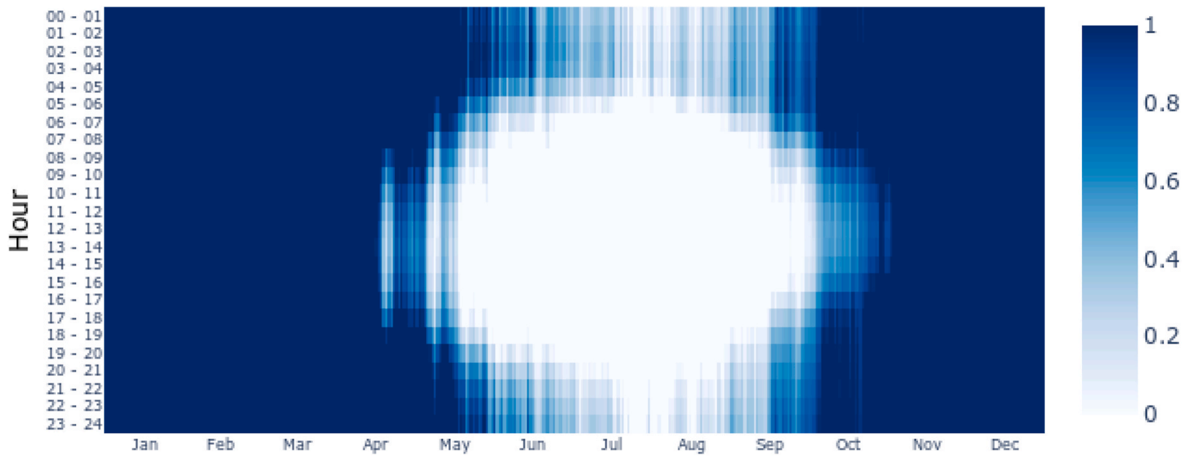

Fig. 7. Share of cooling demand that can be covered by free cooling, based on average Danish temperatures.

Table 2
District heating connection parameters [80].

Parameter	Value
Investment costs [Million €/MW]	0.4
Fixed operation costs [€/MW]	0.0
Variable operation costs [€/MWh]	0.1
Energy loss [%]	10%

sector and the enhanced benefits of a combined implementation.

Each scenario features a distinct portfolio of technologies that data centres are permitted to invest in to meet their cooling load, among the options shown in Fig. 3. Table 3 outlines the level of integration and specific technologies allowed for each scenario. In every scenario, investment and dispatch decisions are made to minimise the total costs of the energy system.

5. Results

This section presents the systemic impacts of data centre integration by analysing its effects on district heating production, electricity generation, emissions, and costs. Supplementary results on generation capacity are summarised in the appendix. These results focus exclusively on Denmark and do not include the neighbouring countries. In each subsection, results are first presented in absolute terms for the **BASELINE** scenario. After that, the results for each integration scenario (**HEAT**, **FLEX** and **FULL**) are presented as differences relative to **BASELINE** to highlight the net effects of integration.

5.1. District heating production: waste-heat displaces other power-to-heat sources

In the first years, district heating production in **BASELINE** is dominated by thermal power plants using fossil fuels, biomass, and municipal waste, followed by electrified heat, as illustrated in Fig. 8. These plants are gradually displaced by electrified heat except for municipal waste,

Table 3
Scenarios based on the type of integration and allowed portfolio.

Scenario	Level of integration	Means of integration	Technology portfolio			
			Free Cooling	Electric Chiller	Cooling Storage	Heat Pump
BASELINE	No integration	–	✓	✓	–	–
FLEX	Electricity sector	Flexible cooling	✓	✓	✓	–
HEAT	DH sector	Waste-heat recovery	✓	✓	–	✓
FULL	Full integration	Both	✓	✓	✓	✓

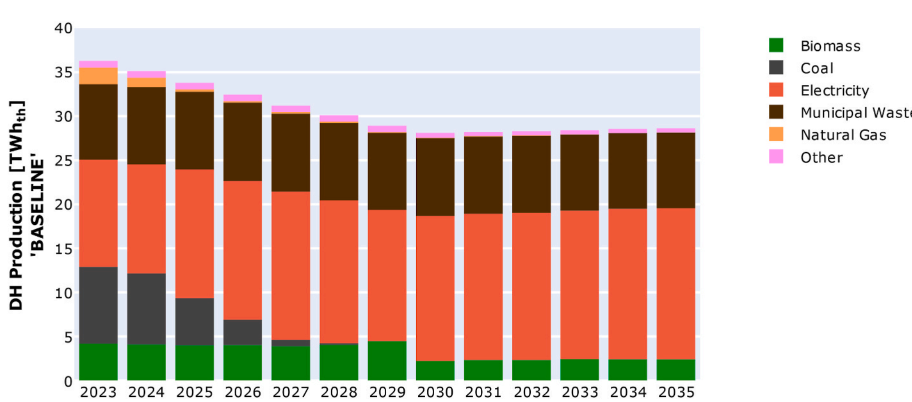

Fig. 8. District heating production by fuel in scenario BASELINE.

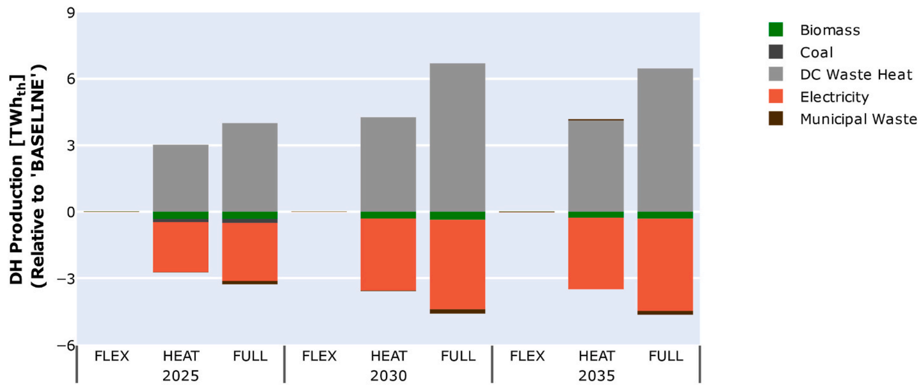

Fig. 9. Change in district heating production per scenario by fuel, relative to 'BASELINE'.

Table 4
Share of data centre waste-heat in district heating production.

	2025	2030	2035
HEAT	9%	16%	15%
FULL	12%	24%	22%

which has priority access to the market and remains constant over the analysed period. The share of thermal generation goes from 62% to 35% in 2023-2035, with natural gas and coal being displaced by 2028.

Net changes in district heating production are depicted in Fig. 9. **FLEX** shows practically no changes, as data centres cannot recover heat in this scenario. There is significant waste-heat utilisation in **HEAT** and **FULL** at the expense of other power-to-heat technologies. More importantly, waste-heat recovery is higher in **FULL** than in **HEAT**, showing that cooling flexibility allows exploiting waste-heat recovery when it is most helpful for the broader system while cooling is stored for when the data centre needs it. Table 4 summarises the share of data centre waste heat in district heating supply, reaching above 20% in the next decade.

5.2. Electricity generation: sector coupling brings higher exports and lower generation needs

Electricity generation in **BASELINE** is strongly expanded between 2025 and 2035, driven by electricity exports, data centres consumption, and electrified heat (Fig. 10). Net exports account for roughly a third of production. Electricity production becomes dominated by wind and solar, while co-generation plants running on coal and natural gas are displaced by 2028.

Fig. 11 details changes in electricity production in the three integration scenarios. **FLEX** allows temporal demand shifting, altering the availability of surplus electricity for exports. As a result, differences in electricity production go from -0.25 TWh$_{el}$ to $+0.15$ TWh$_{el}$ between 2025 and 2035, closely followed by export differences from -0.23 TWh$_{el}$ to $+0.21$ TWh$_{el}$, as shown in Table 5.

Besides, scenarios **HEAT** and **FULL** show more considerable changes in electricity production due to the displacement of power-to-heat technologies and subsequent reduced electricity demand, thereby freeing up production for simultaneously increasing exports and reducing the generation capacity required to feed the displaced technologies. Approximately 2 GW of installed photovoltaic capacity will be saved in **FULL** from 2030. Additionally, the combined electricity savings of **FLEX** and **HEAT** are higher than those observed in **FULL**, suggesting a synergy effect between flexible cooling and waste-heat recovery.

5.3. System costs: flexibility benefits data centres, while heat recovery the system

Fig. 12 shows the annual system costs in **BASELINE** by cost category. They include the full sectoral scope of this analysis: the electricity, heating, hydrogen, and data centre sectors. System costs are stable until 2027 and rise significantly afterwards due to the generation investments required to meet increasing electricity demand from sector coupling and data centres, as well as electricity exports. Their distribution goes from a roughly equal split between capital, operational and fuel expenses, which reflects current systems with significant thermal generation, to one dominated by capital expenses with a considerable reduction of fuel costs, reflecting a future system sector dominated by wind and solar energy.

Table 6 summarises the impacts on annual system-wide costs due to data centre integration, with the highest savings occurring in the **FULL** integration scenario, reaching up to 7.0% in 2030 alone. Fig. 13 details those by type, where two main trends are observed. Firstly, savings increase over time in all scenarios; secondly, the synergic effect between

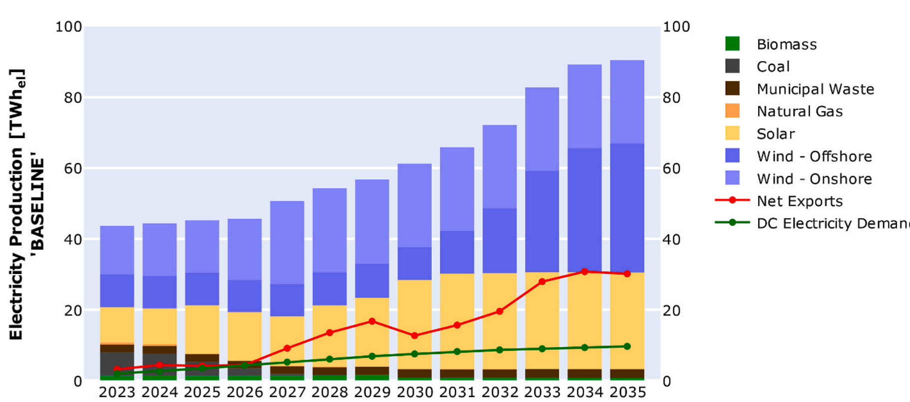

Fig. 10. Electricity production in scenario BASELINE.

