Future Cities and Environment

A Comprehensive Technical Analysis of Retrofitting a Danish Residential Area into a Positive Energy District

TECHNICAL ARTICLE

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ABSTRACT

Aligned with Denmark's growing smart energy networks encompassing district heating and electricity grids and in harmony with the country's ambitious energy and environmental objectives, this study aims to elevate the investigation from individual buildings to consider districts and cities. In pursuit of this objective, a case study of an Odense district in Denmark was considered for modeling, simulation, and energy performance improvement. The selected residential area was modeled using City Energy Analyst, an open-source urban scale modeling tool, accounting for different building attributes as well as the particulars of energy networks and supply systems. The validation of a baseline scenario is predicated upon real-world data collected on-site to serve as the benchmark for exploring and evaluating various scenarios and measures for enhancing energy efficiency. Consequentially, eight distinct energy enhancement packages were designed, modeled, and simulated individually. The results were analyzed, and it was shown that an energy improvement package consisting of retrofitting buildings' constructions, indoor thermal comfort setpoint management, heating system upgrade, photovoltaic-thermal unit installation, and heat pump integration, along with a seasonal energy storage system, is capable of enhancing the overall energy efficiency quotient of the area, establishing a positive energy district with an excess in heat and electricity production.

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INTRODUCTION

In pursuit of achieving a net zero greenhouse gas (GHG) emission in the EU by 2050, the European Commission (EC) has devised a long-term strategy focused on sustainable solutions to reduce GHG emissions (European Commission, 2019). According to the EC's plan, improving energy efficiency in buildings plays a crucial role as they are accountable for 40% of energy consumption and approximately 35% of emissions (Potrč et al., 2021). Recognizing the significant impact of buildings on energy consumption and GHG emissions, it becomes essential to enhance the design and construction of new buildings and to optimize the performance and operation of existing ones through systematic, energy-efficient, and cost-effective retrofitting processes (Hagenau et al., 2020; Cremer et al., 2022; Alavirad et al., 2022; Jradi et al., 2018). In this regard, the European Union (EU) has committed to achieving an overall 55% carbon reduction compared to 1990 levels by 2030 (European Union, 2021).

Building energy modelling has been extensively utilized in the existing body of literature as a valuable tool for enhancing the design, operation, and optimization of building performance (Yang et al., 2022). The domain of energy modelling and simulation, focusing on single buildings and facilities, has reached a high level of maturity, and widely available commercial tools are commonly employed to achieve accurate building modelling and performance predictions (Chen et al., 2022). Assessing the economic feasibility of employing building energy modelling, it was reported that the investment in developing a detailed building dynamic energy model typically yields a payback period of approximately 1 to 2 months (HOK, 2016). This short payback period provides strong support for the adoption of model-driven approaches in the decision-making process related to the design, operation, control, and commissioning of both new and existing buildings.

Recently, there has been a notable increase in the number of research studies focusing on energy modelling, analysis, and performance optimization of urban areas, districts, and cities (Ali et al., 2021). However, when it comes to dealing with building clusters, this approach remains relatively underdeveloped, lacking well-established and validated standard procedures for modeling large building clusters. As a result, the accuracy of predictions is affected, and direct comparisons become challenging (Eicker, 2019). In recent times, various models and methodologies have emerged to predict energy consumption in building districts and cities on a small to medium scale. Examples of these tools include CitySim, UrbanSim "UCB," Urban Modelling Interface "UMI," and City Energy Analyst "CEA." These tools estimate the energy demand of an area based on its surroundings, size, and climate conditions (Sola et al., 2020).

One of the recent endeavors to enhance the energy performance of cities and large districts on a large scale is the introduction of "Positive Energy Districts" (PED) (Lindholm et al., 2021). The fundamental concept behind PEDs involves creating designated areas within the boundaries of a city or district capable of generating more energy than they consume annually, resulting in a net surplus. To achieve this, these areas are designed to be adaptable and responsive to the unpredictable fluctuations in the energy market while also reducing reliance on centralized energy networks. This is made possible through the implementation of decentralized solutions, renewable energy systems, energy storage technologies, and improved control and management practices. As part of the effort to meet energy and environmental targets in the EU, the EU Commission has proposed general regulatory conditions to facilitate the implementation of Positive Energy Districts within real urban contexts by 2050. While PEDs offer various technical and economic advantages, they are still in the early stages of development, and the realization of fully functional PEDs remains more of an objective than a current reality. Nonetheless, the EU has initiated a project with the ambitious goal of planning and developing a hundred PEDs by 2025 (Monti et al., 2016; Bruck, et al., 2022). This initiative could serve as a significant catalyst in establishing PEDs not only in Europe but also in other regions worldwide.

Given the rapid advancement of smart and adaptable grids on a large scale (Lund et al., 2022), it is crucial to shift focus from examining individual building performance and instead, scale up the efforts towards integrated building clusters and interconnected energy-efficient and flexible cities and neighborhoods. However, there is presently a lack of established and validated procedures and standards for modeling large-scale building clusters dedicated to the district or city level (Jepsen et al., 2022). This scarcity has a significant impact on the overall accuracy and consistency of the results (Jepsen et al., 2020). Over the past few decades, Denmark has focused its legislative efforts, theoretical research, and practical applications on enhancing the design and operation of individual buildings and facilities.

In line with the expansion of smart energy networks in Denmark in terms of district heating and electricity grids, along with the ambitious energy and environmental goals in the country, this study aims to upscale the investigations from a building level to a district and city level. In this regard, a case study of a district in Odense, Denmark, is considered a case study for modeling, simulation, and performance improvement. The considered residential area will be modeled using an open-source urban scale modeling tool, City Energy Analyst (CEA) (The A/S Group – ETH Zurich, 2022) considering the different characteristics of buildings along with the specifications of the energy networks and supply systems. A base-case scenario is validated using actual data collected onsite. The base-case scenario will serve as a baseline to investigate and assess various options and possibilities for energy performance enhancement. Thus, eight different energy improvement packages are considered, simulated, and evaluated individually. The results were analyzed, and an optimal package was selected for further evaluation, improving the overall energy scheme in the district and turning it into a positive energy district (PED). The results of this study will serve as guidance and support for decision-making in the district and corresponding municipality, providing recommendations that are in line with the current plans to retrofit the buildings and the corresponding energy supply systems in the upcoming years.

While a large body of investigations has been presented in the last two decades on improving and enhancing the energy efficiency in Danish buildings and facilities, this work upscales the effort towards a district and city level, aiming to accelerate the transition towards a green and sustainable Danish energy sector. The dynamic energy simulation-based city-scale approach used in this work overcomes the uncertainties and assumptions associated with traditional energy planning tools currently in use. It allows for investigating various energy network retrofit scenarios, considering dynamic building performance and the impacts of various internal and external parameters. In addition, this study provides a foundation for creating Denmark's first initiative towards establishing a PED, aligning with the recent European Union strategy that seeks to implement and duplicate 100 Positive Energy Neighborhoods across Europe by 2025. In addition, the energy retrofitting work supports the Danish energy and environmental goals of attaining a fossil fuel-free energy production and supply sector by 2050, as well as the national building energy retrofit strategy and the European energy renovation wave.

CASE STUDY

The district of Søhus is considered a case study in the current investigation to design, model, and implement a full-scale retrofit analysis and assessment, considering the energy supply systems as well as the buildings and facilities physical envelopes and constructions. In addition, an investigation on the possibility of establishing the areas as the first Positive Energy District (PED) in Odense, Denmark, will be performed. Søhus is located on the northern outskirts of Odense, 6 km from the center. It was originally a small village that only consisted of a few farms. However, a huge evolution and development have happened in the last decades, and the district today is a lively residential and housing area. The selection of the area was based on the current plans for implementing a full retrofit project in the district as well as the availability of data on the energy supply systems, buildings, and facilities. The area of interest is shown in Figure 1.

