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Research article

Power-to-Heat solutions: The Danish district heating system

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Abstract: The aim of this report is to investigate the potential of using surplus electricity generated by wind turbines in a power-to-heat (P2H) setup serving the Danish district heating market. The research establishes a theoretical position on variable renewable energy, district heating, heat pumps, boilers, and thermal energy storage through academic literature and industry professional reporting research. The empirical section touches upon the same topics, focusing on total energy production, curtailment, and district heating (DH) in Denmark. An analysis of the amount of curtailed power production in combination with electricity spot prices was used to calculate the corresponding heating demand that could be achieved if the power was used for large-scale heat pumps and electric boilers. It was found that the potential power-to-heat supply ranges from 18,100 to 63,380 households across the scenarios analyzed. The conclusion is that there seems to be a clear potential for redirecting the surplus electricity into DH to meet part of the Danish heat demand, and that the ongoing technological development of DH, thermal energy systems (TES), and variable renewable energy (VREs) in combination with market conditions favors a focus on sector coupling and P2H in the future.

Keywords: district heating; heat pumps; variable renewable energy; thermal energy

Nomenclature: ATES: aquifer thermal energy storage; BTES: borehole thermal energy storage; CHP: combined heat and power; CO_2: carbon dioxide; COP: coefficient of performance; DH: district heating; DHN: district heating network; DKK: Danish krone; DK1/DK2: Denmark's 2 electricity price zones—DK1 (West Denmark) and DK2 (East Denmark); GWh: gigawatt-hour; kWh: kilowatt-hour; MWh: megawatt-hour; MW: megawatt; P2H: power-to-heat; P2HH: power-to-hydrogen and heat; PTES: pit thermal energy storage; TES: thermal energy storage; TTES: tank thermal energy storage; VRE: variable renewable energy

1. Introduction and background

With energy prices soaring in Denmark since 2021 as a result of a perfect storm caused by increased demand after the COVID-19 pandemic, relatively poor weather conditions, and a substantially decreased supply of gas from Russia, the need for effective and smart sector coupling, electrification, and storage of energy continues to be a heavily prioritized topic in the national energy planning. In 2020, the Danish government passed a proposal with the objective of being climate neutral and non-reliant on fossil fuels by 2050 [1]. This has enabled opportunities for innovative, responsive, and resilient energy planning solutions [2].

As Denmark is at the forefront of development and implementation within both wind energy and DH, it is relevant to investigate if synergies can be exploited. A main drawback of harvesting wind energy is the inability to efficiently store electricity, as large-scale storage solutions in the form of batteries are hindered by swift deterioration and power loss. Accordingly, the surplus electricity produced under optimal weather conditions in periods with low demand (e.g., most commonly during nighttime) is often exported to neighboring countries at a cheap rate [3]. Within the utility sector, the combined heat and power (CHP) production plants are continuously investing in modernization to decrease the reliance on fossil fuels and pursue a completely renewable energy mix. An example is the construction of the largest seawater heat pump in Denmark for DIN Forsyning in Esbjerg, dimensioned at 50 MW with a coefficient of performance (COP) of 3.65 paired with a new 60 MW biomass boiler [4]. But what has happened on the field in other parts of the world?

The potential of power-to-heat in the Swedish district heating system has already been analyzed in 2017, where it was found that the availability of thermal storage enhances the feasibility of power-to-heat applications, whereas the presence of waste heat diminishes the viability of power-to-heat processes [5]. In Germany, in a similar study from 2014, it was found that the maximum theoretical potential to convert electricity into heat through a power-to-heat facility equates to 32 GW [6].

The power-to-heat environmental approach in relation to CO_2 emissions was studied in a paper published in 2019, where it was revealed that at a country level, combined heat and power leads to less CO_2 emissions [7].

The impact of power-to-heat in relation to wind integration was presented in a study in 2020 [8]. That research primarily aimed at illustrating the functioning of district heating supply technologies under varying market conditions and their impact on determining optimal capacities for power-to-heat and thermal storage. The relation to electricity distribution was also studied [9], while several technoeconomic analyses have investigated the power-to-heat case [10,11].

In another case, the power-to-heat option was examined against various renewable energy sources, such as biomass, as well as against the German and Danish electric mixes, characteristic examples of systems with high shares of wind energy [12]. Norway, Sweden, and Germany emerge as significant energy trading partners for Denmark, with notable variations in annual net import levels. These discrepancies can be attributed to differences in national energy mixes, such as Norway's extensive use of hydropower. Similar to the biomass paper, a case on the optimization of power-to-hydrogen and heat (P2HH) was examined, highlighting primarily security benefits via an innovative P2HH dispatch model proposed [13].

Unavoidably, the impact of the power-to-heat option on energy and electricity markets has been explored in recent papers. In a specific study, the focus was on incentivizing flexible power-to-heat operations in district heating by redesigning electricity grid tariffs. The authors emphasized the importance of technology utilization and increasing energy viability through incentives for flexible power-to-heat operation [14]. Another paper by Javanshir et al. [15] proposed a daily routine for operating district heating networks (DHNs) equipped with power-to-heat technologies in multiple energy markets. The study delved into the intersection of district heat networks and electricity balancing markets, highlighting potential synergies [15]. Additionally, Jimenez-Navarro et al. [16] explored the coupling of heating and power sectors, focusing on the role of centralized combined heat and power plants and district heat in a European decarbonized power system [16]. Such papers collectively contribute to a comprehensive understanding of the multifaceted impact of power-to-heat options on energy landscapes and emphasize the need for integration and optimization in the evolving energy sector. The importance of the power-to-heat approach to the balancing market in several countries has also been examined. The integration of DH systems is recognized as crucial for enhancing the stability and flexibility of the European energy grid. Research highlights that their ability to provide balancing services has broad implications for achieving a sustainable and resilient energy landscape across the European Union. Denmark represents a frontrunner in this transition, with a highly developed DH sector that serves as a practical testbed for these concepts. Therefore, this paper uses Denmark as a case study.

The scope of this paper is to investigate the high-level feasibility and assess the potential for sector coupling and power-to-heat (P2H) by analyzing the usage of the available surplus of electricity as a power source for, e.g., large-scale heat pumps and electric boilers within the heating utility sector. The paper will investigate the topics of functional principles of P2H 4th generation DH, TES as a means to meet both the required peak and base load heat demand, and financial considerations for using the surplus electricity as a source for heating.

2. Methodology

2.1. Purpose

The paper aims to answer the following questions: "What is the potential of using residual electricity in a P2H setting within the Danish DH market, and are the technologies for the production and storage of thermal energy feasible to utilize?" The research is characterized by its exploratory nature, seeking to delve into the topic to unearth valuable insights. The primary goal is to identify key findings that can serve as a foundation for directing and shaping future investigations in the field. This approach allows for a comprehensive exploration of the topic, facilitating a better understanding and paving the way for more targeted and informed research endeavors in the future.