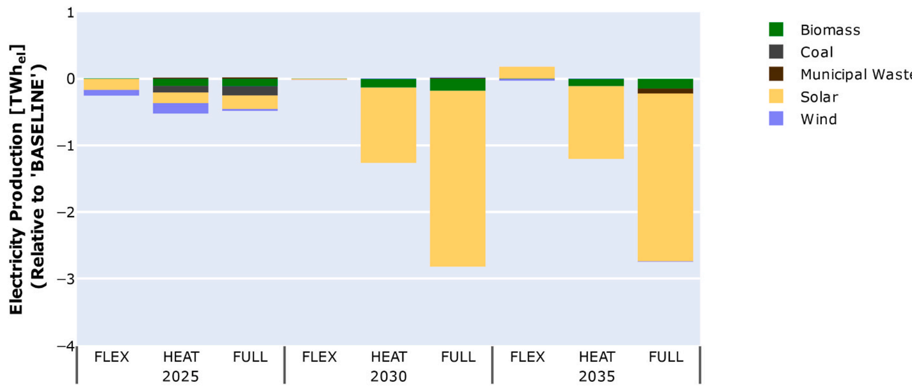

Fig. 11. Change in electricity production per scenario, relative to 'BASELINE'.

Table 5
Changes in net electricity exports [TWh$_{el}$] based on integration scenarios relative to BASELINE.

Scenario	2025	2030	2035
BASELINE	4.09	12.68	30.13
FLEX	−0.23	+0.08	+0.21
HEAT	−0.15	+1.24	+3.24
FULL	−0.01	+2.08	+5.73

flexible cooling and waste heat recovery is also present, with cost savings in **FULL** being higher than those of **HEAT** and **FLEX** combined.

Contrary to the results above, **FLEX** provides higher savings than **HEAT**, mostly from reduced chiller capacity within data centres, thus primarily benefiting data centre operators. Savings in **FULL** and **HEAT** also include fuel and operational expenses from displaced heat generators, benefiting the energy system as a whole. However, extending the district heating network to the location of each data centre offsets part of these savings. District heating connection expenses are slightly lower in **FULL**, as cooling storages reduce the peak capacity of heat pumps and the district heating network connection.

5.4. *Carbon emissions: the benefits lie in the short-term*

Fig. 14 depicts emissions in **BASELINE** scenario, where a strong decarbonisation path is observed until 2030, in which co-generation units are steadily displaced. However, complete decarbonisation is not achieved as some natural gas is kept in use by heat-only boilers outside district heating areas. The carbon emission costs are insufficient to completely decarbonise the system within the analysed period.

Table 7 summarises the impacts of data centre integration on carbon emissions, with relative changes of less than ±2%. Fig. 15 shows that emissions reduction in **FLEX** is marginal, mainly affecting electricity generation from carbon-free sources. The main benefit in terms of emissions comes from waste-heat recovery. In the long-term, the change in emissions is smaller as the system is mainly decarbonised where data centres are located. This results in practically all emission savings being associated with an earlier coal phase-out in the short term.

5.5. *Cooling portfolio in data centres*

Cooling generation in data centres is summarised in Table 8, showing that full integration increases the share of heat pumps by approximately 20%, compared to **FULL**, while doubling storage utilisation.

Fig. 16 illustrates the hourly cooling production within data centres, highlighting distinct seasonal patterns in **FLEX** and **HEAT**. Cooling storages (**FLEX**) are exclusively active in summer when free cooling is unavailable, enabling electric chillers to maintain a steady load. Conversely, heat pumps (**HEAT**) primarily operate in winter, relying on free cooling as the peak producer, whilst their generation in summer is severely limited. Full integration (**FULL**) allows these two technologies to complement each other and operate year-round, enabling heat pumps

Table 6
System cost and differences due to integration.

Annual system costs [Million €]	Year			
	2025	2030	2035	2023-2035
BASELINE	2678	2961	4289	40,916
FLEX	−49 (−1.8%)	−96 (−3.3%)	−121 (−2.8%)	−1042 (−2.5%)
HEAT	−29 (−1.1%)	−64 (−2.2%)	−71 (−1.7%)	−687 (−1.7%)
FULL	−72 (−2.7%)	−207 (−7.0%)	−243 (−5.7%)	−2092 (−5.1%)

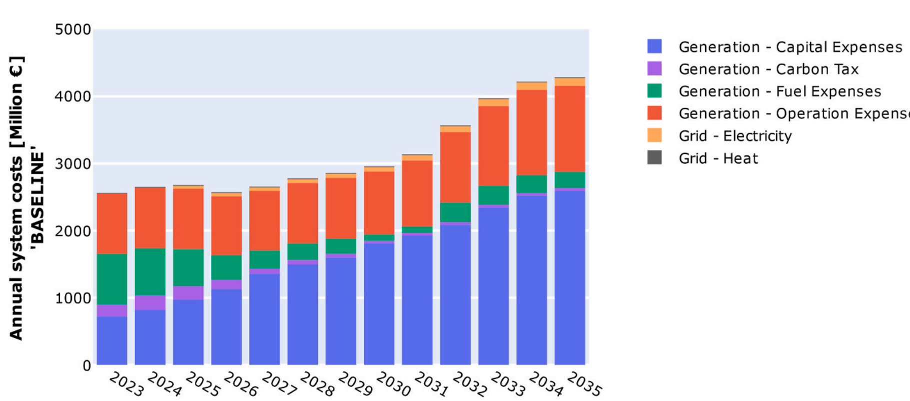

Fig. 12. System costs in scenario 'BASELINE'.

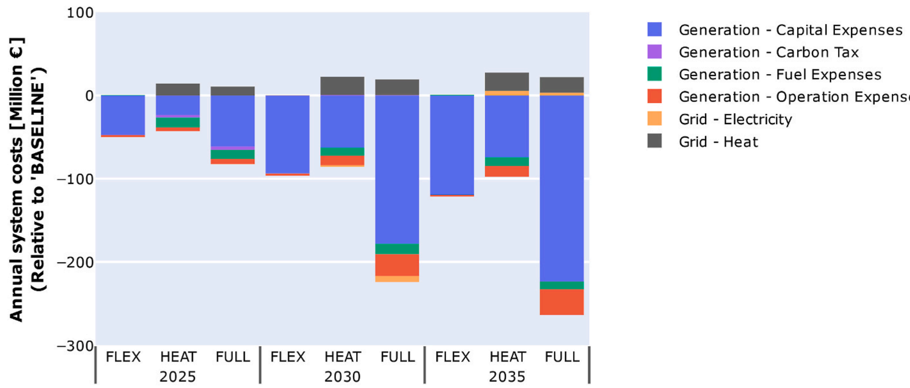

Fig. 13. Change in system costs per scenario relative to 'BASELINE'.

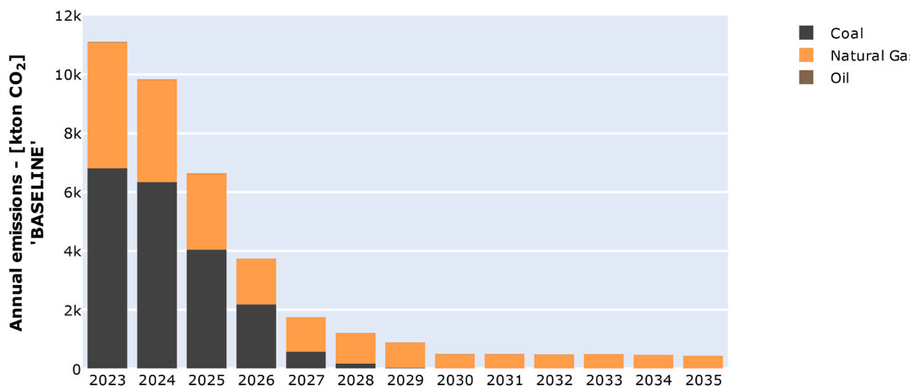

Fig. 14. System carbon emissions in scenario 'BASELINE'.

Table 7
System emissions and differences due to integration.

Annual CO_2 emissions [kton]	Year			
	2025	2030	2035	2023-2035
BASELINE	6633	490	433	37,987
FLEX	−2.4 (−0.0%)	−2.1 (−0.4%)	+0.2 (+0.1%)	+47 (+0.1%)
HEAT	−99.1 (−1.5%)	+6.7 (+1.4%)	+0.8 (+0.2%)	−294 (−0.8%)
FULL	−138.0 (−2.1%)	+4.9 (+1.0%)	+0.2 (+0.1%)	−518 (−1.4%)

to operate mostly at constant load. Fig. 17 depicts the district heating demand and heat recovered from data centres, indicating that heat pumps can supply the summer base demand by 2035, thanks to full integration.

5.6. *Sensitivity analysis: data centre demand pathways*

The scenarios presented so far considered the "medium" data centre projection from Ref. [70], previously shown in Fig. 6. This sensitivity analysis tests how the lowest and highest demand projections affect system costs and carbon emissions. Two situations are compared: no integration, as in **BASELINE**, against fully integrated data centres, as in **FULL**. The previous section showed how impacts from data centres could be alleviated with different levels of integration. In this sensitivity, we explore how effectively full integration mitigates the effects of the

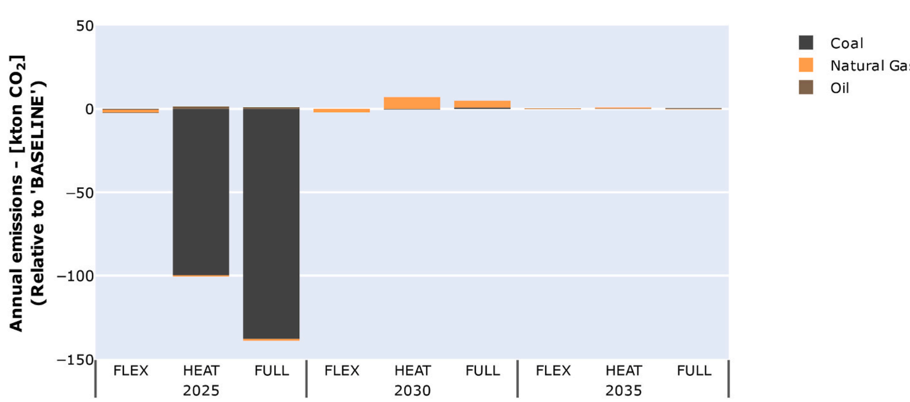

Fig. 15. Change in system carbon emissions per scenario, relative to 'BASELINE'.

Table 8
Data centre cooling generation by technology.

Year	Scenario	Free cooling	Electric Chiller	Heat Pump	Thermal Storage[a]
2025	**BASELINE**	63%	37%	0%	0%
	FLEX	62%	38%	0%	14%
	HEAT	14%	16%	70%	0%
	FULL	7%	0%	93%	28%
2030	**BASELINE**	63%	37%	0%	0%
	FLEX	62%	38%	0%	13%
	HEAT	28%	27%	45%	0%
	FULL	24%	6%	70%	28%
2035	**BASELINE**	63%	37%	0%	0%
	FLEX	62%	38%	0%	13%
	HEAT	36%	30%	34%	0%
	FULL	34%	13%	53%	29%

[a] Indicates cooling demand met by thermal storage, while other technologies show cooling generation and sum up to 100%.

data centre industry. For this reason, the following results are presented relative to a situation where no data centres are installed in Denmark (NO-DC).