The area is to be modeled and examined in CEA to simulate different combinations of production units and building retrofits as part of a future PED. The area consists of over 40 buildings, with data available for 37 of the buildings. Most of the buildings are houses and residential apartments, and they were established in the 1980s and 1990s. Thus, the possible retrofitting of the buildings to reduce demand and thereby pave the way for a PED implementation is to be considered. The whole district has been connected to a local district heating grid since 1998, providing the buildings' needs for space heating and domestic hot water. In this regard, the annual total heating demand of Søhus is reported as 1856 MWh, based on 2022 numbers. Additionally, in terms of the heating source mix, the heat supply is delivered by combined heat and power plants fired with coal, straw, and wood pellets. Thus, a mix of renewable and non-renewable sources of production is currently in use. In line with the holistic Danish 2050 Energy Strategy, which aims to achieve 100% independence of fossil fuels in the Danish energy mix in 2050 (Lund et al., 2009), one of the major aims of retrofitting the district and establishing a PED is to phase out the conventional fossil-fuel energy resources currently in use and shift towards a 100% renewable energy-based production. Nevertheless, the design of the PED will also aim towards providing excess heat and electricity, maximizing the positive energy and environmental impacts.

Figure 1 The district chosen for investigation.

Figure 2 provides a flowchart of the study workflow stages, starting from data collection to model development and finally the design of a positive energy district.

CITY-SCALE MODELING

City-scale modeling tools, including City Energy Analyst (CEA), capable of modeling on a city/scale level are getting more attention, especially with the overall transition towards interconnected cities and districts. In this regard, these tools can be used for energy network design and strategy implementation, building and facility retrofitting, operational strategy investigation, capacity sizing, and service management (Wong et al., 2021; Bi et al., 2022; Horak et al., 2022). Another perspective regarding fostering city-scale and district-scale modeling and evaluation is the economic added value and impacts. Overall, the investment costs for projects dealing with building scale or even facility scale are generally very high, with long payback years. On this basis, investing in and investigating projects on a larger scale, in particular when involving collective energy supply systems, would enhance the economic feasibility of the projects and increase their profitability. In this regard, modeling and simulation of districts and large-scale areas is an effective means of investigating the technical, economic, and environmental impacts of designing and retrofitting energy supply systems and building envelope construction. This can serve as a basis to support decision making and planning and provide effective and feasible recommendations and actions.

In this work, City Energy Analyst (CEA) tool is used for modeling the considered district and simulating various scenarios and retrofitting packages, as well as investigating the establishment of a PED. The use of holistic modeling and simulation white-box modeling tools as CEA allows for investigating the collective high-level impact of considering different aspects and actions without compromising the accuracy and comprehensiveness of modeling. When considering these actions for each building individually, a major loss of accuracy at the level of energy supply networks occurs. In addition, using such tools provides the flexibility of changing and investigating the impact of various parameters, dealing with the energy systems, building envelope, loads, and services. Nevertheless, control and management operational strategies can be tested and evaluated against pre-defined performance indicators. Also, it is important to consider when modeling and simulating such large-scale districts and areas that different tools have their own strengths and drawbacks.

CEA is a tool developed by the ETH Zurich as free open-source software for energy modeling and analysis of systems from street level to city level (Fonseca et al., 2016). The tool includes sub-packages for optimization, demand forecasting, technology potential evaluations, technical and economic analysis, and visualization platforms. Demand calculations are one of the core features of CEA. As shown in Figure 3, the process for CEA scenario development is highly dependent on the demand calculation carried out. At the level of demand calculations, all defined preprocessing inputs are integrated and considered for the analysis before further visualization and development of the scenarios.

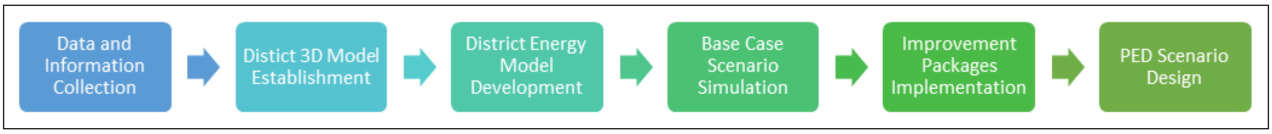

Figure 2 Flowchart of the study workflow stages.

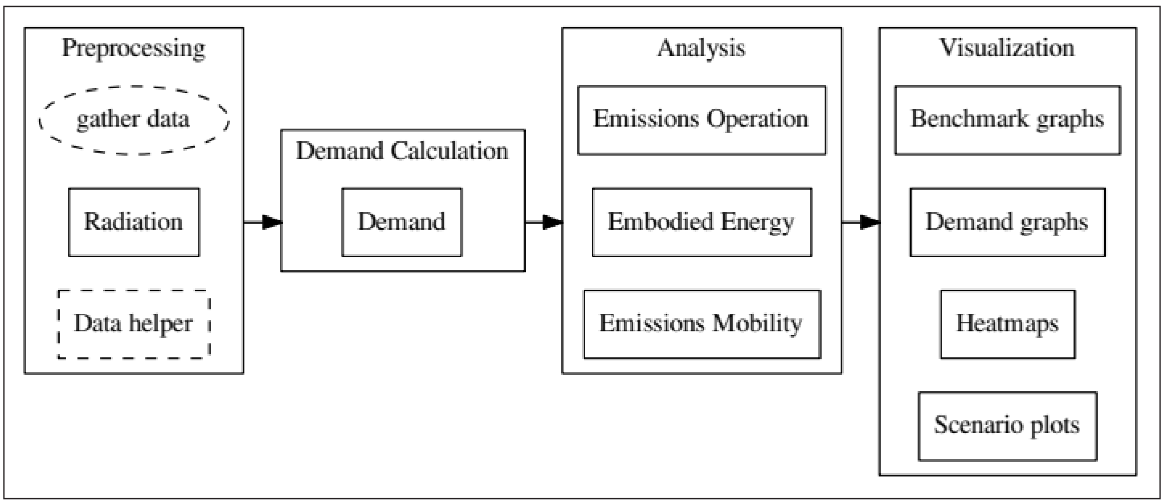

Figure 3 CEA main workflow blocks.

In this regard, demand calculation takes into account the building and room typology, envelope specifications, weather data, loads, schedules, occupancy patterns, gross floor area, and indoor comfort constraints.

CEA is chosen to model the district case study and simulate its performance as the tool congregates all the energy modeling aspects needed, from envelope constructions to energy supply systems, along with the corresponding analysis, evaluations, and results presentation and visualization capabilities. CEA uses a white box modeling approach and is built on a tedious definition of various building specifications and characteristics. The input data for the model is divided into inputs defined manually using the input editor and built-in inputs called from the respective tool database.

Furthermore, the aim of a detailed modeling of the considered district using a white box modeling approach is to develop a model that can be used to examine various packages and evaluate different energy measures and possible improvements on various levels to identify the optimal scenario from a technical and economic perspective. The most vital part of the development of the model was integrating and loading all input data related to the district targeted. In particular, input data have been manually integrated from the Danish building regulations, energy supply system datasheets, and weather conditions data.

As CEA initially doesn't provide standardized parameters of the building envelope related to Danish buildings, data in this regard have been added, based on the Danish building regulation, and loaded into the CEA Database Editor in the form of standards for the envelope assemblies. In this regard, different standards were defined, considering the different Danish building standards over the years: BR61, BR79, BR95, BR2006, BR2010, BR2015, and BR2018. By identifying the age of each building in terms of the year of construction or the year of the last renovation, a building standard is assigned to each building. Each building standard contains information on the different constructions in terms of the corresponding U-values, including external walls, partitions, roofs, grounds, and windows. intervals for the construction year for the buildings. The standards then define the envelope assembly for that specific building, setting the type of construction, floor, wall, and so on, based on the standard.

In terms of the energy supply system, a district heating system was defined in CEA to provide space heating and domestic hot water needs to the buildings and houses in the district. In addition, an energy mix representing the Danish electricity grid was developed in CEA to characterize the Danish electricity supply in the actual area, with inputs including the average efficiency of the system, CO_2 emissions, and electricity prices. All houses and buildings in the area are connected to the main electricity grid.