2.2. Data collection and analysis

Sources from both national and European governmental bodies and professional associations have been used to develop a coherent understanding of the topics. Most of the data is of a secondary quantitative nature and required data cleaning and preparation. Collection of data has primarily been conducted directly through Energinet, which is a public company under the Ministry of Climate, Energy and Utilities, or from sources referencing data from here. Accordingly, the results are presented in the empirical section, where the underlying data sources are referenced. The results from the empirical section are juxtaposed with the theoretical position and findings in an attempt to answer the research question.

2.3. Delimitations

As the report focuses on assessing the high-level potential of electricity-to-heat conversion in Denmark, the following delimitations have been applied: The dimensioning and design of technical components have been left out, and the report focuses on electricity generated from wind turbines and thereby excludes photovoltaics.

3. Theoretical position

3.1. Variable renewable energy (VRE)

At the core of the green transition discussion, the deployment and integration of renewable energy are regarded as essential for tackling both the environmental and energy mix challenges in the current market. Wind power generators and solar photovoltaic panels—generally referred to as VRE sources—show the potential to support the transition to a fossil fuel-free energy market [17]. Nevertheless, these solutions have their drawbacks, particularly regarding their intermittent production nature based on their dependence on weather and temporal conditions. Solar power generation, for instance, relies on sunlight, and its output can be significantly affected by cloud cover, seasonal variations, and nighttime. Similarly, wind power is contingent on wind speeds, which can fluctuate unpredictably. The intermittent nature of renewable energy production poses challenges for maintaining a consistent and reliable power supply, especially during periods of low natural resource availability. This intermittency underscores the importance of developing effective energy storage solutions and smart grid technologies to address the variability and ensure a stable and continuous power supply from renewable sources. This implies a high degree of variability in production, which, according to Estanqueiro & Couto [18], can range between minutes, days, months, and years. In practice, this involves periods with surplus electricity production.

There are three options available when the conditions lead to excess power production: redirecting the produced electricity for use in other locations through the grid, storing the electricity with batteries, and curtailment of the plants [19]. Curtailment entails that production is stopped, which can be a necessity if the produced electricity cannot be redirected [20]. The common objective is to avoid destabilizing the grid by overloading it.

It is worth mentioning that this study focuses more on wind energy integration, almost deliberately excluding photovoltaic (PV) generation. This scoping decision was made for two primary reasons: First, the current energy system in Denmark is predominantly dominated by wind power, making it the most significant source of variable renewable generation and curtailment. Second, the temporal generation profile of PV (daytime, summer) is inversely correlated with the region's peak electricity demand and heat demand (evening, winter), meaning its integration dynamics would differ substantially. While the inclusion of PV would offer a more complete picture of a fully renewable system, its exclusion here allows for a more focused and in-depth analysis of wind-specific challenges.

On a national scale, during the last decade, Denmark has been importing more electricity than exporting, but is projected to have a net import of −6.7 TWh by 2025 [21]. Key trading partners are Norway, Sweden, and Germany, where the annual variance in net imports can be vastly different due to the difference in the national energy mix, e.g., the high degree of hydropower utilization in Norway. Storing the produced electricity is currently achieved by using batteries, and development within this area is continuously happening, as it is a necessity for solving the challenge of ensuring a balance between load and supply in the energy sector [22]. However, results show that storing electricity as thermal energy through conversion has a better performance, costs less, and results in a flatter load profile than direct electricity storage [23]. The following sections describe the high-level components required for sector coupling between the VRE sources and the role of DH in a P2H context by looking at the future direction of DH, electric large-scale heat pumps and boilers, and TES options.

3.2. District heating

DH is a network of transmission pipes connecting commercial, industrial, and residential buildings to a heat production source. The Scandinavian DH landscape is slowly transitioning into the 4th generation [24]. The new generation is characterized by having smart low-temperature systems with a significant reduction in supply temperature from 80 to 50 °C, interconnected with smart electricity and gas grids. This transition is not merely a temperature shift but a systemic change that enables the integration of low-grade renewable heat sources and creates a crucial link between the thermal and power sectors. Lund et al. [24] mentioned that the transition requires increased efficiency and integration of large-scale heat pumps in combination with TES. The synergy between these technologies is fundamental: large-scale heat pumps efficiently convert electrical energy into heat, while TES provides the critical flexibility to decouple heat production from demand, allowing the system to act as a thermal battery for the smart grid. The argument is further supported by [25], who predicted an increase to 50% of district heating in the total heat demand by 2050, which will be supplied partly (25%–30%) by large-scale electric heat pumps.

3.3. Heat pumps

Heat pumps are already being used within DH. For large-scale solutions, especially in cities with access to seawater, this can be used as a heat source, which is advantageous in comparison to, e.g., thermal solar panels, as the physical footprint is smaller, making it more suitable for densely populated areas. Since the 1970s and the third generation of DH, centralized power plants in Denmark have been subject to Kraftvarmekravet, which entails that the plants must have cogeneration of electricity and heat. As the plants were originally created for power production purposes and based on fossil fuels, the objective of the Kraftvarmekravet (cogeneration requirement) was to ensure that the excessive waste heat was used. However, with the heavily increased power production from VRE sources, the necessity for power production in the plants is diminishing. Nevertheless, due to the volatile nature of the VREs, it still serves an essential purpose to ensure a stable supply and load balancing. VRE plays a crucial role in ensuring a stable supply and facilitating load balancing within the energy grid. The inherent variability in production, caused by factors such as changes in weather conditions for solar and wind power, could potentially lead to fluctuations in energy generation. However, the integration of VRE into the energy mix contributes to diversification and resilience.

Renewable energy sources, even with their intermittent nature, provide a valuable means of reducing dependence on traditional fossil fuels, thereby mitigating environmental impacts. Their inclusion in the energy portfolio enhances energy security by promoting diversity in the sources of power generation. Additionally, advancements in energy storage technologies, smart grid management, and predictive analytics have been instrumental in addressing the intermittency challenge associated with VRE. Accordingly, there have been discussions brought up by the Danish district heating association and politicians regarding the removal of the Kraftvarmekravet, as it has been a limiting factor in optimally dimensioned heat production. It has now been changed so that alternative production facilities can be constructed if they are more socio-economically beneficial than CHP [26].

Heat pumps can use the following heat sources: sewage water, ambient water, industrial heat waste, geothermal water, flue gas, district cooling, and solar heat storage [27]. The functioning principle for the large-scale electric heat pumps is that the heat source, e.g., seawater, is pumped through an intake pipe and passes through an evaporation chamber, where heat exchange happens, as the energy is transferred from the heat source to a refrigeration liquid. The most used types are CO_2 and NH_3. The refrigerant is at a low pressure, which results in a phase change from liquid to gas even though the heat source is as low as 10 °C at the inlet and 7 °C at the outlet. The vapor reaches a compressor that increases pressure and temperature. Hereafter, a heat transfer process happens as the heated refrigerant exchanges heat with the water that circulates in the DH system. The water from the return lines is heated from 30 to 70 °C in the supply line, and the cycle continues in this manner.