Fig. 18 depicts the additional costs due to the energy supply for data centres. The distance between both lines represents the cumulative savings from data centre integration up to that year. By 2035, integration offsets a significant share of the costs associated with their energy demand: 66%, 63%, and 57% for low, medium, and high-demand situations, respectively. **This reveals the cost to society of not integrating data centres, as it demonstrates that full integration can significantly alleviate the energy supply cost incurred by their operations.** Fig. 18 also shows lower returns from integration at higher levels of data centre demand, but still over 50%, indicating that integration is worth promoting in any projected scenario. Additionally, costs from integrated data centres level off after 2033, whereas no-integration costs keep rising. This suggests that integration is more effective the more flexible and coupled the electricity and district heating sectors are, allowing the synergies from combined flexible electricity consumption and waste-heat recovery to be fully exploited.

Fig. 19 shows the additional cumulative emissions from data centres' energy supply. Contrary to costs, integration offsets more emissions than those associated with non-integrated data centres' demand. **This shows data centre integration as an effective tool for decarbonisation and highlights the environmental costs of non-integration.** Net emission savings (shown as a negative value) from integration occur from the first year and reach their peak by 2027; a trend slowly reversed in later years as the system is mostly decarbonised by that point. For this reason, early adoption of integration is essential to exploit its decarbonising potential. By 2035, integration has mitigated emissions for 760–1050 ktons (difference between green and red lines), equivalent to 180% of all emissions that non-integrated data centres would have incurred, regardless of demand level.

6. Discussion

Data centre cooling-based flexibility by itself has a limited potential, as shown by **FLEX** carrying zero or marginal effects on energy production and emissions. However, it brings significant cost savings due to reduced investments in electric chillers needed to cover peak cooling demand in summer periods without free cooling. For this reason, these

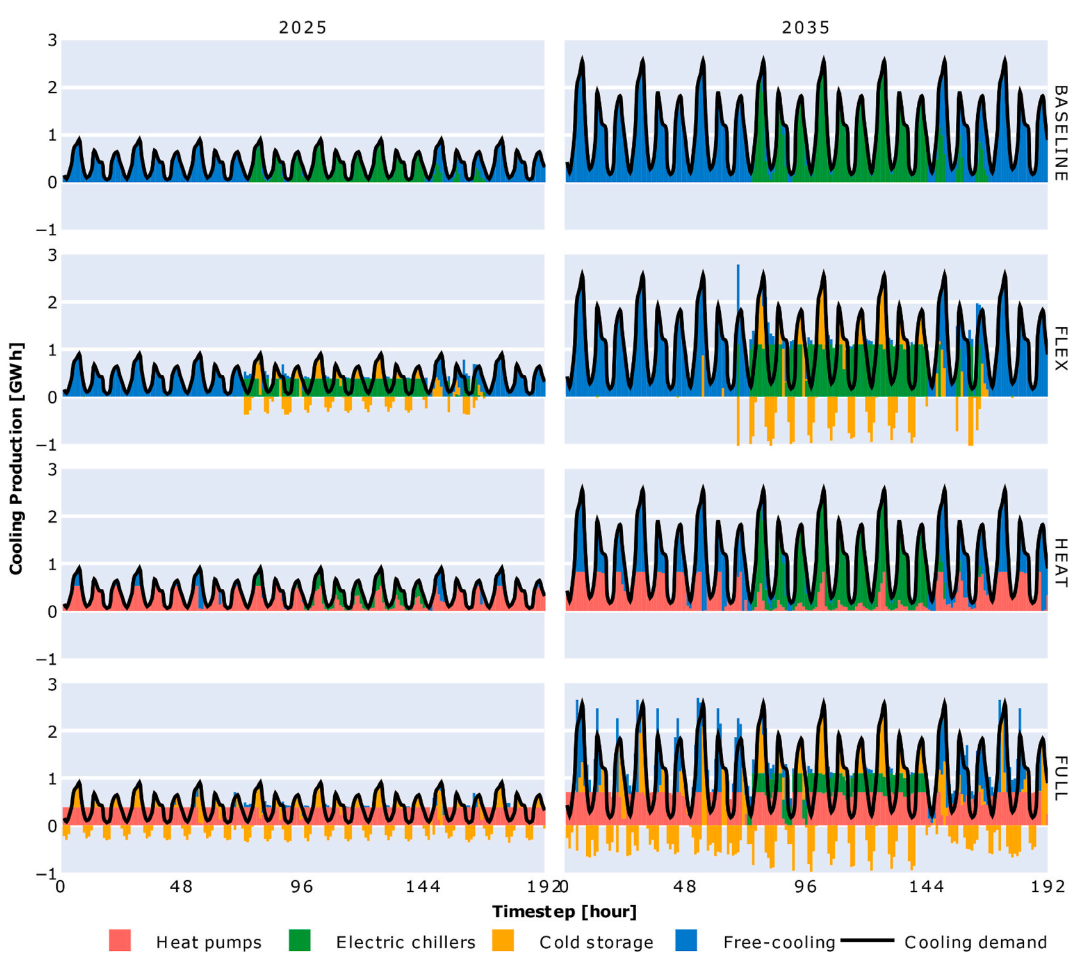

Fig. 16. Hourly profile of cooling demand and generation.

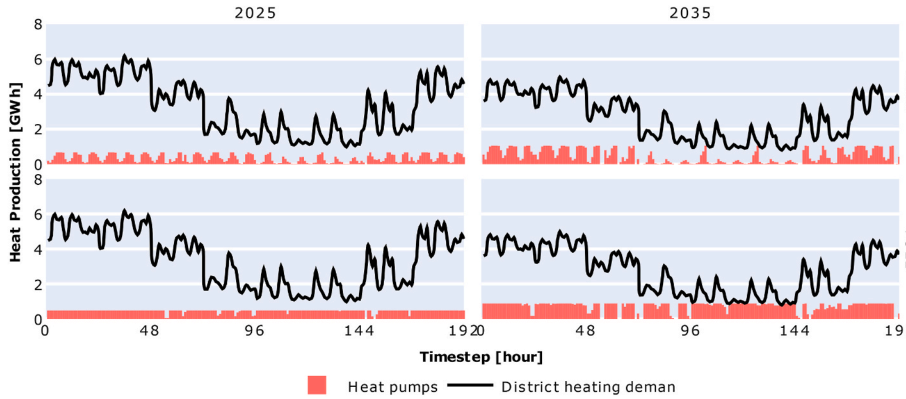

Fig. 17. Hourly profile of waste-heat recovery and district heating demand.

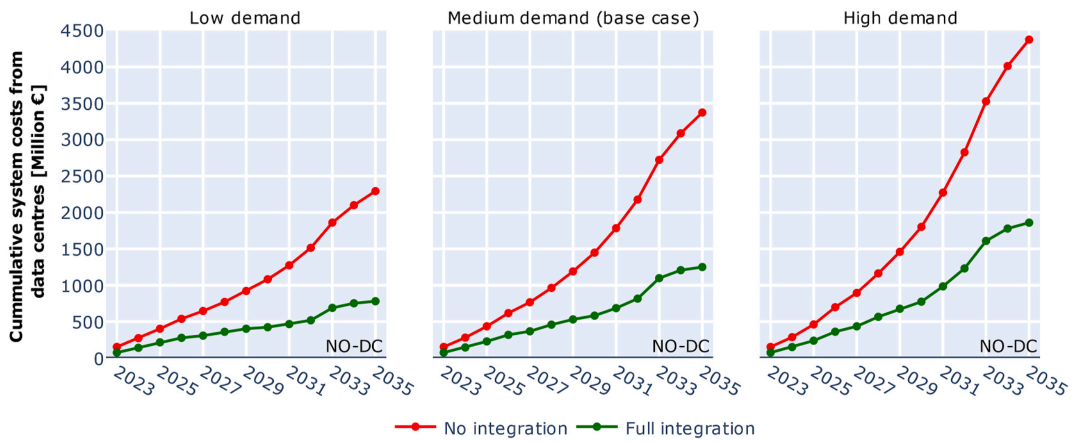

Fig. 18. Cumulative data centre energy supply costs.

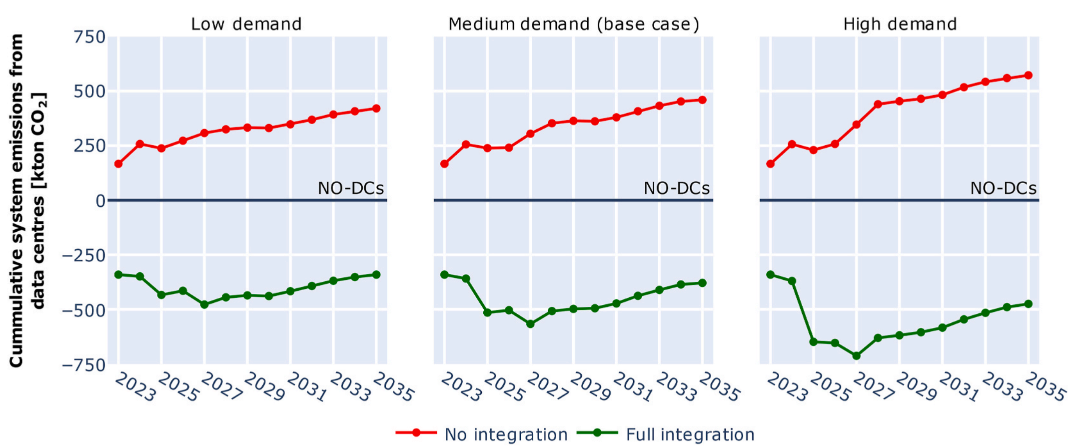

Fig. 19. Cumulative data centre energy supply emissions. Positive values represent increased emissions; negative ones represent net emissions savings.

gains are estimated to mostly benefit data centre operators financially. On the other hand, several factors explain the reduced effect of flexibility alone in the rest of the system. Firstly, cooling generation for data centres accounts for less than 2% of the total system demand and only 9% of total data centre demand. Secondly, cooling storages compete with cheap but inflexible free-cooling, which is abundant in this study case and is prioritised whenever possible, thus operating only in summer periods. Lastly, the energy system becomes highly flexible thanks to other Power-to-X technologies, further reducing the need for flexibility. Consequently, exclusive cooling-based flexibility is deemed economically beneficial at a facility level.