As the inputs related to the database information were defined as shown above, additional information was added and defined using the CEA input editor. This includes ensuring that the district typology is correct and relating each building and house in the district to its relative and corresponding building standard defined above, depending on the construction or renovation year. Additionally, the buildings' loads, schedules, energy system setpoints, occupancy numbers, and indoor comfort constraints were defined and integrated into the developed model. Most of this information relied on collected information from the different houses and buildings in the area and data from the Danish building registry (BBR) (BBR, 2018).

As the input data were introduced in the different CEA modeling modules and the buildings' geometry, topology, orientation, and specifications were defined, the overall building 3D model was generated. Figure 4 shows the overall architectural 3D model of the district developed by CEA.

PRELIMINARY ANALYSIS

While developing the base case model for the district of investigation, different preliminary observations were

Figure 4 3D model of Søhus district in CEA.

considered. These observations provided the basis for some of the later investigations in terms of actions and measures definition, packages examination, and PED design. It has also helped in addressing some of the initial default assumptions in CEA, leading to a more accurate and comprehensive initial base case model.

INDOOR COMFORT CHARTS

While developing the model, it was observed that the comfort charts had the data divided into summer and winter periods. On this basis, the summer period is defined as the cooling period, and the opposite is true with winter. However, as the buildings in the area have no cooling systems implemented, with only ventilation units scattered in a few buildings, the winter period was only considered in this study to calibrate the heating setpoints implemented in the model. On this basis, the model is set to have a full heating period throughout the year. Neglecting the summer cooling period, the model will operate with a single temperature interval for the whole year. Heating setpoints ranging between 19 and 22°C were employed in different buildings depending on their age, type, and use. The resulting comfort chart for the whole year in one of the district buildings is illustrated below in Figure 5, interpreting the indoor comfort data simulated over a whole year. It is obvious that for the majority of the occupied hours over the year, the indoor temperatures lie within the acceptable comfort range in CEA. However, it is also clear that in the summer, as there are no cooling systems implemented, the indoor temperature can get as high as 34°C.

DISTRICT GROSS FLOOR AREA

The floor area of the different buildings included was preloaded in CEA employing the street maps data, stating both the total floor area of each building and the gross floor area of the whole district. Since it is not possible to go into depth with the street map data as it is built into CEA and not exposed through the corresponding dashboard, the data is compared with geographical and cumulative floor area data for all buildings considered in Søhus based on BBR. It was shown that the initial gross area of the district reported in CEA is 32% higher than that reported in BBR. Thus, a major mismatch is identified, which would significantly affect the modeling accuracy and the subsequent simulation results. Investigating this in depth has resulted in identifying a major issue in the analogy of building and space definition in CEA. It was found that CEA considered different types of boxes, including bins, storage spaces, sheds, and other types of structures, to be conditioned building areas. This has led to an increase in the overall gross area of the district by around 32%. These issues were addressed manually by eliminating these structures, resulting in a gross area gap of around 2.1% between the CEA district area and the cumulative area calculated based on the Danish building registry. This gap is deemed acceptable, and thus, the resulting model of the district is considered satisfactory for subsequent simulations, analyses, and evaluations.

BASE CASE SCENARIO

After the preliminary analysis, the resulting model with the updated geometry and the defined heating setpoints, as well as the loads, schedules, and construction specifications, was considered to simulate the district base case scenario's performance. This will serve as the baseline scenario with no changes and will serve as a basis for comparison for all suggested improvement measures and packages. The supply system is simulated using the fuel mix from Fjernvarme Fyn, the district heating company supplying the area (Fjernvarme Fyn, 2020). The resulting heat demand for the base-case scenario is found to be 2388 MWh/year for space heating and domestic hot water. Comparing this to the actual heating demand in the area of investigation, a difference of 6.3% was highlighted. On this basis, the district model predictions are deemed satisfactory and thus can be used as a basis for subsequent measures and package evaluation. No validation with respect to electricity consumption was done as there is no single electricity provider in the area, making it very complicated to have a cumulative electricity consumption number. The heat demand profile for each month is illustrated in Figure 6.

IMPROVEMENT PACKAGES

Considering the base case scenario reported above as a baseline, multiple improvement packages were designed and simulated, targeting different components in the district, including energy systems, supply networks, buildings' envelope constructions, and operational

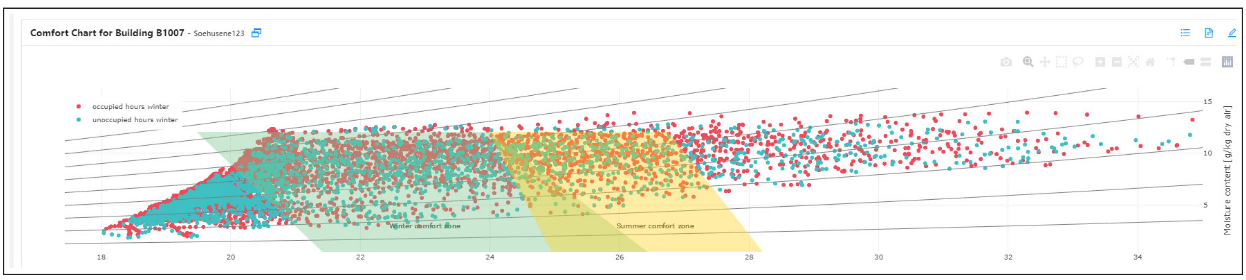

Figure 5 Comfort chart for building B1007 in the district.

control strategies. The considered packages are implemented and examined individually. An overview of the eight packages considered is illustrated in Table 1, showing the respective measure mix of each package. Considering each package, the impact of the changes and modifications implemented on the overall energy consumption of the area is to be evaluated. On this basis, the optimal measures and actions are to be highlighted and used to investigate a scenario to retrofit the area into a positive energy district.

PACKAGE 1 – ENVELOPE RETROFITTING

The first package aims at upgrading the buildings' envelope, targeting the different building constructions, including external walls, roofs, and windows. the difference between the building regulations standards. In this package, each of the building components is upgraded to comply with the set regulations and guidelines for building construction provided in the BR10 building regulation in Denmark. This has been implemented by increasing building wall and roof insulation levels to comply with the set U-values in the regulations, in addition to replacing windows with upgraded double-glazed windows, as recommended in the building regulations. The resulting reduction in heating energy consumption is shown in Table 2, highlighting around 37% savings in two of the buildings considered in the district after envelope construction upgrades.

Upscaling this package to all the buildings in the district, if all buildings were retrofitted to comply with the BR10 standard, the total heat demand would be reduced by around 35% from 2388 to 1551 MWh/year. The impact on the comfort chart is also examined, and the resulting comfort chart of one of the buildings in the area after the construction upgrade is shown in Figure 7. It is very clear in the figure that most of the time, the indoor temperature in the building is in the range of 18–22°C, which is the acceptable range for indoor comfort satisfaction. This shows that the increase in envelope

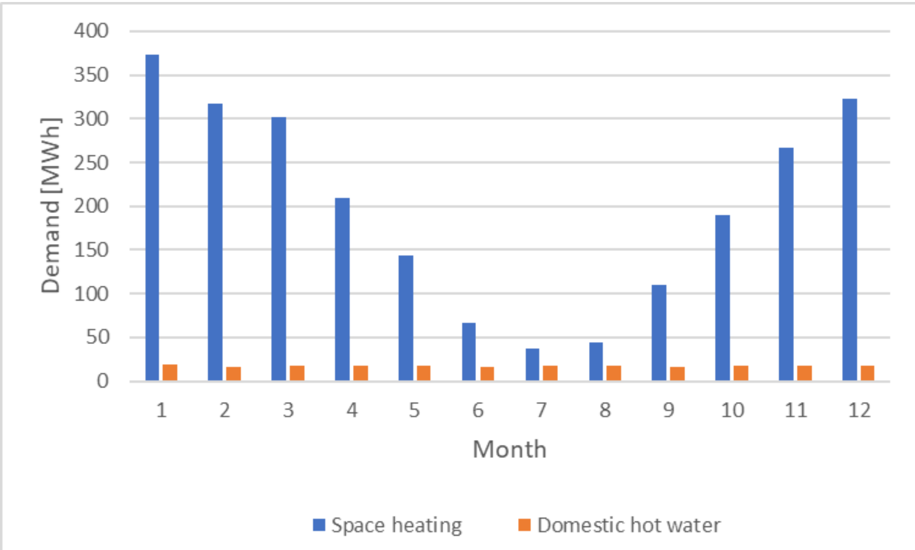

Figure 6 Predicted district monthly heat demand.