The integration of large-scale heat pumps in DH networks allows the utilization of renewable energy sources and the recovery of industrial waste heat. In combination with TES, it enables flexibility in the energy sector and supply resilience through short-term (daily/weekly) and seasonal durations [28]. At a European level, the outlook for large-scale heat pumps indicates an increase in total capacity of 80% by 2030. A major driver behind this is the continued investment in VRE sources for electricity production and favorable financial and energy policies aimed at phasing out fossil-based heat sources.

3.4. Electric boilers

In addition to heat pumps, Danish utilities use electric boilers for heat production, which can help increase the flexibility of the energy systems [29]. Their primary value lies in their ability to provide rapid, large-scale demand-side response, converting surplus renewable electricity into storable heat and thus helping to balance the power grid. The working principle of the electric boilers is as follows: Electric coils are heated and, through a heat exchanger, heat is transferred to the water used for district heating. Presently, the adoption of electric boilers in Denmark is not widespread, and their usage is primarily confined to backup applications to address peak demand scenarios. The prevalent trend suggests that these boilers are not yet extensively integrated into mainstream usage, with their role primarily focused on providing supplementary support during periods of heightened demand for heating or energy. This is explained by Danish electricity taxation and tariffs being quite high compared to those of other Scandinavian countries. This economic framework currently discourages their use for bulk energy production, limiting their operation to strategically valuable moments of grid congestion or high heat demand. In comparison to the heat pumps, electric boilers present advantages such as a very low start-up duration, which makes them ideal for responding to demand. They offer a simpler, lower-capital-cost technology for providing power-to-heat services, though with a lower overall energy efficiency than heat pumps. Furthermore, using a combination of heat sources makes it possible for utilities to avoid over-dimensioning combustion boilers, as the increased seasonal demand can be met through the integration of different heat sources. In comparison with natural gas and biomass boilers, electric boilers also have a higher efficiency of approximately 99%. Electric boilers represent a key flexibility technology whose economic viability and systemic role are directly tied to the evolving regulatory and market conditions of the integrated energy system.

3.5. Thermal energy storage

In Denmark, there are currently four available types of TES for commercial use. The high-level characteristics of the TES technologies are provided in Table 1.

Table 1. Comparison of TES storage characteristics (author's own production based on [30]).

Storage technology				
TTES (tank thermal energy storage)	PTES (pit thermal energy storage)		BTES (borehole thermal energy storage)	ATES (aquifer thermal energy storage)
Storage medium				
Water	Water	Gravel-water	Dirt/rock	Sand-water
Heat capacity (kWh/m^3)				
60–80	60–80	30–50	15–30	30–40
Storage volume for 1 m^3 water equivalent				
1 m^3	1 m^3	1.3–2 m^3	3–5 m^3	2–3 m^3
Storage temperature				
5–95 °C	5–95 °C		−5 to 90 °C	2–20 °C
Water equivalent price (m^3)				
800–1500 DKK (>2000 m^3)	150–300 DKK (>50.000 m^3)		150–300 DKK (>50.000 m^3) incl. buffer tank	40–250 DKK
Use scenarios				
Short-term storage (<30.000 m^3) and buffer tank	Seasonal storage for production of over 20,000 annually and short-term (>30.000 m^3)		Seasonal storage for production over 20.000 MWh annually	Requires a high cooling demand

A brief explanation of the technologies and usage examples is given in the following sections. The information has been acquired through a report commissioned by Energistyrelsen (2013) regarding heat storage technologies and large-scale heat pumps in the Danish DH market.

3.5.1. Tank thermal energy storage (TTES)

TTES is the most common technology used by utility companies for load balancing. Consequently, these tanks are mainly used for short-term storage. Short-term storage refers to storage cycles with a maximum duration of a week, whereas long-term storage options can be used for seasonal load balancing across, e.g., summer and winter periods, where the supply and demand patterns change considerably. In 2013, the estimated storage volume of TTES was approximately 875,000 m^3, with an average storage volume of 3,079 m^3, and very few examples of tanks above 10,000 m^3 [30]; 77% of the utilities were using TTES technology.

3.5.2. Pit thermal energy storage (PTES)

This technology has been especially used for geographically remote utilities that utilize thermal solar panels as a heating source [31]. Examples include the cities of Marstal, Gram, Dronninglund, and Vojens. The former was one of the first to use the technology in Denmark, and the capacity has been increased gradually. Currently, this utility supplies 1,600 households with heat through primarily thermal solar catchers that occupy an area of approximately 58,000 m^2. The system is dimensioned to supply 50%–55% of the demand through solar, 40% through wood chip boilers, and 2%–3% from a heat pump. The high amount of solar energy in the supply mix entails a very large surplus during the summer, as values as low as 10% could supply enough for the demand. Accordingly, the utility has simultaneously had a PTES storage constructed with a capacity of 75,000 m^3, which allows the utility to seasonally store the excess heat production from summer to meet the increased demand during the winter period. Other mentioned DH cases are similar in nature but vary considerably in size; the one in Vojens was, at the time of commissioning, the largest PTES in Denmark, at a capacity of 200,000 m^3. The benefit of PTES is the enormous capacity, in comparison to TTES, at a significantly lower price. Furthermore, the reported weekly loss for TTES is 3%–5%, whereas the PTES has a weekly heat loss of approximately 1.6%, which makes it more suitable for long-term storage. Another benefit of the PTES is that it still undergoes technological improvements to increase efficiency, whereas the TTES technology is in a more mature stage, where the cost-benefit of further technological development is less feasible. However, the main drawback of the PTES is the extremely high construction costs, geographical size requirements—hindering its development in densely populated urban areas—and, e.g., the system requirements of a large-scale heat pump and/or thermal solar catchers that can exploit surplus production of electricity to be used in a P2H context or direct heat production.

3.5.3. Borehole thermal energy storage (BTES)

BTES technology uses boreholes of 30–100 m, where water can circulate and slowly transfer heat to the surrounding surface, which is the storage medium. Hereby, the BTES initially heats up the core and, as the temperature increases, it expands toward the outer perimeter. The technology can be used for both heating and cooling, depending on the requirements. As seen from the table, the advantages and characteristics are, in many instances, like those of PTES. However, the drawbacks include a slow heat charge and discharge, and the requirement for heat pumps at the utilities. Additionally, there are certain requirements for the composition of the ground at the sites, which entail extensive pre-analysis. For instance, the soil must be unsaturated by water as the risk of movement of the groundwater poses a risk that the stored heat will be transported away unintendedly. The BTES technology has been used in Denmark, but not to the same extent as TTES and PTES. The first instance of BTES in Denmark was in Brædstrup, where 48 boreholes with a depth of 45 m were put into operation in 2012 with a total estimated capacity of 19,000 m^3 of soil, corresponding to an estimated 630 MWh annually with an expected heat loss of 23%.