On the other hand, waste-heat recovery (**HEAT**) carries considerable impacts not only in the district heating systems but also in the electricity sector, thanks to their high future electrification. According to our findings, data centres can provide up to 24% of the Danish district heating supply in the next decade, in line with the results obtained by Refs. [63,81]. Additionally, they displace other power-to-heat technologies, such as heat pumps and electrolysers. The outcome is a lower electrical demand for heating purposes, as conventional heat pumps are less efficient than those within data centres, due to the lower heat source temperature of the former. The energy system adjusts to this situation in two ways: with a higher electricity surplus committed for exports and reduced investments in photovoltaic capacity of up to 1 GW, contributing significantly to cost savings. This highlights the importance of considering cross-sector interactions while assessing the benefits of waste-heat recovery in the energy system.

More importantly, synergic effects are unlocked from the combined use of flexibility and waste-heat recovery (**FULL**), as flexibility decouples data centre cooling demand from heat generation by heat pumps. Therefore, heat pumps displace more free cooling during winter and generate cooling throughout summer. In this scenario, heat recovery is 57% higher than in **HEAT** in 2035, strengthening its effects on electricity generation, costs, and emissions. The synergy is revealed as the savings in costs and emissions are 21% and 100% larger, respectively, than the combined values from **FLEX** and **HEAT**. This synergy underscores the potential of turning data centres into a sector-coupling interface, amplifying integration gains.

Emission savings take place only in the short-term due to an earlier coal phase-out and reach up to 2% per year in 2025. However, data centres do not contribute to these savings after 2030, as the system is already mostly decarbonised. These results align with the current European regulatory efforts to incentivise data centres to connect to district heating networks [82] and the Danish regulation of third-party district heating supply [83]. These results also highlight that future policy should promote heat recovery as soon as possible and foment electrical flexibility due to the abovementioned synergic effects.

The sensitivity analysis evaluates how different data centre growth projections affect system costs and emissions while also assessing how effective integration is to alleviate the effects of the data centre industry on energy supply. Full integration mitigates between 57% and 66% of the cumulative energy supply associated with non-integration. The larger benefits are realised in the long term, suggesting that integration is more effective in a strongly coupled system. More importantly, integration is shown to offset more carbon emissions than non-integrated data centres would have generated, resulting in negative emissions for the energy system receiving this industry (+180%, regardless of the scenario). These results underline the capacity of integration to function as a tool for decarbonisation.

All in all, this work refocuses the perspective of data centre sustainability analysis from the facility to the systemic level by considering the substitution effects triggered by their integration. It shows how system evolution influences its effects, e.g., carbon savings occur before 2030 because of fast decarbonisation. Finally, this study emphasises the enhanced gains obtained from two-sided integration that allows data centres to strengthen the adaptability of the energy system through sector coupling.

6.1. Limitations and future work

Certain limitations in the modelling methodology stem from adopting a purely linear model formulation, rather than one permitting integer variables. The linear formulation, preferred by its speed and tractability, does not account for unit commitment constraints. Nevertheless, the absence of these constraints likely has a limited influence on the results, considering the high participation of flexibility options in the model [84]. Another limitation emerges from consolidating similar, yet distinct, district heating networks into singular nodes. While this method reduces the model's complexity, it leads to data centres impacting generators in different networks. Nevertheless, most of the data centres considered in this analysis are expected to arrive near networks large enough to accommodate their heat output.

Several limitations of this analysis could affect the magnitude of these results. Regarding flexibility, the low temporal resolution (with only 192 timesteps) might limit the cost-effectiveness of storage technologies. Additionally, neither partial-load efficiencies nor start-up costs have been represented, effectively improving the potential for flexible operation of all energy generation assets. Furthermore, the potential from participation in balancing power markets is not considered, as there is no uncertainty between generation and demand profiles implemented in this analysis. The flexibility potential from data centres could also be improved by implementing temporal shifting of workloads and backup batteries, which has been widely analysed from a facility-focused perspective [29,85,86]. Moreover, these results are based on a single hourly electricity consumption profile. Considering different consumption profiles seems desirable as the flexibility potential depends on the mismatch between this consumption and variable renewable sources.

On the other hand, further detail in the spatial dimension would limit the potential of district heating networks to accept data centres' waste heat. District heating networks are currently lumped together based on their scale, merging networks that are not geographically close. For this reason, not all heat could be used if, for example, the data centre is located next to a network with low heat demand. Improving these issues would also allow for optimising the location of data centres themselves, so that their waste heat is recovered in the areas that need it the most.

Finally, further work could be carried out to test the universality of these results in other contexts with different shares of renewable energy, other climate conditions, lighter sector coupling, or fewer connections to larger neighbouring energy systems. This work will serve as a basis for analyses aimed at investigating policies promoting data centre integration in aspects such as subsidies, price ceilings present in current Danish regulation [83], and allocation of investments between data centre operators and district heating companies.

7. Conclusions

This paper estimates the potential impacts of integrated data centres providing flexible-cooling and waste-heat recovery in the Danish energy system by 2035. This estimation is based on an extended version of the Balmorel energy system that includes the cooling portfolio of data centres, allowing them to invest in cooling storage and heat pumps, in addition to conventional electric chillers and free cooling. Three scenarios are considered to evaluate the singular impacts of demand response and waste-heat recovery separately, as well as the synergies from a combined operation. These scenarios are benchmarked against data centres operating conventionally without integration.

The following findings are gained throughout the analysis: Firstly, flexible cooling (**FLEX**) operates exclusively in summer and reduces the electric chiller's capacity. Despite having only marginal effects on energy production and emissions, it saves 2.5% of total system costs. Secondly, waste-heat recovery (**HEAT**) displaces other power-to-heat technologies, reducing emissions by 0.8% and costs by 1.7%. However, heat recovery declines sharply during the summer months. Most important, however, are the synergies resulting from combining the two technologies, as they complement each other and operate year-round. As a result, 50% more waste-heat is recovered, reaching a level around the base district heating demand during summer. On the one hand, cost savings increase to 5.1%, mainly due to lower investments in power-to-heat technologies and electricity generation required to operate them. On the other hand, emission savings rise to 1.4% thanks to lower coal-based co-generation. Therefore, full integration amplifies the benefits achieved by partial integration.

Due to the high uncertainty in data centre development projections, a sensitivity analysis is conducted to explore how the above results adjust as demand levels vary. It is found that cost and emission savings increase as demand increases, albeit offering diminishing returns concerning costs. Integration offsets about 60% of the energy supply costs that non-integrated data centres would incur. More importantly, it has the potential of saving a quantity equivalent to 180% of their emissions, regardless of the level of demand, thanks to the displaced coal-based heat generation. This highlights integration as an effective tool for decarbonising energy systems in a context where the continued expansion of this industry may further challenge the ability to meet climate targets.

Establishing an additional sector interface through data centre integration further decarbonises the heating sector, frees up renewable electricity capacity, enhances system adaptability, and improves energy security by using local resources. However, although integration yields economic benefits throughout the entire period, environmental gains are only realised in the short-term. Therefore, any supporting policies should encourage a fast adoption of integration and ensure that waste-heat recovery is complemented with cooling flexibility.

The methodology developed in this article is applicable to any other energy system facing similar data centre development to assess the range of outcomes arising from their deployment and potential benefits from integration. It can also be adapted to represent other economic sectors with similar uses for cooling, e.g., supermarkets or pharmaceuticals. Although this analysis focuses on Denmark, these results could be relevant to other regions with relatively cold climates, high shares of variable renewable electricity, and extensive district heating networks.

CRediT authorship contribution statement

Juan Jerez Monsalves: Conceptualization, Methodology, Software, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Claire Bergaentzlé:** Conceptualization, Writing – review & editing, Validation, Supervision. **Dogan Keles:** Conceptualization, Writing – review & editing, Validation, Supervision.

Declaration of competing interest

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

Data availability

The link to data/code has been shared in the article.

Acknowledgements

This paper derives from the research activities of the "Cool-Data" project, funded by the Innovation Fund Denmark (Project number: 0177-00066B). The authors are responsible for the content of this work.

A. Appendix – Complementary Results

Table A1
District heating production by fuel type and scenario, in TWh_{th}.

Year	Fuel	Scenario			
		BASELINE	FLEX	HEAT	FULL
2025	**Biomass**	3.99	4.01	3.67	3.67
	Coal	5.35	5.35	5.21	5.17
	DC Waste Heat	0.00	0.00	3.03	4.00
	Electricity	14.60	14.59	12.34	11.98
	Municipal Waste	8.82	8.82	8.81	8.68
	Natural Gas	0.27	0.27	0.29	0.29
	Other	0.75	0.75	0.75	0.72
	Total	**33.78**	**33.79**	**34.10**	**34.51**
2030	**Biomass**	2.22	2.24	1.91	1.86
	DC Waste Heat	0.00	0.00	4.27	6.70
	Electricity	16.46	16.44	13.20	12.41
	Municipal Waste	8.82	8.82	8.80	8.63
	Natural Gas	0.06	0.06	0.06	0.06
	Other	0.55	0.55	0.54	0.53
	Total	**28.11**	**28.11**	**28.78**	**30.19**
2035	**Biomass**	2.40	2.41	2.13	2.08
	Coal	0.00	0.00	0.00	0.00
	DC Waste Heat	0.00	0.00	4.12	6.47
	Electricity	17.15	17.14	13.91	12.98
	Municipal Waste	8.59	8.57	8.65	8.42
	Natural Gas	0.02	0.02	0.02	0.02
	Other	0.46	0.46	0.46	0.46
	Total	**28.62**	**28.60**	**29.29**	**30.43**

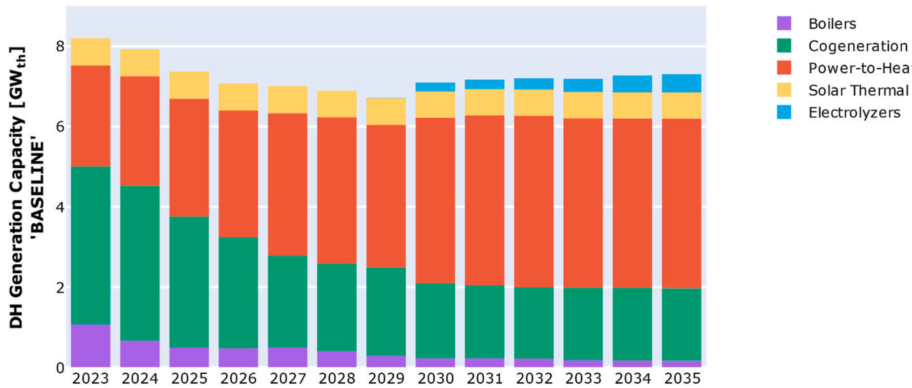

Fig. A1. District heating generation capacity, by technology type, in 'BASELINE' scenario.