Technology	Base Case	P1	P2	P3	P4	P5	P6	P7	P8
DH (current mix)	X								
DH (fossil free mix)					X				
Heat pump implementation								X	X
PV installation						X		X	
PVT installation							X		X
Envelope constructions upgrade		X							
Temperature setpoints management			X						
Heating systems retrofitting				X					

Table 1 Improvement packages overview.

BUILDINGS	BASE CASE [MWH/YEAR]	UPGRADED ENVELOPE [MWH/YEAR]	HEATING ENERGY SAVINGS [%]
B1000	86,935	54,766	37
B1030	64,618	40,059	38

Table 2 Resulting heat demand after envelope upgrade.

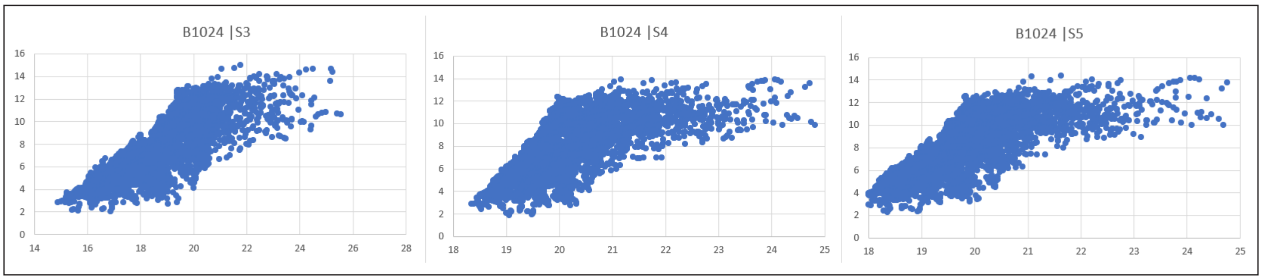

Figure 7 Comfort chart for building B1024 after upgrading to BR10 constructions level.

insulation decreases the temperature range, which is expected as the higher degree of insulation affects the degree of heat transfer. On the other hand, no significant change in the moisture levels was observed.

PACKAGE 2 – TEMPERATURE SETPOINTS MANAGEMENT

The control setpoint temperatures are examined through multiple scenarios testing varying combinations of indoor setpoint temperatures. The initial setpoint and setback temperatures of the heating system for the base case model were 20/21°C. This will be the reference for the scenarios developed. In this regard, two scenarios were developed for testing control temperatures of heating setpoint and setback temperatures of 18/22°C and 20/24°C.

Based on the evaluation, it was shown that the decrease in the setback temperature naturally results in lower indoor temperatures. It was shown that for buildings with an up-to-date envelope, the reduction of the setback to 18°C would not be a problem. For instance, building B1024 complies with BR10 regulation and only sees a minor reduction in temperatures because of the change in the setback temperature. In contrast, the increase in the setpoint temperature does not have any significant effect on the comfort chart, and thus there is no need for comfort to achieve higher temperatures in relation to comfort zones. Furthermore, the increase in the setpoint results in a higher heat demand, which is not desired. A final scenario is conducted to gather the knowledge achieved from the first two scenarios, testing with a control temperature of 18/20°C. This was chosen as the reduction of the setback temperature to 18°C did not have a significant negative impact on the comfort chart and would naturally result in a reduction of the heat demand. The resulting comfort chart is illustrated in Figure 8 (a) and (b), for buildings B1000 and B1024, respectively. Overall, the resulting comfort chart shows good indoor temperatures and moisture levels for B1024 and fine results for B1000, where we see a higher variance in temperature. The results are illustrated and compared against the base case scenario in Table 3, showing the reduction in demand for each temperature setting scenario.

PACKAGE 3 – HEATING SYSTEMS RETROFITTING

In this package, the heating system is examined, testing two different types of systems: space radiators and floor heating units. The baseline reference is using radiators with inlet and outlet temperatures of 90/70°C. The first scenario tested was using space radiators with modified setpoints of (70/55°C), the resulting heat demand showed a 12% reduction. The heat losses are significantly reduced through a lower temperature throughout the system; the surface area of low-temperature radiators is larger to ensure sufficient heat and increase efficiency. Lower-temperature space heating units can furthermore increase overall indoor comfort by minimizing over- and undershooting of the system and thereby ensuring more even temperature distribution throughout the building. Another option was also investigated, involving retrofitting the heating system and implementing a floor heating option. This resulted in around 24% savings on the heating demand of the buildings in the district of the buildings in the district, as shown in Table 4.

PACKAGE 4 – FOSSIL FUELS-FREE DISTRICT HEATING MIX

This package examines the implementation of different sources of production, considering the integration of a fossil fuel-free scenario into the district heating system supporting the area. The initial baseline was based on data for the current fuel mix in the area, provided in 2020. On this basis, fossil fuel sources of production are omitted and replaced by heat pumps. The resulting fuel mix consists of power plants using straw, incineration,

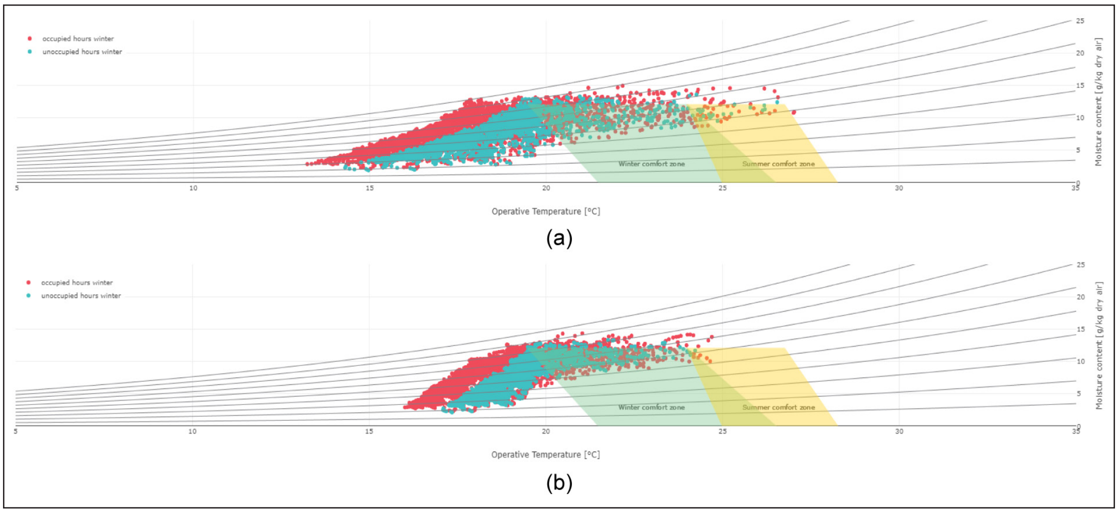

Figure 8 Comfort charts for **(a)** B1000 and **(b)** B1024 buildings.

	BASE CASE	18/22°C TEMP. SETTING	20/24°C TEMP. SETTING	18/20°C TEMP. SETTING
Heat Demand [MWh/year]	2399	2351	2014	–13%

Table 3 Heat demand with various temperature settings.

	SPACE RADIATORS (70/55°C)	FLOOR HEATING (40/35°C)
Heat demand Savings (%)	12	24

Table 4 Heat demand with different heating elements.

	EFFICIENCY/ COP	PRODUCTION HOURS
Straw	0,93	2070
Incineration	1,15	3251
Wood chips	1	804
Heat pump	3	2635
Total		8760

Table 5 Resulting heating fuel mix.

and wood chips, in addition to heat pumps, where incineration covers the highest number of hours. The resulting efficiency of the supply system is 1.66. The efficiency (COP) and number of production hours of each supply unit are illustrated in Table 5.