3.5.4. Aquifer thermal energy storage (ATES)

The ATES technology uses boreholes as well, where groundwater from aquifers is used, both in cold and hot water wells. ATES systems are particularly relevant in situations where seasonal demands require cooling and heating. For instance, in the summer, water from the cold well can be pumped up through a heat exchanger in the building, and heat is then transferred from the building circuit to the water that is then stored in the hot well. In essence, ATES systems offer a sustainable and energy-efficient means of managing the varying heating and cooling demands of buildings by harnessing the natural thermal capacity of the subsurface aquifer. This innovative approach not only contributes to energy savings but also aligns with environmentally conscious practices in the realm of building climate control. When the temperature drops, e.g., in the winter, the flow is reversed, and heat can be "extracted" and used to meet the heating demand. ATES is very rarely used in Denmark compared to, e.g., the Netherlands. One of the main drawbacks is the requirement for extensive hydrogeological assessments, and the fact that the cooling demand in Denmark is insignificant. Therefore, alternative storage technologies outperform ATES in Denmark. One of the only examples in Denmark is in Bjerringbro, which was put into operation in 2013 in collaboration with Grundfos and their headquarters, as using the technology was feasible due to the production cooling demand.

4. Empirical findings

4.1. Wind power production

The following section will focus on the overall volume of electricity produced in Denmark from onshore and offshore turbines in MWh. The data has been acquired through Energinet's electricity balance dataset, which breaks down electricity production by source. As the historical data is not available before 2018, the period that is included is from January 1, 2018, to December 31, 2022. As can be seen from Table 2, the total production continues to increase because of favorable weather conditions and an increase in total installed capacity.

Table 2. Wind power production in Denmark, 2018–2022 (author's own work based on [32]).

Year	2018	2019	2020	2021	2022
Installed capacity (GW)	5.58	6.11	6.12	6.26	7.03
Onshore production (MWh)	9,462,417	10,294,510	10,091,019	8,838,236	10,483,064
Offshore production (MWh)	4,412,138	5,088,883	6,306,418	7,159,799	8,426,924
Wind total (MWh)	13,874,554	15,383,393	16,397,437	15,998,035	18,909,988

4.2. Residual wind power

Furthermore, the amount of residual electricity is calculated. In this context, residual electricity refers to the amount of electricity exported. Denmark primarily exports electricity to continental Europe, referred to as the continent, and Sweden and Norway, referred to as the Nordic Countries.

According to this data, Danish electricity exports generally take place during the night. Nevertheless, when looking at the total yearly balance, Denmark is a net importer of electricity and has been since 2011 [21]. Therefore, it is only relevant to investigate if the electricity exports, down to an hourly level, are advantageous from a financial perspective.

4.3. Development of spot electricity price

A report made by the Danish Ministry of Energy investigated the feasibility of heat pumps in a district heating setting [33]. Part of the report assessed the electricity spot price levels at which heat pumps are a better alternative for operation than boilers using either biomass or conventional sources of fuel. The assessment was conducted for different types of heat pumps, divided into small, medium, and large-scale heat pumps, characterizing typical operating conditions for each. As the focus of this report is on large-scale heat pumps, such characteristics will be used for the following comparative analysis. The larger the heat pump, the lower the COP is estimated to be. The report mentions an expected COP value from the large-scale heat pumps of 3.5, which is in accordance with the expected COP value from the 50 MW heat pump in Esbjerg by DIN Forsyning mentioned in the introduction. Furthermore, this value is used to convey a conservative estimation, as many assumptions are necessary. Figure 1 illustrates the evolution of historical electricity spot prices as an average of DK1 and DK2. These terms refer to a split in the Danish electricity system, which has been divided into two zones. The former covers West Denmark (Jutland and Fyn), which is connected to the Central European frequency area, and the latter covers Zealand and Bornholm, which is connected to the Nordic frequency area. Price data has been acquired through Nordpool—a European power exchange with available day-ahead prices—and was only available at a monthly granularity level for the period evaluated.

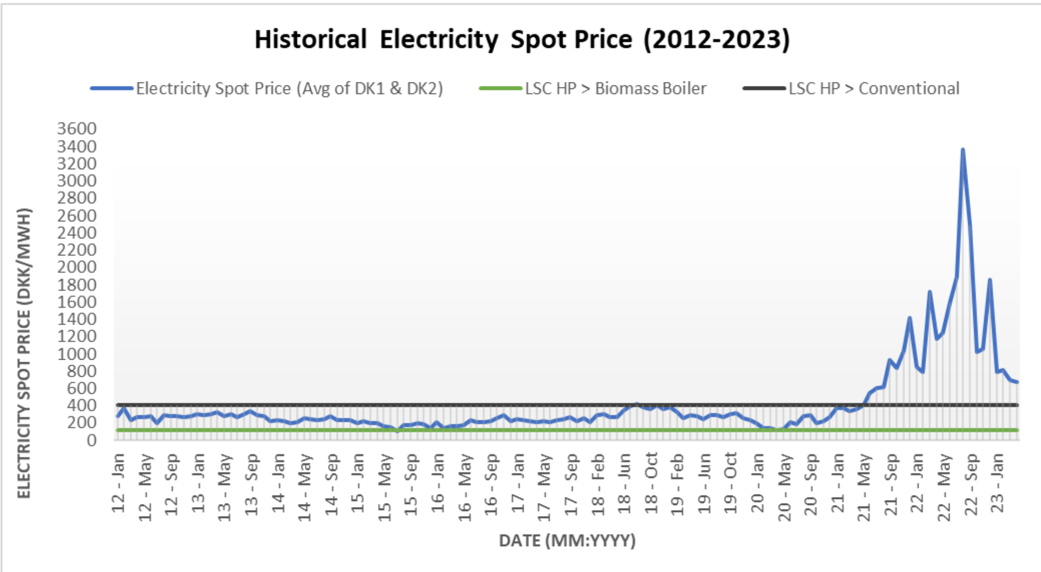

Figure 1. Electricity spot price (2012–2023) (author's own work based on Nordpool, 2023).

The blue line in the graph shows a relatively stable average monthly electricity price from 2012 to Q2 2021 that primarily fluctuates between 200 and 400 DKK/MWh. Hereafter, an extremely rapid and consistent increase happens as a result of the conflict in Ukraine and COVID-19, which led to monthly average electricity prices topping at 3,371 DKK/MWh in August 2022. The development in prices indicates that the electricity seems to have begun stabilizing again at pre-2022 levels, indicated by the rapid decline in price up until April 2023. The grey line in the graph represents the intercept at which the economic incentive of operating the conventional (natural gas) boilers outperforms large-scale heat pumps with an approximate COP of 3.5, based on the report introduced at the beginning of the section. The green line in the graph represents the intercept at which the economic incentive of operating the biomass boilers outperforms large-scale heat pumps with an approximate COP of 3.5.

Another way to look at the price of electricity is through the consumer-experienced price. In this sense, Statistics Denmark [34] provided the electricity prices for both household and non-household consumers according to their consumption on a biannual basis. DH utility companies fall within the non-household consumer category, where the average annual price for consumption above 150 GW was 520 DKK/MWh in 2018, 470 DKK/MWh in 2019, 390 DKK/MWh in 2020, 770 DKK/MWh in 2021, and 1,600 DKK/MWh in 2022.

Nevertheless, due to the lack of granularity in the electricity price data, where the lowest available level is monthly, it is not possible to determine the financial benefits and drawbacks implied by the electricity export. Hence, the paper will address the utilization of curtailed power as a renewable fuel for P2H.