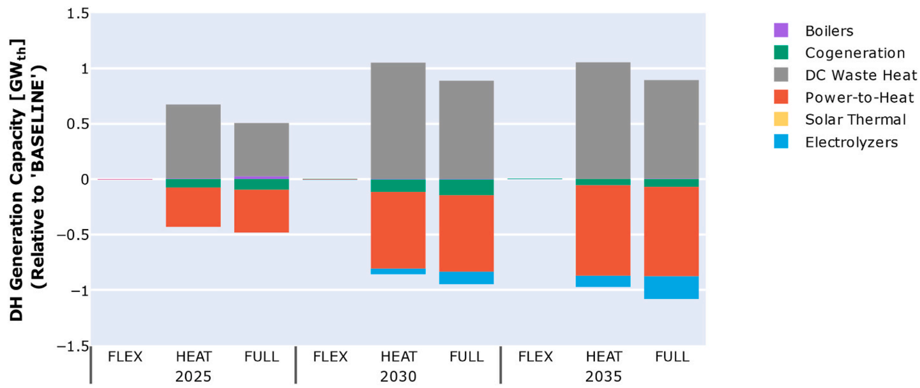

Fig. A2. Change in district heating generation capacity by technology type per scenario, relative to 'BASELINE'.

Table A2
Electricity generation by fuel type and scenario, in TWh$_{el}$.

Year	Fuel	Scenario			
		BASELINE	FLEX	HEAT	FULL
2025	**Biomass**	1.26	1.26	1.15	1.15
	Coal	4.02	4.02	3.92	3.88
	Municipal Waste	2.14	2.14	2.16	2.16
	Natural Gas	0.16	0.16	0.16	0.16
	Other	0.03	0.03	0.03	0.03
	Solar	13.66	13.49	13.50	13.46
	Wind - Offshore	9.24	9.24	9.24	9.24
	Wind - Onshore	14.75	14.66	14.59	14.72
	Total	**45.26**	**45.00**	**44.75**	**44.80**
2030	**Biomass**	0.74	0.75	0.61	0.56
	Municipal Waste	2.42	2.42	2.42	2.44
	Natural Gas	0.07	0.07	0.07	0.07
	Other	0.06	0.06	0.06	0.06
	Solar	25.15	25.14	24.02	22.51
	Wind - Offshore	9.29	9.29	9.29	9.29
	Wind - Onshore	23.56	23.56	23.56	23.57
	Total	**61.29**	**61.29**	**60.03**	**58.50**
2035	**Biomass**	0.67	0.68	0.56	0.53
	Municipal Waste	2.50	2.49	2.50	2.42
	Natural Gas	0.03	0.03	0.03	0.03
	Other	0.06	0.06	0.06	0.06
	Solar	27.31	27.48	26.22	24.79
	Wind - Offshore	36.47	36.46	36.47	36.47
	Wind - Onshore	23.52	23.50	23.52	23.51
	Total	**90.56**	**90.70**	**89.36**	**87.81**

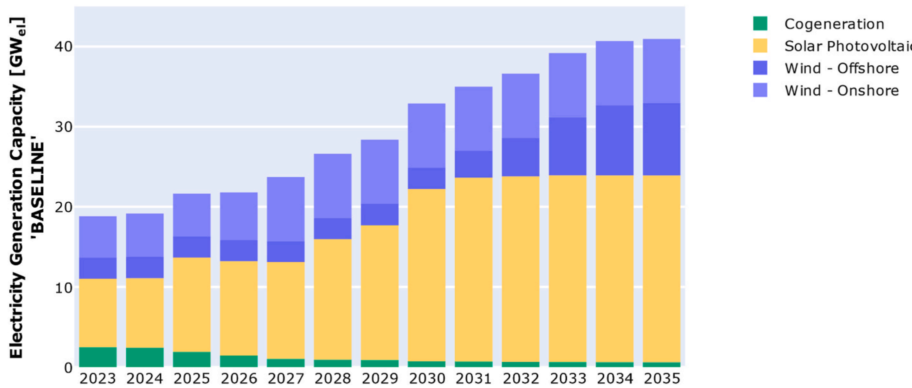

Fig. A3. Electricity generation capacity, by technology type, in 'BASELINE' scenario.

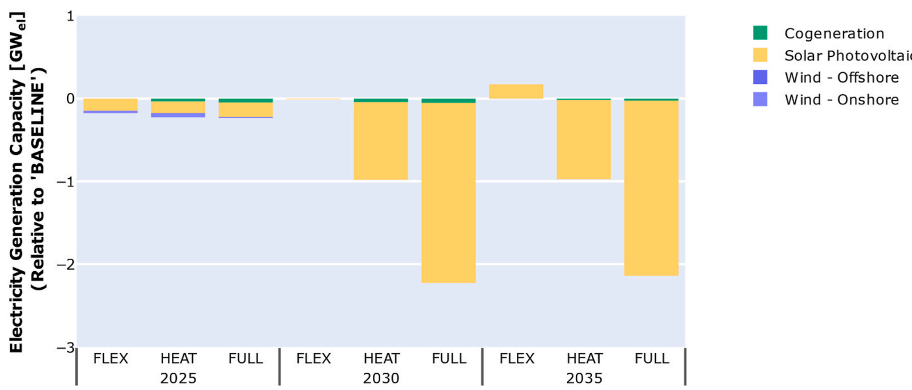

Fig. A4. Change in electricity generation capacity by technology type, relative to 'BASELINE'.

Table A3
Annual system costs by scenario, in million €.

Year	Category	Scenario			
		BASELINE	FLEX	HEAT	FULL
2025	**Generation - Capital Expenses**	974	927	951	913
	Generation - Carbon Tax	197	197	194	193
	Generation - Fuel Expenses	551	552	539	540
	Generation - Operation Expenses	902	900	898	896
	Grid - Electricity	41	41	41	41
	Grid - Heat	12	12	26	22
	Grid - Hydrogen	0	0	0	0
	Total	**2678**	**2629**	**2649**	**2606**
2030	**Generation - Capital Expenses**	1810	1717	1748	1632
	Generation - Carbon Tax	37	37	37	37
	Generation - Fuel Expenses	94	94	84	81
	Generation - Operation Expenses	937	934	925	910
	Grid - Electricity	67	67	65	60
	Grid - Heat	12	12	34	31
	Grid - Hydrogen	4	4	4	3
	Total	**2961**	**2865**	**2897**	**2755**
2035	**Generation - Capital Expenses**	2594	2475	2520	2371
	Generation - Carbon Tax	39	39	39	39
	Generation - Fuel Expenses	238	238	227	228
	Generation - Operation Expenses	1286	1284	1273	1255
	Grid - Electricity	115	115	120	118
	Grid - Heat	12	12	34	31
	Grid - Hydrogen	5	4	4	3
	Total	**4289**	**4168**	**4218**	**4045**

Table A4
Annual emissions by source and scenario, in kton CO_2.

Year	Fuel	Scenario			
		BASELINE	FLEX	HEAT	FULL
2025	**Coal**	4042.3	4042.0	3942.5	3904.3
	Natural Gas	2581.0	2579.3	2580.3	2579.9
	Oil	9.8	9.5	11.2	10.8
	Total	**6633.2**	**6630.7**	**6534.0**	**6495.1**
2030	**Coal**	4.0	4.0	3.7	4.8
	Natural Gas	477.8	475.7	484.8	481.9
	Oil	7.8	7.8	7.8	7.8
	Total	**489.6**	**487.5**	**496.3**	**494.5**
2035	**Coal**	2.3	2.2	2.4	2.8
	Natural Gas	428.8	429.2	429.5	428.6
	Oil	2.3	2.3	2.3	2.3
	Total	**433.4**	**433.6**	**434.2**	**433.6**

B. Appendix – Selected model data

Table B1
Fuel prices

Fuel Price	Year												
	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
NUCLEAR	0.758	0.758	0.758	0.758	0.758	0.758	0.758	0.758	0.758	0.758	0.758	0.758	0.758
NATGAS	6.843	7.245	7.647	7.782	7.918	8.053	8.189	8.324	8.421	8.518	8.615	8.711	8.808
COAL	2.469	2.521	2.573	2.593	2.613	2.633	2.653	2.673	2.68	2.686	2.693	2.7	2.706
LIGNITE	0.832	0.858	0.884	0.91	0.936	0.962	0.989	1.015	1.012	1.01	1.007	1.004	1.002
FUELOIL	7.429	8.096	8.764	9.431	10.098	10.766	11.433	12.1	12.072	12.044	12.016	11.988	11.96
LIGHTOIL	11.936	12.603	13.27	13.937	14.605	15.272	15.939	16.607	16.579	16.55	16.522	16.494	16.466
MUNIWASTE	−3.259	−3.259	−3.259	−3.259	−3.259	−3.259	−3.259	−3.259	−3.259	−3.259	−3.259	−3.259	−3.259
STRAW	5.764	5.963	6.163	6.362	6.562	6.761	6.961	7.16	7.34	7.52	7.701	7.881	8.061
WOOD	6.872	7.083	7.294	7.504	7.715	7.925	8.136	8.347	8.532	8.718	8.904	9.09	9.276
WOODWASTE	0.651	0.651	0.651	0.651	0.651	0.651	0.651	0.651	0.651	0.651	0.651	0.651	0.651
WOODCHIPS	6.2	6.2	6.2	6.2	6.2	6.2	6.2	6.2	6.2	6.2	6.2	6.2	6.2
BIOGAS	12.716	12.716	12.716	12.716	12.716	12.716	12.716	12.716	12.716	12.716	12.716	12.716	12.716
WASTEHEAT	0.088	0.088	0.088	0.088	0.088	0.088	0.088	0.088	0.088	0.088	0.088	0.088	0.088
PEAT	1.53	1.578	1.626	1.674	1.722	1.77	1.817	1.865	1.861	1.856	1.851	1.847	1.842

Table B2
Carbon emissions tax.

Year	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
CO_2 tax [€/ton]	15.77	22.01	29.72	37.08	45.3	54.39	64.34	75.16	78.17	81.17	84.18	87.18	90.19

Table B3
Technology options and costs.