Overall, the supply demand is 1438.79 MWh/year, which is 40% less than the initial baseline case. The demand for each month is illustrated in Figure 9. Looking into a fossil-free retrofit is important here, considering the technical, economic, and environmental impacts. Overall, the initial system would most likely undergo a retrofit in the near future, considering the initial plans in the municipality of Odense to install heat pumps.

PACKAGE 5 – PHOTOVOLTAIC SYSTEM INSTALLATION

The district considered has no PV systems implemented currently. This package addresses the large-scale integration of PVs in the considered area. The PV production is modeled in CEA with two scenarios considering where the PV units are installed: roof installation only and roof and wall installation in combination. Naturally, the expected result is a higher potential for roof and wall installation, with a larger area for possible installation depending on the solar potential. The resulting electricity production potential of a roof-only installation is 286.68 MWh/year, whereas the potential of a roof-and-walls PV installation is around 838 MWh/year.

In addition, the resulting monthly production potentials of both scenarios are illustrated in Figure 10 (a) and (b). The PV production with roof installation has a high variation between the highest and lowest producing months, where most of the production is between May and August. In contrast, with a roof and wall installation, the production is more even throughout the year, and the south side panels have significant potential that can be utilized. Both installations can be integrated into a resulting system depending on the needs of the system, yet both installations would most likely need to be supported by a storage system.

PACKAGE 6 – PHOTOVOLTAIC-THERMAL SYSTEM INSTALLATION

The implementation of PVT is also examined. Again, two scenarios are developed, testing both roof installation and roof and wall combinations. Similar trends are

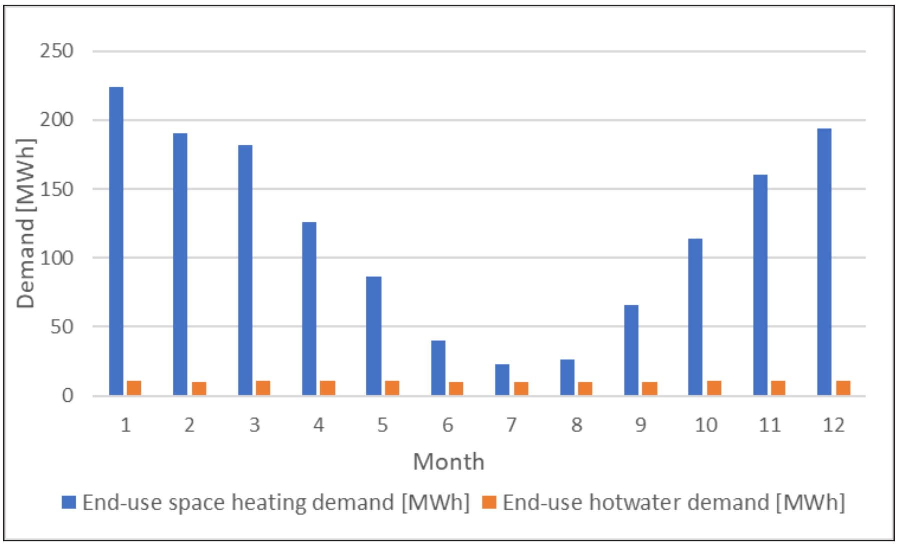

Figure 9 District heat supply with the new fuel mix.

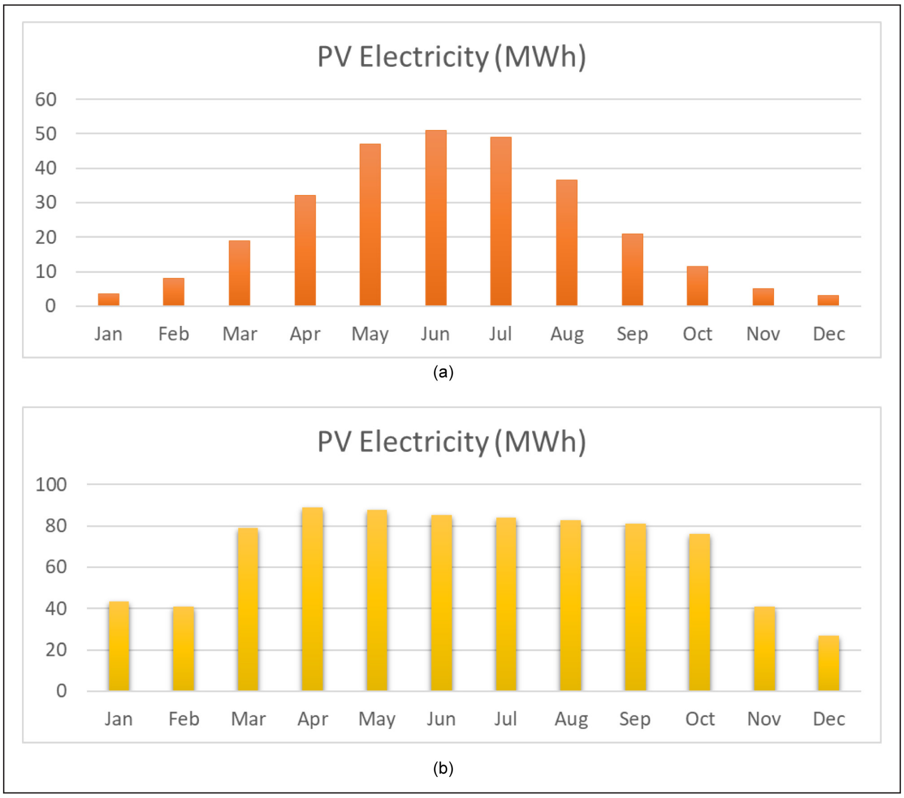

Figure 10 PV generation potential when installed on **(a)** roofs and **(b)** roofs and external walls.

expected here as in the previous package, with higher production when considering installation on both roofs and walls in combination and, furthermore, a more even production.

The PVT panels can produce heat and electricity simultaneously. The resulting production of the two scenarios is illustrated below in Figure 11 (a) and (b), with two bars for each month representing the heat and electricity production. The soft-edged bars are for electricity production, and the black-edged bars denote heat production. The electricity production from the two installations is quite different; in the roof only, all the production occurs between April and September. On the other hand, the roof and wall installation have high electricity production throughout the year and in the colder months compared to the roof installation. The results follow the expected trend with the highest production from the roof and wall installation, and the resulting productions are listed in Table 6.

PACKAGE 7 – PHOTOVOLTAICS AND HEAT PUMPS COMBINATION

In this package, the combination of the previously developed PV system and a heat pump is examined. This allows combining the potential of heat production by HP with the electricity production from PV, although