4.4. Potential from wind turbine curtailment

Curtailment is an unavoidable situation for wind turbines. It entails the temporary shutdown of wind turbines due to specific conditions, including maintenance, bird and bat protection, wind speeds lower than the dimensioned cut-in speed, extreme wind speeds, and regulatory requirements. Surprisingly, regulatory requirements are, by far, the major cause of curtailment for wind turbines in Denmark. Estimates reveal that approximately 90% of Danish “nedregulering” (curtailment) was “specialregulering” (special curtailment) to mitigate bottlenecks in the German transmission grid. Although both Danish power plants and wind producers are compensated heavily to reduce the electricity production in these periods, it is not an ideal situation to have wind turbines shut down when the conditions otherwise allow for energy harvesting. As the German electricity infrastructure develops, the need for this curtailment will decrease, and the electricity generated in these periods can be used in Denmark or exported to neighboring markets.

The following section shows the volume of curtailed electricity. The same electricity production from Energinet has been used and is analyzed for the same time span. In addition to the produced volume, information regarding the percentage of curtailed production was investigated. Due to poor data availability, several sources had to be used to gather and calculate the curtailed energy. For 2019 and 2020, the percentage of curtailed electricity was 1.3% and 4%, respectively [35]. In 2018, the percentage was approximately 2% [36]. Lastly, as no data was available for 2022 and 2023, the curtailment was calculated from the average of the preceding years, as well as an average curtailment value from [37]. Accordingly, these years ended at an estimated curtailment of 1.38%. It is important to note that this estimation approach introduces a degree of uncertainty, and the results are sensitive to this key parameter. In Table 3, these values have been combined with the annual production from wind turbine production to estimate the amount of electricity that was not produced as a result of the curtailment measured in GWh. Therefore, the volumes for 2022 and 2023 should be interpreted as well-reasoned approximations.

Table 3. Wind power production and curtailment in Denmark.

Year	2018	2019	2020	2021	2022
Onshore production (GWh)	9462	10,295	10,091	8838	10,483
Offshore production (GWh)	4412	5089	6306	7160	8427
Wind total (GWh)	13,875	15,383	16,397	15,998	18,910
Curtailment	300.00	199.98	655.90	221.37	261.66
Curtailment percentage	2.16%	1.30%	4%	1.38%	1.38%

These values have been used to create a stacked bar chart that illustrates the amount of curtailed electricity in comparison to the amounts produced on an annual basis (Figure 2).

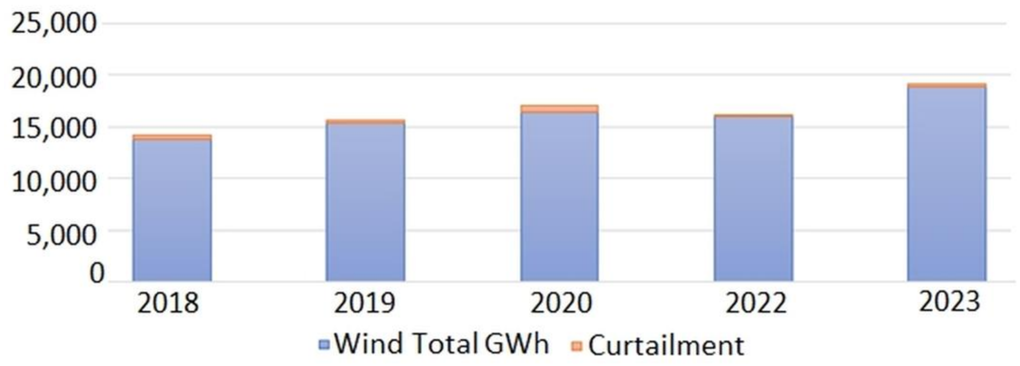

Figure 2. Wind power production and curtailment in Denmark.

These results indicate that on a national level, 328 GWh could have been produced if curtailment had not happened. As touched upon previously, it can be assumed that 10% of this is regular curtailment, whereas the remaining 90% is special curtailment due to the German market. Accordingly, 295 GWh could have been produced.

If 295 GWh of curtailed wind energy is used to power heat pumps with a COP of 3.5, the total heat produced would be

$$295\ GWh\ x\ 3.5 = 1032.5\ GWh$$

Regarding CO_2 emissions from natural gas, these are 0.202 kg/kWh, so ideally, the following value could have been avoided:

$$1032.5\ GWh\ x\ \frac{202\ g\ CO2}{kWh} = 208.57\ \text{million kg CO2}$$

which could reach 208,570 tons of CO_2 annually. This estimate represents the maximum potential annual CO_2 reduction from using curtailed wind energy for P2H in Denmark's DH networks.

Additional savings could come from reducing reliance on biomass and other fuels, although those sources are already considered relatively "low carbon" sources compared to fossil fuels.

4.5. District heating in Denmark

With more than two-thirds of residential buildings connected to district heating, Denmark has one of the most extensive DH networks in Europe [38]. Currently, the heat supply is provided by a mix of CHP and heat-only plants, with CHPs accounting for around 66% of the total supply. According to the data, heat production is mainly based on renewable fuel—48.8% biomass, 23.0% waste, and 9.8% natural gas—and, in some cases, supported by heat pumps and resistive electric boilers (4.8%). The DH utility companies in Denmark fall under a non-profit policy, as the heating supply law states that the prices can only be based on production, i.e., fuel selection and technology used, distribution, and administration. Hence, these represent the main key "influencers" of the price paid by the end consumer [39]. This implies that the heating price varies considerably across the country according to the location of the DH utility company and its production facilities, as shown by the data from Forsyningstilsynet [40].

5. Discussion

Based on the curtailed power, it is interesting to analyze how much heat could have been produced instead. The calculation is rather simple and based on the following formula, calculating the COP, where Q is the heat output, and E is the electrical energy used.

$$COP = Q/E$$

The results of the analysis are presented in Table 4, which contains three different scenarios: one where all curtailed electricity is used to power electric boilers, one where it is used for large-scale heat pumps, and a hybrid scenario with an even mix. The calculation does not take transmission losses into account and disregards the sizing of the electric boilers and heat pumps. The research solely aims to provide an overview of the potential heat that could have been produced.

Table 4. Heat conversion (simplified; curtailed power).

Year	Available electricity (curtailed) (MWh)	Resistive electric boiler		Heat pump		Hybrid (50% HP, 50% EB)	
		COP	Heat (MWh)	COP	Heat (MWh)	COP	Heat (MWh)
2018	300,000	1	300,000	3.50	1,050,000	2.25	675,000
2019	199,980	1	199,980	3.50	699,930	2.25	449,955
2020	655,900	1	655,900	3.50	2,295,650	2.25	1,475,775
2021	221,370	1	221,370	3.50	774,795	2.25	498,083
2022	261,660	1	261,660	3.50	915,810	2.25	588,735

According to Forsyningstilsynet [40], the demand for an average 130 m^2 house is estimated to be 18.1 MWh, which means that utilizing the average curtailed electricity for power-to-heat would be sufficient to supply approximately 18,100 homes in the first scenario, 63,380 homes in the second scenario, and 40,700 homes in the last scenario.