Technology group	Fuel type	Available from year	Economic lifetime (years)	Investment cost (M€/MW)	Annual O&M costs (k€/MW)	Variable O&M cost (€/MWh_{out})	Variable O&M cost (€/MWh_{in})
BIOGASMETHANATION	BIOGAS	2020	25	0.889	35.562	4.234	
BIOGASMETHANATION	BIOGAS	2030	25	0.741	29.635	3.528	
BIOGASUPGRADING	BIOGAS	2020	15	0.419	10.388		
BIOGASUPGRADING	BIOGAS	2030	15	0.373	9.31		
BIOMETHDAC	HYDROGEN	2020	25	1.25	0.01		
BOILER	ELECTRIC	2020	30	0.947	7.84		
BOILER	ELECTRIC	2020	20	0.069	1.049	0.882	
BOILER	ELECTRIC	2020	20	0.147	1.049	0.882	
BOILER	ELECTRIC	2020	12.5	0.059	0		
BOILER	ELECTRIC	2030	30	0.915	7.513		
BOILER	ELECTRIC	2030	20	0.059	1	0.98	
BOILER	ELECTRIC	2030	20	0.137	1	0.98	
BOILER	MUNIWASTE	2020	25	1.903	79.766	6.215	
BOILER	MUNIWASTE	2030	25	1.814	74.764	6.23	
BOILER	NATGAS	2020	25	0.059	1.911	1.078	
BOILER	NATGAS	2020	20	0.304	20.09		
BOILER	NATGAS	2020	15	0.015	0.172	0.274	

(*continued on next page*)

Table B3 (*continued*)

Technology group	Fuel type	Available from year	Economic lifetime (years)	Investment cost (M€/MW)	Annual O&M costs (k€/MW)	Variable O&M cost (€/MWh_{out})	Variable O&M cost (€/MWh_{in})
BOILER	NATGAS	2030	25	0.049	1.862	0.98	
BOILER	NATGAS	2030	20	0.294	19.502		
BOILER	STRAW	2020	25	0.872	50.274	0.588	
BOILER	STRAW	2030	25	0.823	47.432	0.588	
BOILER	WOODCHIPS	2020	25	0.666	31.556	0.98	
BOILER	WOODCHIPS	2020	15	0.216	3.234	0.323	
BOILER	WOODCHIPS	2030	25	0.637	30.576	0.98	
BOILER	WOODPELLETS	2020	25	0.706	32.34	0.499	
BOILER	WOODPELLETS	2020	20	0.666	49.098		
BOILER	WOODPELLETS	2030	25	0.676	30.674	0.499	
BOILER	WOODPELLETS	2030	20	0.796	59.045		
COMBINEDCYCLE	NATGAS	2020	25	1.43	28.714	4.312	
COMBINEDCYCLE	NATGAS	2020	25	1.682	28.714		2.544
COMBINEDCYCLE	NATGAS	2020	25	1.274	28.714		2.199
COMBINEDCYCLE	NATGAS	2020	25	0.733	28.714	4.312	
COMBINEDCYCLE	NATGAS	2020	25	0.862	28.714		2.544
COMBINEDCYCLE	NATGAS	2030	25	1.349	27.244	4.116	
COMBINEDCYCLE	NATGAS	2030	25	1.587	27.244		2.511
COMBINEDCYCLE	NATGAS	2030	25	1.176	27.244		2.181
COMBINEDCYCLE	NATGAS	2030	25	0.691	27.244	4.116	
COMBINEDCYCLE	NATGAS	2030	25	0.813	27.244		2.511
ELECTRICITY_BATTERY	ELECTRIC	2020	20	0.402	0.371		
ELECTRICITY_BATTERY	ELECTRIC	2020	20	0.42	2.66		
ELECTRICITY_BATTERY	ELECTRIC	2030	20	0.322	0.297		
ELECTRICITY_BATTERY	ELECTRIC	2030	20	0.336	2.128		
ELECTROLYZER	ELECTRIC	2020	25	0.647	12.74		
ELECTROLYZER	ELECTRIC	2020	25	0.637	12.74		
ELECTROLYZER	ELECTRIC	2030	30	0.451	8.82		
ELECTROLYZER	ELECTRIC	2030	30	0.441	8.82		
ENGINE_IC	NATGAS	2020	25	0.931	9.555		2.487
ENGINE_IC	NATGAS	2020	25	0.791	9.555	5.292	
ENGINE_IC	NATGAS	2030	25	0.882	9.114		2.399
ENGINE_IC	NATGAS	2030	25	0.75	9.114	4.998	
FUELCELL	HYDROGEN	2020	15	1.47	0.01	9.8	
FUELCELL	HYDROGEN	2030	20	0.784	0.01	3.92	
GASTURBINE	NATGAS	2020	25	0.715	19.11		1.958
GASTURBINE	NATGAS	2020	25	0.578	19.11		1.811
GASTURBINE	NATGAS	2020	25	0.491	19.11	4.312	
GASTURBINE	NATGAS	2030	25	0.686	18.228		1.949
GASTURBINE	NATGAS	2030	25	0.549	18.228		1.77
GASTURBINE	NATGAS	2030	25	0.466	18.228	4.116	
H2_STORAGE	HYDROGEN	2020	25	0.056	0.003		
H2_STORAGE	HYDROGEN	2030	30	0.044	0.003		
HEATPUMP	ELECTRIC	2020	12	0.431	63.374		
HEATPUMP	ELECTRIC	2020	25	0.708	2.023	2.023	
HEATPUMP	ELECTRIC	2020	18	1.715	68.11		
HEATPUMP	ELECTRIC	2020	25	0.645	1.96	1.764	
HEATPUMP	ELECTRIC	2020	25	1.467	18.386		
HEATPUMP	ELECTRIC	2030	12	0.431	41.774		
HEATPUMP	ELECTRIC	2030	25	0.666	2.023	1.821	
HEATPUMP	ELECTRIC	2030	18	1.47	62.475		
HEATPUMP	ELECTRIC	2030	25	0.58	1.96	1.666	
HEATPUMP	ELECTRIC	2030	25	1.369	16.528		
PIT	HEAT	2020	20	0.001	0.003		
PIT	HEAT	2020	20	0	0.003		
PIT	HEAT	2030	20	0.001	0.003		
PIT	HEAT	2030	20	0	0.003		
RESERVOIR_PMP	ELECTRIC	2020	60	0.285	0.735		
SOLARHEATING	SUN	2020	30	0.269	0.061	0.206	
SOLARHEATING	SUN	2020	25	0.56	0.016		
SOLARHEATING	SUN	2030	30	0.247	0.055	0.294	
SOLARHEATING	SUN	2030	30	0.49	0.016		
SOLARPV	SUN	2020	35	0.412	6.86		
SOLARPV	SUN	2030	40	0.294	5.684		
STEAMREFORMING	NATGAS	2020	25	1.019	28.316		
STEAMREFORMING	NATGAS	2020	25	0.571	19.479		
STEAMTURBINE	MUNIWASTE	2020	25	7.674	156.8		5.581
STEAMTURBINE	MUNIWASTE	2020	25	8.919	245		5.642
STEAMTURBINE	MUNIWASTE	2020	25	6.523	156.8	24.264	
STEAMTURBINE	MUNIWASTE	2030	25	7.288	147		5.681
STEAMTURBINE	MUNIWASTE	2030	25	8.492	235.2		5.749
STEAMTURBINE	MUNIWASTE	2030	25	6.194	147	23.671	
STEAMTURBINE	NATGAS	2020	30	1.202	37.24	0.804	
STEAMTURBINE	NATGAS	2020	30	1.414	37.24		0.378
STEAMTURBINE	NATGAS	2020	30	0.588	12.051		0.318

(*continued on next page*)

Table B3 (*continued*)

Technology group	Fuel type	Available from year	Economic lifetime (years)	Investment cost (M€/MW)	Annual O&M costs (k€/MW)	Variable O&M cost (€/MWh$_{out}$)	Variable O&M cost (€/MWh$_{in}$)
STEAMTURBINE	NATGAS	2020	30	0.616	37.24	0.804	
STEAMTURBINE	NATGAS	2020	30	0.725	37.24		0.378
STEAMTURBINE	STRAW	2020	25	5.442	254.8		0.599
STEAMTURBINE	STRAW	2020	25	3.318	137.2		0.472
STEAMTURBINE	STRAW	2020	25	2.576	117.6		0.587
STEAMTURBINE	STRAW	2020	25	2.19	117.6	1.893	
STEAMTURBINE	STRAW	2030	25	5.176	245		0.599
STEAMTURBINE	STRAW	2030	25	3.222	127.4		0.477
STEAMTURBINE	STRAW	2030	25	2.443	107.8		0.585
STEAMTURBINE	STRAW	2030	25	2.077	107.8	1.888	
STEAMTURBINE	WOODCHIPS	2020	25	5.886	274.4		1.079
STEAMTURBINE	WOODCHIPS	2020	25	3.245	58.8		1.085
STEAMTURBINE	WOODCHIPS	2020	25	3.689	137.2		1.088
STEAMTURBINE	WOODCHIPS	2020	25	2.758	58.8	3.741	
STEAMTURBINE	WOODCHIPS	2030	25	5.598	274.4		1.079
STEAMTURBINE	WOODCHIPS	2030	25	3.075	49		1.081
STEAMTURBINE	WOODCHIPS	2030	25	3.495	127.4		1.084
STEAMTURBINE	WOODCHIPS	2030	25	2.614	49	3.728	
STEAMTURBINE	WOODPELLETS	2020	25	5.454	264.6		0.506
STEAMTURBINE	WOODPELLETS	2020	25	2.861	127.4		0.494
STEAMTURBINE	WOODPELLETS	2020	25	2.254	62.72		0.517
STEAMTURBINE	WOODPELLETS	2020	25	1.691	39.2	1.519	
STEAMTURBINE	WOODPELLETS	2030	25	5.187	254.8		0.506
STEAMTURBINE	WOODPELLETS	2030	25	2.713	117.6		0.492
STEAMTURBINE	WOODPELLETS	2030	25	2.156	59.78		0.517
STEAMTURBINE	WOODPELLETS	2030	25	1.604	39.2	1.515	
WATERTANK	HEAT	2010	40	0.003	0.008		
WATERTANK	HEAT	2010	30	0.402	16.333	0.686	
WINDTURBINE_OFFSHORE	WIND	2020	27	1.83	48.02	4.802	
WINDTURBINE_OFFSHORE	WIND	2020	27	1.421	48.02	4.802	
WINDTURBINE_OFFSHORE	WIND	2030	30	1.592	37.456	3.74	
WINDTURBINE_OFFSHORE	WIND	2030	30	1.202	37.456	3.74	
WINDTURBINE_ONSHORE	WIND	2020	27	1.247	13.72	1.47	
WINDTURBINE_ONSHORE	WIND	2030	30	1.123	12.348	1.401	