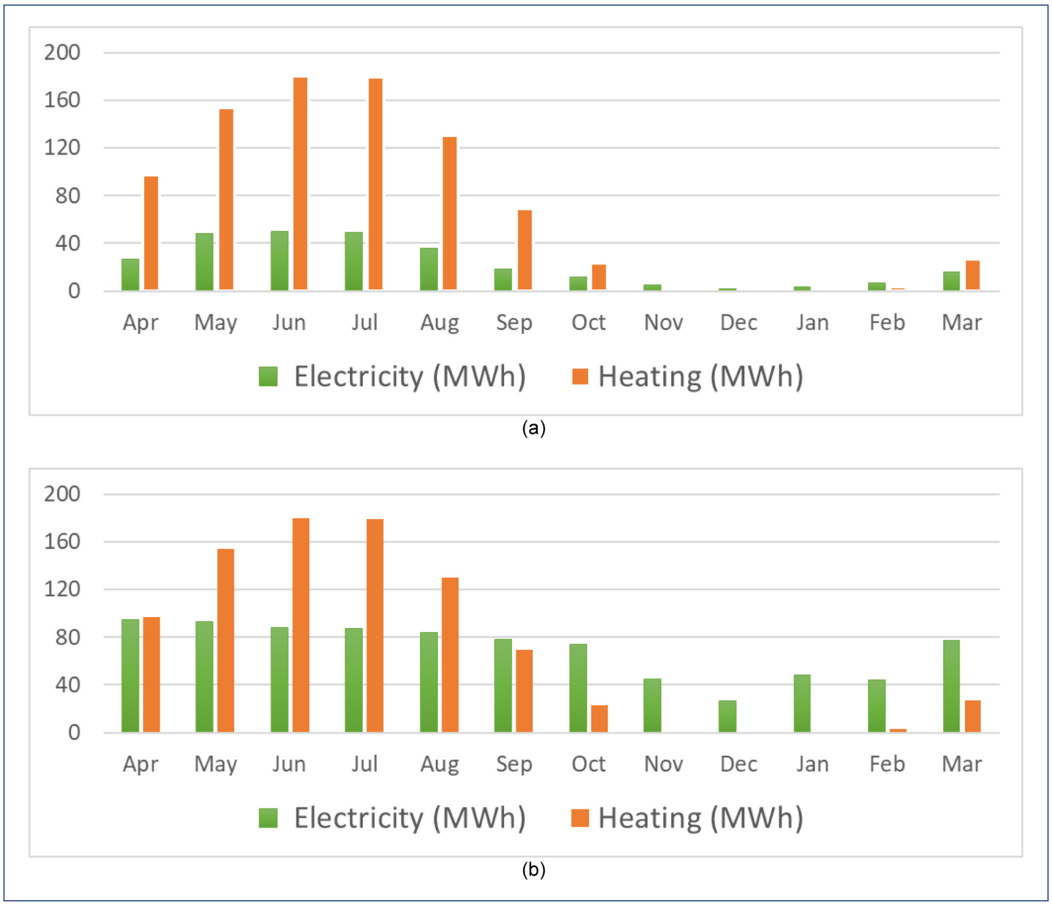

Figure 11 PVT generation potential when installed on **(a)** roofs and **(b)** roofs and external walls.

	ROOF ONLY	ROOF & WALLS
Heat production [MWh/year]	860	857
Electricity production [MWh/year]	289	839

Table 6 PVT heat and electricity production.

the heating production is expected to fluctuate because of the varying COP depending on ambient temperatures. Therefore, the first result of interest is the heat production available considering the COP of a HP and the electricity production from the PV system. The COP for the HP is collected from a simulation developed in EnergyPRO software. On this basis, a monthly COP for the HP is calculated in the software based on time series for inlet and outlet temperatures and outdoor temperatures. The resulting HP monthly production is shown in Figure 12. It is shown that the production is considerably higher in the summer months because of the high electricity production of the PV and the relatively high COP of the HP. Considering the heat production from the HP, the production potential is 3560 MWh/year with the excess electricity produced on the PV after covering the electricity demand. The total heat demand of the system is 2598 MWh/year, considering both space heating and domestic hot water usage.

Figure 13 illustrates the difference between the heat demand and heat pump production with electricity from the PV after covering the electricity demand of the buildings. A positive number highlights an excess heat generation where a negative number shows a deficit in supply. This illustrates the point mentioned before regarding the production pattern of the HP and PV, resulting in high production in the summer months. Since the heat demand is not covered in the colder months, it would be necessary to have another source of electricity or a seasonal storage facility for the heat to be stored and utilized in months with low production. The advantage of the storage is that the heat is produced in the most efficient months and low heat prices are achieved, although the storage also has disadvantages regarding losses. The implementation of storage is investigated later in the study.

PACKAGE 8 – PHOTOVOLTAIC-THERMAL AND HEAT PUMPS COMBINATION

After the examination of the PV in combination with the HP, a second scenario with the HP is developed. Here, the PV system is replaced by a PVT system instead, capable of producing both heat and electricity. Based on the previous package results, it is clear that the roof and wall installation had the highest production; the roof and wall installation scenario is therefore chosen for the PVT system, and the roof only installation is not simulated.

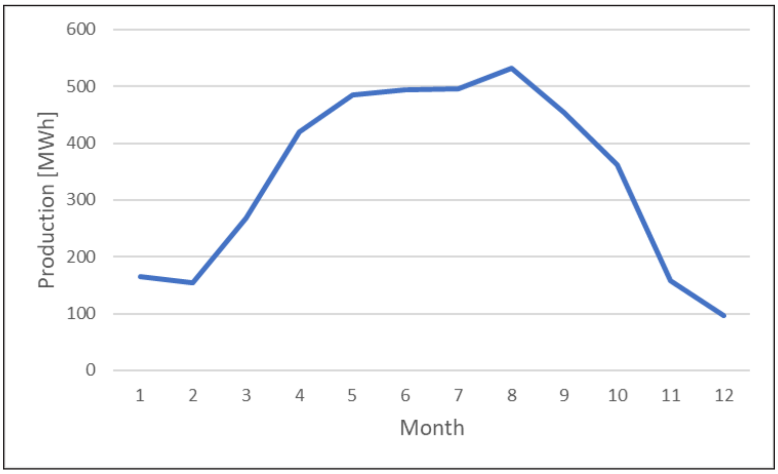

Figure 12 Heat pump monthly production.

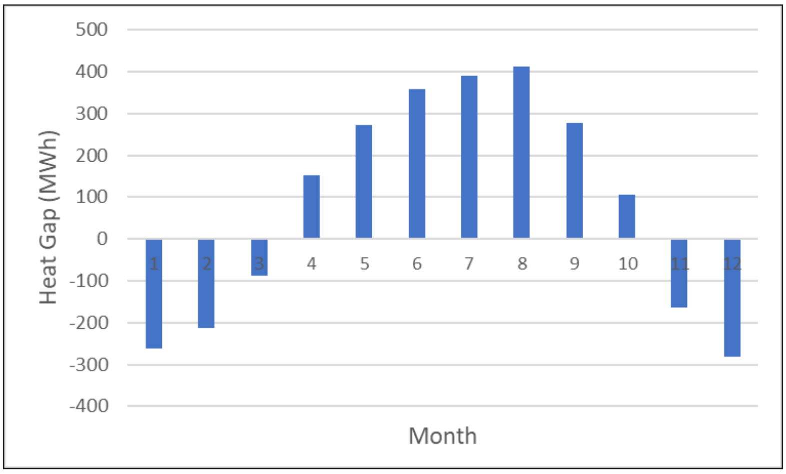

Figure 13 Gap between heat demand and heat supply by HP.

Based on the PV package results, the PVT system implemented in this package would have to produce a significant amount of electricity to utilize the HP and be competitive compared to the PV system. The heat production is volatile compared with the electricity production, as expected, with low production in the colder months and the highest production in the summer months. The production trend of the HP is expected to be almost identical to the previous package since the electricity productions of both the PVT and PV units are almost identical and the same COP profile is used. The maximum production from the HP is 3460 MWh/year if all electricity produced from the PVT after covering the electricity demand is used as input in the HP. The main difference in this package is that some of the gap between the heat demand of the buildings and the heat supplied by the heat pumps is going to be filled by the heat provided by the PVT units. Since the PVT heat production is happening in the summer months, the primary difference between the PV and the PVT systems would in this case be the deficit in the summer months. However, the results showed that there is still a negative deficit in heat production in four months throughout the year. The total deficit is 217 MWh/year after covering both demands, based on the excess heat produced and the COP of the HP. Considering the total energy production of the two HP packages, it is concluded that the PVT system in combination with the HP results in the highest energy production. Although the amount of extra production compared with the PV+HP package is in the summer months, when the heating needs are not as high,

POSITIVE ENERGY DISTRICT DESIGN

Based on the results reported for the 8 packages examined in this study, a scenario is defined in this section aiming to transform the current area into a positive energy district (PED). As a starting point, the first three packages are to be considered as the basis for the PED design in terms of optimal construction envelope retrofitting, indoor comfort control settings, and heating system retrofitting. These packages affect the total heat demand of the system, which is an important aspect to consider in designing a PED. In this regard, the lower the energy demand of the system, the less energy and capacity investment is required, thus reducing the need for conventional energy resources. Furthermore, a lower peak demand and a lower degree of fluctuations in the demand are important aspects for the implementation of a PED.