Furthermore, it is relevant to investigate the economic aspect of the power-to-heat solutions. As previously stated, the Danish DH market is regulated through a non-profit policy, which implies that any reduction or increase in the cost of heat production will result in a change in the price paid by the customers. Furthermore, as the report aims to provide an overall estimation of the potential for P2H solutions, the costs associated with the installation and commissioning of these applications will not be considered, as this would require the specific design and sizing of the components, i.e., heat pumps, which are site-specific and are not within the scope of the project. Instead, the economic aspect is determined based on the cost associated with the production of heat and, inherently, the price paid by the end consumer. Furthermore, calculations are carried out for the entire amount of curtailed electricity from wind turbines. Table 5 shows the calculated heat price associated with the curtailed electricity for the 2018–2022 period.

Table 5. Associated prices of the curtailed electricity (non-household consumer tariff).

Year	2018	2019	2020	2021	2022
Electr. price (KWh) (DKK)	0.52	0.47	0.39	0.77	1.6
Available energy (curtailed) (MWh)	300,000	199,980	655,900	221,370	261,660
Total electr. cost (DKK)	156,000,000	93,990,600	255,801,000	170,454,900	418,656,000

According to the total heat produced by each application (Table 4), the total price of electricity shown above was used to determine the price of 1 MWh of heat. Furthermore, the average annual consumption of one household, i.e., approximately 18.1 MWh, was used to calculate the total cost required by the customers for heating throughout the year. The results are shown in Table 6, where it can be seen that the superior COP of the heat pump enables considerably lower prices.

Table 6. Curtailed electricity heat prices.

Year		Resistive electric boiler	Heat pump	Hybrid (50% HP, 50% EB)
2018	Heat price by method and year (DKK/MWh)	520	149	231
2019		470	134	209
2020		390	111	173
2021		770	220	342
2022		1600	457	711
2018	Heating cost per household per year in DKK (18.1 MWh per household)	9412	2689	4183
2019		8507	2431	3781
2020		7059	2017	3137
2021		13,937	3982	6194
2022		28,960	8274	12,871

The 2022 prices for heating in Denmark vary according to the city and utility company, ranging between 4273 and 45,291 DKK, with a median value of 14,995 DKK per household. The price distribution is shown in Figure 3.

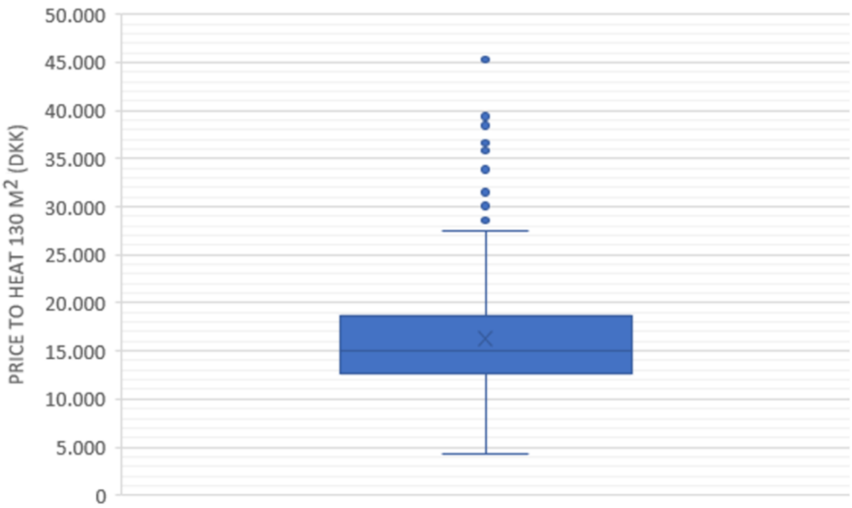

Figure 3. 2022 heat price distribution.

Comparing the current average price with the average P2H-based prices, all three alternatives display a high degree of attractiveness from a consumer economic perspective. Furthermore, heat pumps and hybrid systems appear to be less costly, even in 2022 when the electricity prices increased to a record level.

With the analysis from the previous sections in mind, the need for TES integration becomes clear. The assumptions and scope of the analysis focus on average values, whereas in a practical setting, the electric heat pumps and boilers would most likely be used as measures to meet peak demand or substitute larger parts of the required supply from, e.g., biomass boilers at the utilities. As shown in the analysis, heat pumps are most suitable to use when the electricity prices drop below a certain threshold. In combination with the fact that VRE energy sources are volatile, the optimal production might be at nighttime, when the heating demand is low. Therefore, TES technologies become essential if the utilities want to integrate heat pumps and boilers into their heat production. The current landscape for TES in Denmark seems to favor the heavily used TTES and PTES, whereas BTES and ATES are less favorable due to the lack of cooling demand. The analysis indicates that heat pumps are most effectively utilized when electricity prices dip below a specific threshold [41]. This economic consideration is crucial for optimizing the operation of heat pumps, especially when coupled with the volatile nature of VRE sources. Given this volatility, the most opportune time for optimal heat pump production often aligns with periods when electricity prices are lower, such as during nighttime when heating demand tends to be lower.

In light of this, TES technologies play a pivotal role in the integration of heat pumps and boilers into heat production systems. TES becomes essential for storing excess energy generated during optimal periods, such as low-cost nighttime electricity, and releasing it during times of higher demand. This ensures a more balanced and efficient use of energy resources.

The current landscape for TES in Denmark appears to favor TTES and PTES due to their compatibility with the prevailing conditions. On the other hand, BTES and ATES are less favorable in the Danish context, primarily because there is limited demand for cooling. This suggests that the choice of TES technology is context-specific, influenced by factors such as energy demand patterns and the existing energy infrastructure in a given region.

Examples of storage in operation indicate that the technology is ready to be adopted by the utilities—even for large-scale projects—and enables a steady and secure supply, resulting in lower prices for the end customers.

The main technological challenges for the widespread adoption of power-to-heat (P2H) solutions in Denmark include:

- Wind power curtailment and grid bottlenecks: A significant portion of wind power curtailment in Denmark results from grid bottlenecks, particularly due to Germany's transmission grid limitations [42]. While curtailment can be mitigated with grid upgrades, such as those in Germany, it remains a challenge for efficiently utilizing wind power for heat generation [43].
- Electricity price volatility: The fluctuating electricity prices, driven by factors such as the conflict in Ukraine and COVID-19, pose challenges for the economic feasibility of P2H systems [44,45]. For instance, high electricity prices, as seen in 2022, can make P2H less attractive despite its potential to offer lower-cost heat production when prices stabilize. The economic viability of P2H solutions is closely tied to electricity price trends, which remain unpredictable.
- Storage integration: TES is essential for balancing the intermittency and volatility of wind energy, especially when heat demand does not align with periods of surplus electricity generation. While technologies like TTES and PTES are already in use, the integration of these technologies on a larger scale is crucial to fully utilize P2H solutions.
- Complexity of DH networks: Denmark's DH networks are extensive, and integrating P2H systems, especially large-scale heat pumps and electric boilers, into these networks is complex. These systems must complement existing heat production methods (e.g., biomass and waste-based CHPs), which vary by region.
- Geographic and site-specific factors: The performance of P2H solutions, particularly heat pumps, depends on geographic and site-specific conditions, such as local temperature and heat demand. This makes it challenging to create standardized solutions, requiring tailored approaches based on regional conditions.