C. Appendix – Vapour-compression cycles

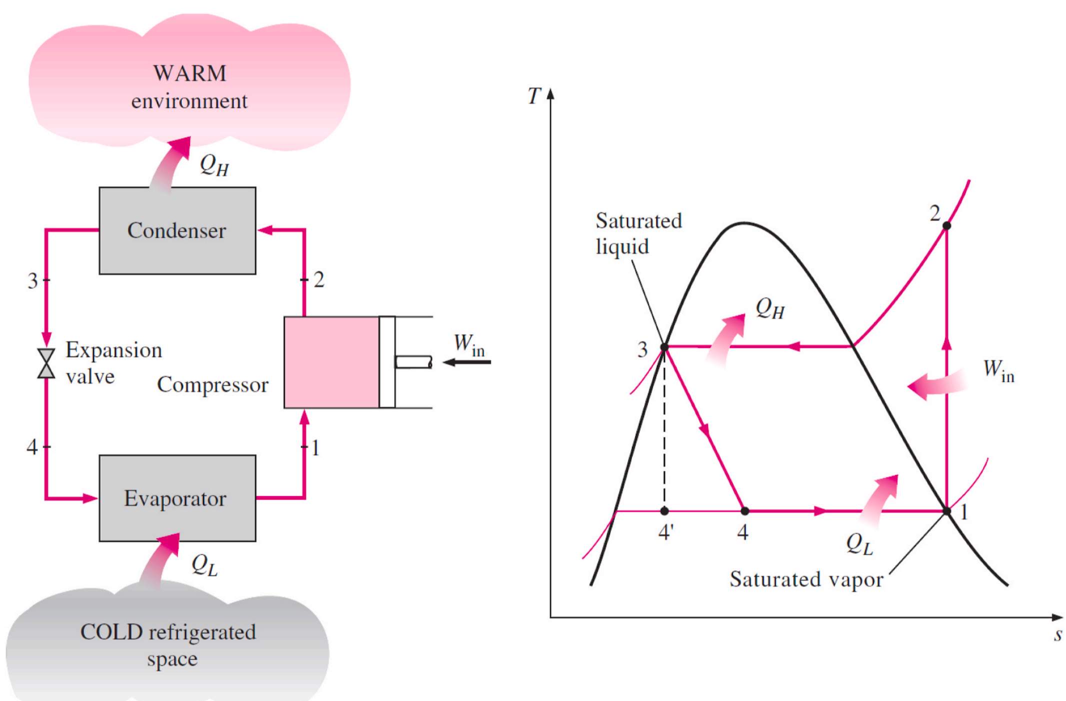

Fig. C1. Schematic and temperature-entropy diagram for an ideal vapour-compression refrigeration cycle [87].

References

[1] International Energy Agency. Data centres and data transmission networks. International Energy Agency; 2022.
[2] International Energy Agency. Global trends in internet traffic, data centres workloads and data centre energy use, 2010-2020. 2022. https://www.iea.org/data-and-statistics/charts/global-trends-in-internet-traffic-data-centres-workloads-and-data-centre-energy-use-2010-2020. [Accessed 13 February 2023].
[3] Kamiya G, Kvarnström O. Data centres and energy – from global headlines to local headaches? International Energy Agency 2019. https://www.iea.org/commentaries/data-centres-and-energy-from-global-headlines-to-local-headaches. [Accessed 27 June 2022].
[4] Jerez Monsalves JJ, Bergaentzlé C, Backer M. Regulatory frameworks and business models for data centres integrated to the energy system. Technical University of Denmark; 2022. https://doi.org/10.11581/DTU.00000242.
[5] Banet C, Pollitt M, Covatariu A, Duma D. Data centres & the grid. Brussels, Belgium: Centre on Regulation in Europe (CERRE); 2021.
[6] COWI. Temaanalyse om store datacentre. Kongens Lyngby, Denmark: COWI; 2018.
[7] Danish Energy Agency. Klimastatus og -fremskrivning 2022: Forbrug af el. Copenhagen, Denmark: Danish Energy Agency; 2022.
[8] Danish Energy Agency. Energistatistik 2020 [energy statistics 2020]. Copenhagen: Danish Energy Agency; 2021.
[9] Danish Energy Agency. Regulation and planning of district heating in Denmark. Copenhagen: Danish Energy Agency; 2016.
[10] The Danish Parliament. Energy agreementvol. 2018; 2018.
[11] Whitehead B, Andrews D, Shah A, Maidment G. Assessing the environmental impact of data centres part 1: background, energy use and metrics. Build Environ 2014;82:151–9. https://doi.org/10.1016/J.BUILDENV.2014.08.021.
[12] Gong X, Zhang Z, Gan S, Niu B, Yang L, Xu H, et al. A review on evaluation metrics of thermal performance in data centers. Build Environ 2020;177:106907. https://doi.org/10.1016/j.buildenv.2020.106907.
[13] Long S, Li Y, Huang J, Li Z, Li Y. A review of energy efficiency evaluation technologies in cloud data centers. Energy Build 2022;260:111848. https://doi.org/10.1016/j.enbuild.2022.111848.
[14] Shao X, Zhang Z, Song P, Feng Y, Wang X. A review of energy efficiency evaluation metrics for data centers. Energy Build 2022;271:112308. https://doi.org/10.1016/j.enbuild.2022.112308.
[15] Oró E, Depoorter V, Garcia A, Salom J. Energy efficiency and renewable energy integration in data centres. Strategies and modelling review. Renew Sustain Energy Rev 2015;42:429–45. https://doi.org/10.1016/j.rser.2014.10.035.
[16] Ahmad RW, Gani A, Hamid SHAb, Shiraz M, Yousafzai A, Xia F. A survey on virtual machine migration and server consolidation frameworks for cloud data centers. J Netw Comput Appl 2015;52:11–25. https://doi.org/10.1016/j.jnca.2015.02.002.
[17] Uddin M, Darabidarabkhani Y, Shah A, Memon J. Evaluating power efficient algorithms for efficiency and carbon emissions in cloud data centers: a review. Renew Sustain Energy Rev 2015;51:1553–63. https://doi.org/10.1016/j.rser.2015.07.061.
[18] Rong H, Zhang H, Xiao S, Li C, Hu C. Optimizing energy consumption for data centers. Renew Sustain Energy Rev 2016;58:674–91. https://doi.org/10.1016/j.rser.2015.12.283.
[19] Fulpagare Y, Bhargav A. Advances in data center thermal management. Renew Sustain Energy Rev 2015;43:981–96. https://doi.org/10.1016/j.rser.2014.11.056.
[20] Ni J, Bai X. A review of air conditioning energy performance in data centers. Renew Sustain Energy Rev 2017;67:625–40. https://doi.org/10.1016/j.rser.2016.09.050.
[21] Liu L, Zhang Q, Zhai Z, John, Yue C, Ma X. State-of-the-art on thermal energy storage technologies in data center. Energy Build 2020;226:110345. https://doi.org/10.1016/j.enbuild.2020.110345.
[22] Ebrahimi K, Jones GF, Fleischer AS. A review of data center cooling technology, operating conditions and the corresponding low-grade waste heat recovery opportunities. Renew Sustain Energy Rev 2014;31:622–38. https://doi.org/10.1016/j.rser.2013.12.007.
[23] Huang P, Copertaro B, Zhang X, Shen J, Löfgren I, Rönnelid M, et al. A review of data centers as prosumers in district energy systems: renewable energy integration and waste heat reuse for district heating. Appl Energy 2020;258:114109. https://doi.org/10.1016/j.apenergy.2019.114109.
[24] Zhang H, Shao S, Xu H, Zou H, Tian C. Free cooling of data centers: a review. Renew Sustain Energy Rev 2014;35:171–82. https://doi.org/10.1016/j.rser.2014.04.017.
[25] Bose R, Roy S, Mondal H, Chowdhury DR, Chakraborty S. Energy-efficient approach to lower the carbon emissions of data centers. Computing 2021;103:1703–21. https://doi.org/10.1007/s00607-020-00889-4.
[26] Ding Z, Xie L, Lu Y, Wang P, Xia S. Emission-aware stochastic resource planning scheme for data center microgrid considering batch workload scheduling and risk management. IEEE/IAS 54th industrial and commercial power systems technical conference (I&CPS), vol. 2018. Niagara Falls, ON: IEEE; 2018. p. 1–9. https://doi.org/10.1109/ICPS.2018.8369969.
[27] Masanet E, Shehabi A, Koomey J. Characteristics of low-carbon data centres. Nat Clim Change 2013;3:627–30. https://doi.org/10.1038/nclimate1786.
[28] Shehabi A, Masanet E, Price H, Horvath A, Nazaroff WW. Data center design and location: consequences for electricity use and greenhouse-gas emissions. Build Environ 2011;46:990–8. https://doi.org/10.1016/j.buildenv.2010.10.023.
[29] Vasques TL, Moura P, de Almeida A. A review on energy efficiency and demand response with focus on small and medium data centers. Energy Efficiency 2019;12:1399–428. https://doi.org/10.1007/s12053-018-9753-2.
[30] Guo C, Luo F, Cai Z, Dong ZY. Integrated energy systems of data centers and smart grids: state-of-the-art and future opportunities. Appl Energy 2021;301:117474. https://doi.org/10.1016/j.apenergy.2021.117474.
[31] Skach M, Arora M, Hsu C-H, Li Q, Tullsen D, Tang L, et al. Thermal time shifting: decreasing data center cooling costs with phase-change materials. IEEE Internet Comput 2017;21:34–43. https://doi.org/10.1109/MIC.2017.2911418.
[32] Cioara T, Anghel I, Bertoncini M, Salomie I, Arnone D, Mammina M, et al. Optimized flexibility management enacting data centres participation in smart demand response programs. Future Generat Comput Syst 2018;78:330–42. https://doi.org/10.1016/j.future.2016.05.010.
[33] Cioara T, Anghel I, Salomie I, Antal M, Pop C, Bertoncini M, et al. Exploiting data centres energy flexibility in smart cities: business scenarios. Inf Sci 2019;476:392–412. https://doi.org/10.1016/j.ins.2018.07.010.
[34] Oró E, Taddeo P, Salom J. Waste heat recovery from urban air cooled data centres to increase energy efficiency of district heating networks. Sustain Cities Soc 2019;45:522–42. https://doi.org/10.1016/j.scs.2018.12.012.
[35] Zhang C, Luo H, Wang Z. An economic analysis of waste heat recovery and utilization in data centers considering environmental benefits. Sustain Prod Consum 2022;31:127–38. https://doi.org/10.1016/j.spc.2022.02.006.
[36] Jodeiri AM, Goldsworthy MJ, Buffa S, Cozzini M. Role of sustainable heat sources in transition towards fourth generation district heating – a review. Renew Sustain Energy Rev 2022;158:112156. https://doi.org/10.1016/j.rser.2022.112156.
[37] Pärssinen M, Wahlroos M, Manner J, Syri S. Waste heat from data centers: an investment analysis. Sustain Cities Soc 2019;44:428–44. https://doi.org/10.1016/j.scs.2018.10.023.
[38] Robinius M, Otto A, Heuser P, Welder L, Syranidis K, Ryberg D, et al. Linking the power and transport sectors—Part 1: the principle of sector coupling. Energies 2017;10:956. https://doi.org/10.3390/en10070956.
[39] Robinius M, Otto A, Syranidis K, Ryberg DS, Heuser P, Welder L, et al. Linking the power and transport sectors—Part 2: modelling a sector coupling scenario for Germany. Energies 2017;10:957. https://doi.org/10.3390/en10070957.
[40] Burandt T, Xiong B, Löffler K, Oei P-Y. Decarbonizing China's energy system – modeling the transformation of the electricity, transportation, heat, and industrial sectors. Appl Energy 2019;255:113820. https://doi.org/10.1016/j.apenergy.2019.113820.
[41] Buttler A, Spliethoff H. Current status of water electrolysis for energy storage, grid balancing and sector coupling via power-to-gas and power-to-liquids: a review. Renew Sustain Energy Rev 2018;82:2440–54. https://doi.org/10.1016/j.rser.2017.09.003.
[42] Meibom P, Karlsson K. Role of hydrogen in future North European power system in 2060. Int J Hydrogen Energy 2010;35:1853–63. https://doi.org/10.1016/j.ijhydene.2009.12.161.
[43] Durakovic G, del Granado PC, Tomasgard A. Powering Europe with North Sea offshore wind: the impact of hydrogen investments on grid infrastructure and power prices. Energy 2023;263:125654. https://doi.org/10.1016/j.energy.2022.125654.
[44] Gea-Bermúdez J, Bramstoft R, Koivisto M, Kitzing L, Ramos A. Going offshore or not: where to generate hydrogen in future integrated energy systems? Energy Pol 2023;174:113382. https://doi.org/10.1016/j.enpol.2022.113382.
[45] Lester MS, Bramstoft R, Münster M. Analysis on electrofuels in future energy systems: a 2050 case study. Energy 2020;199:117408. https://doi.org/10.1016/j.energy.2020.117408.
[46] Schemme S, Samsun RC, Peters R, Stolten D. Power-to-fuel as a key to sustainable transport systems – an analysis of diesel fuels produced from CO 2 and renewable electricity. Fuel 2017;205:198–221. https://doi.org/10.1016/j.fuel.2017.05.061.
[47] Victoria M, Zeyen E, Brown T. Speed of technological transformations required in Europe to achieve different climate goals. Joule 2022;6:1066–86. https://doi.org/10.1016/j.joule.2022.04.016.
[48] Hansen K, Breyer C, Lund H. Status and perspectives on 100% renewable energy systems. Energy 2019;175:471–80. https://doi.org/10.1016/j.energy.2019.03.092.
[49] Victoria M, Zhu K, Brown T, Andresen GB, Greiner M. The role of storage technologies throughout the decarbonisation of the sector-coupled European energy system. Energy Convers Manag 2019;201:111977. https://doi.org/10.1016/j.enconman.2019.111977.
[50] Nagel NO, Kirkerud JG, Bolkesjø TF. The economic competitiveness of flexibility options: a model study of the European energy transition. J Clean Prod 2022;350:131534. https://doi.org/10.1016/j.jclepro.2022.131534.
[51] Gea-Bermúdez J, Jensen IG, Münster M, Koivisto M, Kirkerud JG, Chen Y, et al. The role of sector coupling in the green transition: a least-cost energy system development in Northern-central Europe towards 2050. Appl Energy 2021;289:116685. https://doi.org/10.1016/j.apenergy.2021.116685.
[52] Neumann F, Zeyen E, Victoria M, Brown T. Benefits of a hydrogen network in europe. SSRN Journal 2022. https://doi.org/10.2139/ssrn.4173442.
[53] Gunkel PA, Bergaentzlé C, Græsted Jensen I, Scheller F. From passive to active: flexibility from electric vehicles in the context of transmission system development. Appl Energy 2020;277:115526. https://doi.org/10.1016/j.apenergy.2020.115526.
[54] Sterchele P, Kersten K, Palzer A, Hentschel J, Henning H-M. Assessment of flexible electric vehicle charging in a sector coupling energy system model – modelling approach and case study. Appl Energy 2020;258:114101. https://doi.org/10.1016/j.apenergy.2019.114101.
[55] Lund PD, Lindgren J, Mikkola J, Salpakari J. Review of energy system flexibility measures to enable high levels of variable renewable electricity. Renew Sustain Energy Rev 2015;45:785–807. https://doi.org/10.1016/j.rser.2015.01.057.