Retrofitting the buildings constructed before 1980 to correspond to the latest Danish Regulation Standard results in a 35% reduction of the space heating demand, where 27 buildings are to be retrofitted. Based on the envelope package results, the buildings in the resulting scenario are to be retrofitted to all follow the BR10 regulation. The next package is the examination of the control setpoints for the heating system. As it is already known, all buildings in the resulting scenario will be insulated to a high degree as they all follow BR10 regulation; the high setpoints are not of interest. Instead, a setback and setpoint combination of 18/20°C is considered, yielding a balanced solution. The last package for the input parameters is the heating system upgrade, where a floor heating system is considered, allowing a higher heat demand reduction and better indoor comfort conditions.

Measures from all three packages are naturally included in the resulting scenario, as they all were able to achieve reductions in heat demand and improvements in the comfort charts. The energy savings achieved result in higher positive energy production and, thereby, more energy that can be sold to surrounding systems. In terms of renewable energy-driven systems and alternative heating units, a technical solution of a combination of HP and PVT was chosen, considering the evaluation and analysis presented in the packages above. Considering the different measures combined in this scenario, the resulting heat demand is found to be 1421 MWh/year, and the end-use electricity demand is 145 MWh/year. The new heat demand profile is illustrated below in Figure 14.

The PVT can produce 857 MWh/year of heat and 839 MWh/year of electricity; the production is shown in Figure 15. Considering the contribution of the heat production from the PVT to the total heat demand, the heat demand left for the HP to cover is 564 MWh/year.

From the above the results, it is clear to see the challenge of balancing demand and production. The PVT production is highest in the summer months, when the COP of the heat pump is also at its maximum. On the other hand, the heat produced by the PVT in the summer months is more than enough to cover the heat demand. The total excess heat produced is 466 MWh/year from the PVT, which is again a result of low heat demand in the summer months and most heat production happening in the summer months.

Based on the analysis above, integrating storage is needed to optimize and utilize the excess production. If storage was not implemented, the system would be dependent on the heating and electricity grid to deliver

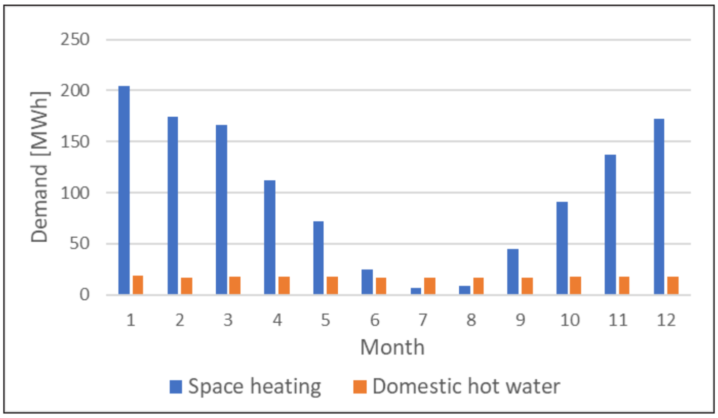

Figure 14 Heat demand profile in the retrofitted district.

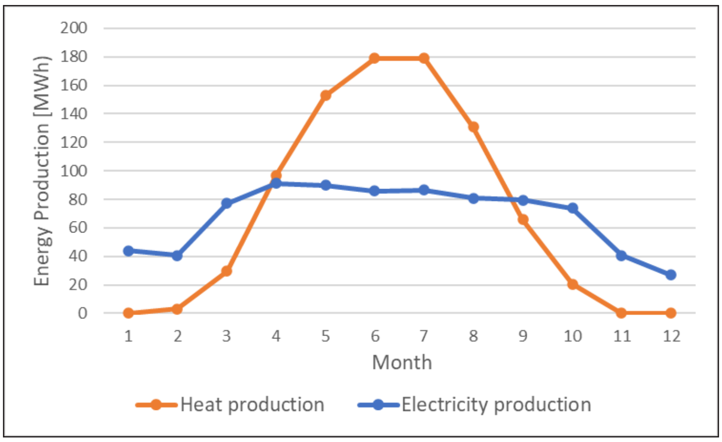

Figure 15 Monthly electricity and heat production of the PVT system.

the demand, as the electricity or heat produced on the PVT is not sufficient to cover the demand in all months. Overall, the demand is not met in January, February, November, and December without the integration of storage. Considering the excess electricity after covering the heat pump demand and the electricity demand for the system, the excess electricity production potential is 395 MWh/year.

If all excess electricity produced is used as input to the heat pump for heat production, the total excess heat production from the HP is 2280 MWh/year, as shown in Figure 16. As a result, 2746 MWh/year is the excess heat production potential for the HP+PVT scenario. Thus, the implementation of a seasonal heat storage solution results in an increase in the total energy production potential of 2280 MWh/year compared with the baseline and a system capable of delivering demand in all months. As a result, a PED is realized with heating and electricity demands covered and excess heat being produced.

Overall, the work carried out in this study concentrated on the technical design, planning, implementation, and evaluation of a PED scenario with various energy improvement measures. While the purely technical approach adopted would provide a preliminary assessment of the added value of different improvement interventions and energy network upgrades, another important factor to consider here is the economic feasibility of the solution. In this regard, it can be noted here that some of the measures, including optimizing the heating setpoints and controlling the heating supply system, don't require large investments and are considered economically feasible. A more detailed economic assessment is needed to evaluate other interventions, such as upgrading the energy mix by replacing fossil-fuel-driven units and installing heat pumps. In terms of the building envelope, generally, such interventions, although associated with relatively long payback periods, are urgent and considered a priority to elevate the building energy efficiency quotient. These are also required by building regulations when deep energy retrofits are carried out. Furthermore, the implementation of PVTs in the district also needs to be evaluated from an economic perspective. Thus, a follow-up study could merge the technical assessment and methodology employed in this research with an economic analysis to explore the financial viability and feasibility of the developed scenarios and implement a more detailed and sophisticated optimization phase to support optimal decision-making.

CONCLUSION

In line with Denmark's expanding intelligent energy networks encompassing both district heating and electricity grids and in alignment with the nation's ambitious energy and environmental goals, this study investigated upscaling efforts and analysis beyond single buildings to encompass entire districts and cities. To achieve this aim, the investigation focused on a specific district in Odense, Denmark, as a case study, employing modeling, simulation, and energy performance enhancement techniques. The residential zone chosen for the study was simulated using City Energy Analyst, an open-source tool for urban-scale modeling. This modeling process considered diverse building characteristics as well as the intricate aspects of energy networks and supply systems. To establish a baseline scenario, real-world data collected on-site was used for validation, serving as a reference for exploring and evaluating multiple scenarios and measures aimed at improving energy efficiency. As a result, eight distinct energy enhancement strategies were formulated, modeled, and individually simulated. In this regard, if the physical envelope in all buildings physical was retrofitted to comply with the BR10 Danish standard, the total heat demand would be reduced by around 35% from 2388 to 1551 MWh/year. Another improvement measure considered is using space radiators with modified setpoints of (70/55°C), leading to 12% reduction in the

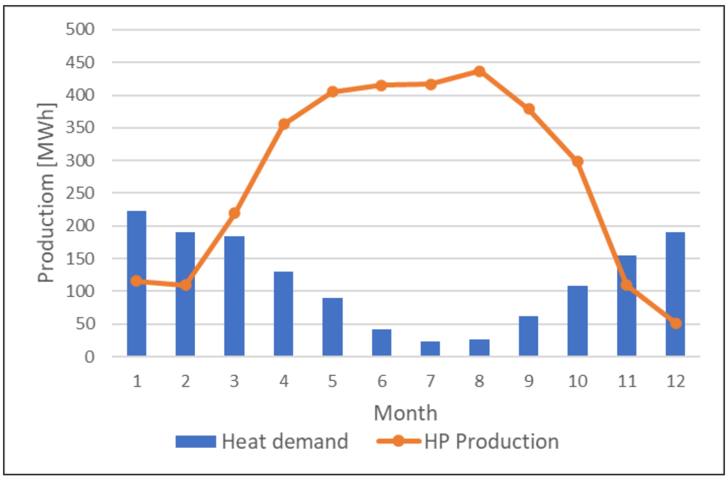

Figure 16 District heat demand and heat pump production with excess heat delivered.

heating demand. Also, the integration of a fossil fuel-free scenario into the district heating system supporting the area allows saving around 40% on the thermal energy generation capacity.