Finally, it should be mentioned that the widespread adoption of P2H, when benchmarked against alternative decarbonization pathways for the Danish DH sector—such as large-scale heat pumps—demonstrates emission reductions that highlight P2H as a complementary and viable route that directly utilizes otherwise-wasted renewable electricity. However, a future sensitivity analysis on capital costs and electricity price volatility will be crucial to further strengthen the robustness of these findings and reduce investment risk.

6. Conclusions

The purpose of the report was to investigate the potential of integrating residual wind-based electricity in the Danish DH network in a P2H setup supported by TES technologies. The results suggest that the considerable amount of curtailed power generated by wind turbines is adequate to fulfil a portion of Denmark's heating demand. By utilizing electric boilers and large-scale heat pumps with appropriate heat sources based on the geographical setting, the DH sector can be a receiver of the surplus electricity when the German transmission grid inevitably sees improvements. The analysis of electricity prices indicates that heat pumps and electric boilers show a high degree of attractiveness from a financial perspective. They can be used both as standalone systems and in combination with biomass boilers to secure a stable and resilient supply. Additionally, TES technology, which is well-developed in Denmark (particularly TTES and PTES), can be used to mitigate the disadvantages of the VRE sources stemming from their intermittent and volatile nature. Across the scenarios analyzed, the potential P2H supply could meet the needs of 18,100–63,380 households. Overall, it was concluded that the integration of renewable P2H solutions in the Danish DH network has a high potential for supporting the development of these systems from an economic, operational, and environmental perspective.

To promote P2H in Danish district heating, policies should focus on financial incentives like subsidies for installations, dynamic electricity pricing to leverage low-cost renewable power, and stronger carbon taxes to make fossil fuels less competitive. Regulatory reforms, including clearer frameworks and sector-coupling legislation, would aid integration, while investment in smart grids, energy storage, and public-private partnerships could drive implementation. Strengthening public awareness and fostering collaboration between utilities and government are also key to accelerating P2H adoption. Other countries can apply this study's findings by adapting P2H technologies to their local renewable energy sources, adjusting policy frameworks to support sector coupling, and investing in thermal energy storage.

The future for P2H, sector coupling, and TES seems promising in Denmark. Therefore, it may be interesting to investigate if Denmark can uphold their position as a forerunner within DH and wind energy in this context as well. Interesting directions for future research into the topic(s) covered in the report include investigating the electricity prices and the effect these have on which heat production technologies are feasible at significantly more complex levels of granularity, case studies on the heat pump project in Esbjerg (once it is put into operation), and detailed analysis of which utility companies could benefit from investing in large-scale PTES and BTES for seasonal storage.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

Conflict of interest

The authors declare no conflicts of interest. George Xydis is an editorial board member for AIMS Energy and was not involved in the editorial review or the decision to publish this article.

Author contributions

Conceptualization, B.S. & N.C.; methodology, B.S. & N.C.; validation, G.X. B.S. & N.C.; resources & data curation, B.S. & N.C. & G.X.; writing—original draft preparation, B.S. & N.C.; writing—review and editing, G.X. All authors have read and agreed to the published version of the manuscript.

References

1. Energistyrelsen (2023). Dansk klimapolitik. Available from: https://www.kefm.dk/Media/638315764817167867/Klimaprogram%202023.pdf.

2. Hansen KE, Xydis G (2023) Long-term heat storage opportunities of renewable energy for district heating networks. *Proc Inst Civ Eng Energy*, 1–22. https://doi.org/10.1680/jener.23.00023
3. Xydis GA, Efthimiadou A, Ucal M (2022) Food to grid: Developing a Multi-Value renewable energy investment ecosystem. *Energy Convers Manage* 266: 115850. https://doi.org/10.1016/j.enconman.2022.115850
4. Energy Supply (2021) De skal levere 50 MW varmepumpe og 60 MW fliskedel til Din Forsyning. *Energy Supply*. Available from: https://www.energy-supply.dk/article/view/773168/de_skal_levere_50_mw_varmepumpe_og_60_mw_fliskedel_til_din_forsyning.
5. Schweiger G, Rantzer J, Ericsson K, et al. (2017) The potential of power-to-heat in Swedish district heating systems. *Energy* 137: 661–669. https://doi.org/10.1016/j.energy.2017.02.075
6. Böttger D, Götz M, Lehr N, et al. (2014) Potential of the power-to-heat technology in district heating grids in Germany. *Energy Procedia* 46: 246–253. https://doi.org/10.1016/j.egypro.2014.01.179
7. Park JH, Lim SY, Yoo SH (2019) Does combined heat and power mitigate CO_2 emissions? A cross-country analysis. *Environ Sci Pollut Res* 26: 11503–11507. https://doi.org/10.1007/s11356-019-04694-1
8. Dorotić H, Ban M, Pukšec T, et al. (2020) Impact of wind penetration in electricity markets on optimal power-to-heat capacities in a local district heating system. *Renewable Sustainable Energy Rev* 132: 110095. https://doi.org/10.1016/j.rser.2020.110095
9. Fambri G, Mazza A, Guelpa E, et al. (2023) Power-to-heat plants in district heating and electricity distribution systems: A techno-economic analysis. *Energy Convers Manage* 276: 116543. https://doi.org/10.1016/j.enconman.2022.116543
10. Wang J, Cai H, You S, et al. (2020) A framework for techno-economic assessment of demand-side power-to-heat solutions in low-temperature district heating. *Int J Electr Power Energy Syst*, 122. https://doi.org/10.1016/j.ijepes.2020.106096
11. Arnaudo M, Giunta F, Dalgren J, et al. (2021) Heat recovery and power-to-heat in district heating networks—A techno-economic and environmental scenario analysis. *Appl Therm Eng* 185: 116388. https://doi.org/10.1016/j.applthermaleng.2020.116388
12. Lamaison N, Collette S, Vallée M, et al. (2019) Storage influence in a combined biomass and power-to-heat district heating production plant. *Energy* 186: 115714. https://doi.org/10.1016/j.energy.2019.07.044
13. Li J, Lin J, Song Y, et al. (2018) Operation optimization of power to hydrogen and heat (P2HH) in ADN coordinated with the district heating network. *IEEE Trans Sustainable Energy* 10: 1672–1683. https://doi.org/10.1109/TSTE.2018.2868827
14. Johannsen RM, Arberg E, Sorknæs P (2021) Incentivising flexible power-to-heat operation in district heating by redesigning electricity grid tariffs. *Smart Energy* 2: 100013. https://doi.org/10.1016/j.segy.2021.100013
15. Javanshir N, Syri S, Tervo S, et al. (2023) Operation of district heat network in electricity and balancing markets with the power-to-heat sector coupling. *Energy* 266: 126423. https://doi.org/10.1016/j.energy.2022.126423
16. Jimenez-Navarro JP, Kavvadias K, Filippidou F, et al. (2020) Coupling the heating and power sectors: The role of centralised combined heat and power plants and district heat in a European decarbonised power system. *Appl Energy* 270: 115134. https://doi.org/10.1016/j.apenergy.2020.115134