[56] Bergaentzle C, Gunkel PA. Cross-sector flexibility, storage investment and the integration of renewables: capturing the impacts of grid tariffs. Energy Pol 2022; 164:112937. https://doi.org/10.1016/j.enpol.2022.112937.
[57] Bergaentzlé C, Jensen IG, Skytte K, Olsen OJ. Electricity grid tariffs as a tool for flexible energy systems: a Danish case study. Energy Pol 2019;126:12–21. https://doi.org/10.1016/j.enpol.2018.11.021.
[58] Møller Sneum D. Barriers to flexibility in the district energy-electricity system interface – a taxonomy. Renew Sustain Energy Rev 2021;145:111007. https://doi.org/10.1016/j.rser.2021.111007.
[59] Luo P, Wang X, Li Y. The impact of datacenter load regulation on the stability of integrated power systems. Sustain Energy Technol Assessments 2020;42:100875. https://doi.org/10.1016/j.seta.2020.100875.
[60] Lahon R, Stanley S, O'Dwyer C, Devine M, Flynn D. Impact of wide-scale data centre growth on power system operation with large share of renewables. 2020 17th international conference on the European energy market (EEM). Stockholm, Sweden: IEEE; 2020. p. 1–6. https://doi.org/10.1109/EEM49802.2020.9221876.
[61] Wahlroos M, Pärssinen M, Manner J, Syri S. Utilizing data center waste heat in district heating – impacts on energy efficiency and prospects for low-temperature district heating networks. Energy 2017;140:1228–38. https://doi.org/10.1016/j.energy.2017.08.078.
[62] Hiltunen P, Syri S. Highly renewable district heat for Espoo utilizing waste heat sources. Energies 2020;13:3551. https://doi.org/10.3390/en13143551.
[63] Petrović S, Colangelo A, Balyk O, Delmastro C, Gargiulo M, Simonsen MB, et al. The role of data centres in the future Danish energy system. Energy 2020;194: 116928. https://doi.org/10.1016/j.energy.2020.116928.
[64] Wiese F, Bramstoft R, Koduvere H, Pizarro Alonso A, Balyk O, Kirkerud JG, et al. Balmorel open source energy system model. Energy Strategy Rev 2018;20:26–34. https://doi.org/10.1016/j.esr.2018.01.003.
[65] Jerez Monsalves J, Gea-Bermúdez J, Bergaentzlé C, Keles D. Integration of data centers as active entities into energy systems modeling. Operations Research Proceedings, Karlsruhe: Springer; n.d.
[66] Balmorel Community. balmorelcommunity/Balmorel at datacenters. GitHub n.d. https://github.com/balmorelcommunity/Balmorel/tree/datacenters (accessed March 28, 2023).
[67] Gea-Bermúdez J, Kitzing L, Koivisto M, Das K, Murcia León JP, Sørensen P. The value of sector coupling for the development of offshore power grids. Energies 2022;15:747. https://doi.org/10.3390/en15030747.
[68] European Commission. A clean Planet for all a European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy. Brussels, Belgium: European Commission; 2018.
[69] Transport and Environment. How to decarbonize the transport sector by 2050. n.d.
[70] Danish Energy Agency. Klimastatus og –fremskrivning 2022: 6A Datacentre. Copenhagen, Denmark: Danish Energy Agency; 2022.
[71] Gea-Bermúdez J, Pade L-L, Koivisto MJ, Ravn H. Optimal generation and transmission development of the North Sea region: impact of grid architecture and planning horizon. Energy 2020;191:116512. https://doi.org/10.1016/j.energy.2019.116512.
[72] Balmorel Community. balmorelcommunity/Balmorel_data at datacenters_short-resolution n.d. https://github.com/balmorelcommunity/Balmorel_data/tree/datacenters_short-resolution (accessed March 10, 2023).
[73] Balmorel Community. balmorelcommunity/Balmorel_data. GitHub; 2023. https://github.com/balmorelcommunity/Balmorel_data. [Accessed 27 June 2022].
[74] Nordic Energy Research, International Energy Agency. Nordic energy technology perspectives. n: d; 2016.
[75] Zhang T, Liu X-H, Li Z, Jiang J, Tong Z, Jiang Y. On-site measurement and performance optimization of the air-conditioning system for a datacenter in Beijing. Energy Build 2014;71:104–14. https://doi.org/10.1016/j.enbuild.2013.12.014.
[76] Danish Energy Agency. Technology data - generation of electricity and district heating. Copenhagen, Denmark: Danish Energy Agency; 2022.
[77] Danish Energy Agency. Technology data - energy storage. Copenhagen, Denmark: Danish Energy Agency; 2020.
[78] Depoorter V, Oró E, Salom J. The location as an energy efficiency and renewable energy supply measure for data centres in Europe. Appl Energy 2015;140:338–49. https://doi.org/10.1016/j.apenergy.2014.11.067.
[79] Danish Meteorological Institute. DMI open data - meteorological observation API n.d. https://confluence.govcloud.dk/display/FDAPI/Danish+Meteorological+Institute+-+Open+Data (accessed August 28, 2022).
[80] Technology data - energy transport. Danish Energy Agency; 2021.
[81] Mathiesen BV, Lund H, Nielsen S, Sorknæs P, Moreno D, Thellufsen JZ. Varmeplan danmark 2021 - en klimaneutral varmeforsyning. Aalborg: Aalborg Universitet; 2021.
[82] Directorate-general for energy. Proposal for a directive of the European parlament and of the council on energy efficiency (recast). European Comission; 2021.
[83] Danish Parliament. Lov om ændring af lov om varmeforsyning, lov om afgift af naturgas og bygas m.v., lov om afgift af stenkul, brunkul og koks m.v. og lov om energiafgift af mineralolieprodukter m.v 2021 (Prisregulering af og energieffektiviseringsordning med afgiftsfritagelse for overskudsvarme).
[84] Poncelet K, Delarue E, D'haeseleer W. Unit commitment constraints in long-term planning models: relevance, pitfalls and the role of assumptions on flexibility. Appl Energy 2020;258:113843. https://doi.org/10.1016/j.apenergy.2019.113843.
[85] Alaperä I, Honkapuro S, Paananen J. Data centers as a source of dynamic flexibility in smart girds. Appl Energy 2018;229:69–79. https://doi.org/10.1016/j.apenergy.2018.07.056.
[86] Li Y, Wang X, Luo P, Pan Q. Thermal-aware hybrid workload management in a green datacenter towards renewable energy utilization. Energies 2019;12:1494. https://doi.org/10.3390/en12081494.
[87] Çengel YA, Boles MA, Kanoglu M. Thermodynamics: an engineering approach. ninth ed. New York, NY: McGraw-Hill Education; 2019.