On this basis, an energy improvement package consisting of building retrofitting, indoor thermal comfort optimization, heating system upgrade, integration of photovoltaic-thermal units, incorporation of heat pumps, and the implementation of a seasonal energy storage system is found to collectively enhance the overall energy efficiency of the area. This comprehensive retrofit package implementation allows for the establishment of a positive energy district with surplus heat and electricity production. The work presented in this paper is in line with the plans and aims of Odense municipality to retrofit the current district heating system through the use of large-scale heat pumps as well as extend the use of photovoltaic-based technology for renewable energy-based electricity supply. In addition, the research provides a foundation for creating Denmark's first initiative towards establishing a PED, aligning with the recent European Union strategy that seeks to implement and duplicate 100 Positive Energy Neighborhoods across Europe by 2025. A potential future study could merge the technical assessment and methodology utilized in this research with an economic analysis to explore the financial viability and feasibility of the developed scenarios. This would offer a more comprehensive perspective on the additional benefits of moving and switching to a positive energy district under Danish conditions. Furthermore, additional work could be devoted to investigating other options for district-scale energy management and optimization, including demand response actions and model predictive control scenarios. Moreover, a detailed implementation of an energy storage solution could be investigated, taking into account the system dynamics and the impact of design parameters.

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COMPETING INTERESTS

The authors have no competing interests to declare.

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REFERENCES

Alavirad, S, Mohammadi, S, Hoes, PJ, Xu, L and **Hensen, JLM.** 2022. Future-Proof Energy-Retrofit strategy for an existing Dutch neighbourhood. *Energy Build*., 260: Article 111914. DOI: https://doi.org/10.1016/j.enbuild.2022.111914

Ali, U. 2021. Review of urban building energy modeling (UBEM) approaches, methods and tools using qualitative and quantitative analysis. *Energy Build*., 246: Article 111073. DOI: https://doi.org/10.1016/j.enbuild.2021.111073

Bi, C and **John, C.** 2022. Integrated assessment across building and urban scales: A review and proposal for a more holistic, multi-scale, system-of-systems approach. *Sustainable Cities and Society*, 82: Article 103915. DOI: https://doi.org/10.1016/j.scs.2022.103915

Bruck, A, Díaz Ruano, S and **Auer, H.** 2022. One piece of the puzzle towards 100 Positive Energy Districts (PEDs) across Europe by 2025: an open-source approach to unveil favourable locations of PV-based PEDs from a techno-economic perspective. *Energy*, 254: Article 124152. DOI: https://doi.org/10.1016/j.energy.2022.124152

Bygnings-og, B. 2018. BBR-oplysninger. Available at: https://bbr.dk/se-bbr-oplysninger.

Chen, Y, Guo, M, Chen, Z, Chen, Z and **Ji, Y.** 2022. Physical energy and data-driven models in building energy prediction: A review. *Energy Rep, 2352–4847*, 8: 2656–2671. DOI: https://doi.org/10.1016/j.egyr.2022.01.162

Cremer, L and **Weber, C.** 2022. Deep energy retrofits: How effective and robust are policy instruments? *Energy Policy*, 170: Article 113210. DOI: https://doi.org/10.1016/j.enpol.2022.113210

Eicker, U. 2019. *Urban Energy Systems for Low-Carbon Cities*. Academic Press.

European Commission. 2019. 2050 Long Term Strategy. Available at: https://ec.europa.eu/clima/eu-action/climate-strategies-targets/2050-long-term-strategy_en.

European Union. The European Climate Law, July 2021. https://climate.ec.europa.eu/eu-action/european-climate-law_en.

Fjernvarme Fyn. 2020. Fuel mix in Odense. Available at: https://www.fjernvarmefyn.dk/media/1754/fjernvarme_fyn_aarsberetning_2020.pdf#page=9.

Fonseca, JA, Nguyen, TA, Schlueter, A and **Marechal, F.** 2016. City Energy Analyst (CEA): integrated framework for analysis and optimization of building energy systems in neighborhoods and city districts. *Energy Build.*, 113: 202–226. DOI: https://doi.org/10.1016/j.enbuild.2015.11.055

Hagenau, M and **Jradi, M.** 2020. Dynamic modeling and performance evaluation of building envelope enhanced with phase change material under Danish conditions. *J Energy Storage*, 30: Article 101536. DOI: https://doi.org/10.1016/j.est.2020.101536

HOK. 2016. Energy Modelling Payback Period. Available at: https://www.hok.com/about/news/2016/05/26/hok-case-studies-reveal-short-payback-of-energy-modeling.

Horak, D, Hainoun, A, Neugebauer, G and **Stoeglehner, G.** 2022. A review of spatio-temporal urban energy system modeling for urban decarbonization strategy formulation. *Renewable and Sustainable Energy Reviews*, 162: Article 112426. DOI: https://doi.org/10.1016/j.rser.2022.112426

Jepsen, B, Haut, T and **Jradi, M.** 2020. Towards energy efficient planning of Danish cities and neighbourhoods, 34th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems (ECOS 2021), June 28 – July 2, 2021, Taormina, Sicily, Italy.

Jepsen, BKH, Haut, TW and **Jradi, M.** 2022. Design, Modelling and Performance Evaluation of a Positive Energy District in a Danish Island. *Future Cities and Environment*, 8(1): 1. DOI: https://doi.org/10.5334/fce.146

Jradi, M, Veje, CT and **Jorgensen, BN.** 2018. A dynamic energy performance-driven approach for assessment of building energy renovation – Danish case studies. *Energy Build*., 158: 62–76. DOI: https://doi.org/10.1016/j.enbuild.2017.09.094

Lindholm, O, Rehman, H and **Reda, F.** 2021. Positioning Positive Energy Districts in European Cities. *Buildings*, 19. DOI: https://doi.org/10.3390/buildings11010019

Lund, H and **Mathiesen, BV.** 2009. Energy system analysis of 100% renewable energy systems—the case of Denmark in years 2030 and 2050. *Energy*, 34(5): 524–531. DOI: https://doi.org/10.1016/j.energy.2008.04.003

Lund, H, Thellufsen, JZ, Sorknæs, P, Mathiesen, BV, Chang, M, Madsen, PT, et al., 2022. Smart energy Denmark. A consistent and detailed strategy for a fully decarbonized society. *Renew Sustain Energy Rev*, 168: Article 112777. DOI: https://doi.org/10.1016/j.rser.2022.112777

Monti, A, Pesch, D, Ellis, K and **Mancarella, P.** 2016. *Energy Positive Neighborhoods and Smart Energy Districts: Methods, Tools, and Experiences from the Field*. Academic Press.

Potrč, S, Čuček, L, Martin, M and **Kravanja, Z.** 2021. Sustainable renewable energy supply networks optimization – the gradual transition to a renewable energy system within the European Union by 2050. *Renew. Sust. Energ. Rev*., 146: Article 111186. DOI: https://doi.org/10.1016/j.rser.2021.111186

Sola, A, Corchero, C, Salom, J and **Sanmarti, M.** 2020. Multi-domain urban-scale energy modelling tools: A review. *Sustainable Cities and Society*, 54. DOI: https://doi.org/10.1016/j.scs.2019.101872

The A/S Group – ETH Zurich, CEA tool [Online]. Available at: https://cityenergyanalyst.com.

Wong, CHH, Cai, M, Ren, C, Huang, Y, Liao, C and **Yin, S.** 2021. Modelling building energy use at urban scale: a review on their account for the urban environment. *Build Environ*., 205: Article 108235. DOI: https://doi.org/10.1016/j.buildenv.2021.108235

Yang, X, Liu, S, Zou, Y, Ji, W, Zhang, Q, Ahmed, A, Han, X, Shen, Y and **Zhang, S.** 2022. Energy-saving potential prediction models for large-scale building: A state-of-the-art review. *Renew. Sustain. Energy Rev*., 156: Article 111992. DOI: https://doi.org/10.1016/j.rser.2021.111992

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