17. Rasmussen NB, Enevoldsen P, Xydis G (2020) Transformative multivalue business models: A bottom-up perspective on the hydrogen-based green transition for modern wind power cooperatives. *Int J Energy Res* 44: 3990–4007. https://doi.org/10.1002/er.5215
18. Estanqueiro A, Couto A (2021) New electricity markets—The challenges of variable renewable energy. *Local Electricity Markets*, 3–20. https://doi.org/10.1016/B978-0-12-820074-2.00016-2
19. Xydis G (2013) Wind energy to thermal and cold storage—A systems approach. *Energy Build* 56: 41–47. https://doi.org/10.1016/j.enbuild.2012.10.011
20. Bird L, Cochran J, Wang X (2014) Wind and solar energy curtailment: Experience and practices in the United States. *National Renewable Energy Laboratory*. Available from: https://docs.nrel.gov/docs/fy14osti/60983.pdf.
21. Energistyrelsen (2022) Global Afrapportering 2022 (GA22): Eludveksling. Available from: https://www.kefm.dk/Media/637867480477626946/GA22%20-%20hovedrapport.pdf.
22. Armand M, Axmann P, Bresser D, et al. (2020) Lithium-ion batteries–Current state of the art and anticipated developments. *J Power Sources* 479: 228708. https://doi.org/10.1016/j.jpowsour.2020.228708
23. Ebrahimi M (2019) Storing electricity as thermal energy at community level for demand side management. *Energy* 193: 116755. https://doi.org/10.1016/j.energy.2019.116755
24. Lund H, Werner S, Wiltshire R, et al. (2014) 4th Generation District Heating (4GDH): Integrating smart thermal grids into future sustainable energy systems. *Energy* 68: 1–11. https://doi.org/10.1016/j.energy.2014.02.089
25. David A, Mathiesen BV, Averfalk H, et al. (2017) Heat roadmap Europe: large-scale electric heat pumps in district heating systems. *Energies* 10: 578. https://doi.org/10.3390/en10040578
26. Horten (2020) Ny projektbekendtgørelse for kollektive varmeforsyningsanlæg i høring. Available from: https://www.horten.dk/nyhedsliste/2020/oktober/ny-projektbekendtgoerelse-for-kollektive-varmeforsyningsanlaeg-i-hoering?fbclid=IwAR3sa_0hX-HHh9Y1pjCQqG2RmrJIp7YcPCpHzcFlsQMb8T9xvWXskk2kvkI.
27. Xydis G, Pechlivanoglou G, Nayeri NC (2015) Wind turbine waste heat recovery—A short-term heat loss forecasting approach. *Challenges* 6: 188–201. https://doi.org/10.3390/challe6020188
28. Euroheat & Power (2022) Large heat pumps in district heating & cooling systems. Available from: https://www.euroheat.org/news/new-report-large-heat-pumps-in-district-heating-and-cooling-systems.
29. Nielsen MG, Morales JM, Zugno M, et al. (2016) Economic valuation of heat pumps and electric boilers in the Danish energy system. *Appl Energy* 167: 189–200. https://doi.org/10.1016/j.apenergy.2015.08.115
30. Energistyrelsen (2013) Udredning vedrørende varmelagringsteknologier og store varmepumper til brug i fjernvarmesystemet. Available from: https://ens.dk/sites/ens.dk/files/Forskning_og_udvikling/udredning_om_varmelagringsteknologier_og_store_varmepumper_i_fjernvarmesystemet_nov_2013.pdf.
31. Strasszer D, Xydis G (2024) Integrating geothermal energy in Hungary: A case study on sustainable urban heating and emissions mitigation through the district heating infrastructure. *Tunnelling Underground Space Technol* 149: 105804. https://doi.org/10.1016/j.tust.2024.105804
32. Energinet (2022) Electricity Balance. Available from: https://www.energidataservice.dk/tso-electricity/ElectricityBalanceNonv.

33. Kortegaard Støchkel H, Lava Paaske B, Clausen KS (2017) Guidebook for large-scale heat pump projects in district heating (Danish: Drejebog til store varmepumpeprojekter i fjernvarmesystemet).
34. Statistics Denmark (2023) Prices of Electricity for non-households by annual consumption, price definition, and energy unit. Available from: https://m.statbank.dk/TableInfo/ENERGI2.
35. Svane K, Enevoldsen P, Xydis G (2023) Using existing cold stores as thermal energy storage. *Environ Sci Pollut Res*, 1–9. https://doi.org/10.1007/s11356-023-27752-1
36. Green Power Denmark (2019) Stoppede vindmøller er kommet for at blive. Available from: https://greenpowerdenmark.dk/nyheder/stoppede-vindmoeller-er-kommet-blive#:~:text=Omfanget%20af%20al%20s%C3%A5kaldt%20nedregulering,for%20nedregulering.
37. Nycander E, Lennart S, Olauson J, et al. (2020) Curtailment analysis for the nordic power system considering transmission capacity, inertia limits and generation flexibility. *Renewable Energy* 152: 942–960. https://doi.org/10.1016/j.renene.2020.01.059
38. Danish Energy Agency (2022) Energy Statistics 2021. Copenhagen: Danish Energy Agency.
39. Danish Energy Agency (2017) Regulation and planning of district heating in Denmark.
40. Forsyningstilsynet (2022) Varmeprisen pr. 1. august 2022. Available from: https://forsyningstilsynet.dk/tal-fakta/priser/varmepriser/priser-pr-1-august-2022?fbclid=IwAR0sGRdVH7qN0pB5mPs48Uu6g7TK8ArbPqw868MBmkkmpxZzAe-6XS-ispU.
41. Wilczynski EJ, Chambers J, Patel MK, et al. (2023) Assessment of the thermal energy flexibility of residential buildings with heat pumps under various electric tariff designs. *Energy Build* 294: 113257. https://doi.org/10.1016/j.enbuild.2023.113257
42. Baral S, Xydis G (2025) Unleashing the economic potential of wind power for ancillary services. *Int J Emerging Electr Power Syst* 26: 155–182. https://doi.org/10.1515/ijeeps-2023-0267
43. Marchi B, Nardin G, Barazzutti A, et al. (2025) Energy dialogue between district heating networks. *J Cleaner Prod* 522: 146378. https://doi.org/10.1016/j.jclepro.2025.146378
44. Bros-Williamson J (2025) Building energy demand pathways for reaching a net-zero carbon society. *Cambridge Prisms: Energy Transitions* 1: e3. https://doi.org/10.1017/etr.2025.10002
45. Adamo A, Martin H, Hoz JDL, et al. (2025) A review of worldwide strategies for promoting high-temperature heat pumps. *Appl Sci* 15: 839. https://doi.org/10.3390/app15020839