International Journal of Sustainable Energy Planning and Management Vol. 24 2019 21–32

International Journal of
Sustainable Energy Planning and Management

RESEARCH and EXPERIMENTATION

Modelling the future low-carbon energy systems - case study of Greater Copenhagen, Denmark

Sara Ben Amer*, **Rasmus Bramstoft, Olexandr Balyk and Per Sieverts Nielsen**

Department of Technology, Management and Economics, Technical University of Denmark, Produktionstorvet, building 424, 2800 Kgs. Lyngby, Denmark

ABSTRACT

In the light of insufficient climate policy on the global and national scale, some ambitious cities are becoming frontrunners of the climate action. Copenhagen, Denmark, is one of them and aims to achieve a CO_2-neutral energy system in 2025. Reaching this goal requires, among other, changes in energy supply portfolio, which can be assessed using energy systems modelling. The aim of this study is to construct and evaluate scenarios for sustainable electricity and heat supply in Greater Copenhagen with a particular focus on the new district, Nordhavn. The energy scenarios are modelled with the energy system model Balmorel, and they are assessed and compared with focus on heat and electricity prices and CO_2 emissions. Sensitivity analyses are conducted considering changes in the coefficient of performance (COP) of heat pumps and the discount rate. The results show that expanding Copenhagen's district heating system to Nordhavn is a promising solution from a socio-economic perspective. If it is chosen that the heating supply in Nordhavn should come from a local source, power-to-heat technologies are preferred. Despite the narrow geographical focus, the challenges discussed in this paper and the method developed are relevant for other urban areas in Europe that aspire to have sustainable energy systems.

Keywords:

Energy systems modelling;
Local energy planning;
Urban energy systems;
Energy scenarios;
Balmorel;

URL: http://doi.org/10.5278/ijsepm.3356

1. Introduction

CO_2 emissions from the energy sector contribute to the climate change significantly. While policies are required for setting the framework conditions, in an increasingly decentral energy sector, the involvement of local municipalities and communities is crucial.

Copenhagen aspires to become CO_2 - neutral by 2025 [1]. This goal encompasses power, heating and transportation. Heating uses up to 40% of the total energy consumption and is the sector over which Danish local municipalities have strongest influence. This paper focuses mainly on heating, electricity and fossil-fuel free transportation.

Copenhagen is one of 33 municipalities in the Capital Region and Region Zealand which are to be free from fossil fuels in 2035 [2]. Devising Copenhagen's roadmap towards the carbon-neutrality goals requires a feasibility evaluation, which can be conducted with energy systems modelling. The role of combined heat and power plants (CHPs) and heat pumps (HPs) is considered here, in view of varying availability of biomass and waste and the possibility of wind power providing more than 100% of electricity supply. Compared to a simple feasibility study, modelling takes into account a dynamic system integration across energy sectors, cost-efficient utilization of storage facilities, cross-border electricity fluctuation and endogenously computed electricity prices. Therefore, the optimization of investment decisions is dynamic and coherent, because the model can calculate key input parameters determining the economic feasibility.

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*Corresponding author – e-mail: sbea@dtu.dk

Acknowledgement of value

I am not formally involved in the research conducted by Sara Ben Amer et al., but I believe that both the methodology and results authored by them could have a positive effect on my own area of activity, by providing perspectives for planning the future CO_2-neutral Copenhagen.

Niels Bethlowsky Kristensen, Climate and energy planner in the City of Copenhagen

Abbreviations

CHP - combined heat and power
COP - coefficient of performance
DH - district heating
EV - electric vehicle
GC - Greater Copenhagen
HP - heat pump
P2H - power-to-heat

This paper's purpose is to construct and evaluate scenarios for energy supply in Greater Copenhagen (GC), by comparing different electricity and heating supply mixes, prices and CO_2 emissions. A similar approach for another town is taken e.g. by ref. [3]. The results form a basis for providing recommendations for the municipal energy planning activities, focusing on integrated energy supply. This study aims to answer the following research questions, focusing on Copenhagen and Nordhavn:

- What scenarios are plausible as of 2020, 2025, 2035 and 2050?
- Based on the results of the modelled scenarios, which energy mix is preferable from a socio-economic perspective?
- How sensitive are the results to selected assumptions?

Methods for modelling of decentralized and community energy systems have been reviewed e.g. by refs. [4,5]. This Special Issue contains articles which focus on modelling of a specific Swedish municipal energy system [6] and a local district heating system in Poland [7]. The Danish examples of municipal analyses are: modelling of energy scenarios implementing HPs, wind power, biomass and electrolysers in Sønderborg [8] and heat supply and heat savings in Helsingør [9]. Ref. [10] found out that large-scale HPs operate better when connected to the distribution instead of transmission grid in Copenhagen's DH system. Ref. [11] showed how heat savings, HPs and low-temperature DH could be implemented in Copenhagen. Refs. [12,13] highlighted the need for aligning local energy planning with national strategies. Ref. [14] assessed options for locating a HP in Nordhavn. Ref. [15] evaluated an integrated power, heat and transport system in Nordhavn, where HPs and electric vehicles (EVs) were implemented.

While all this literature has touched upon the future energy system in Copenhagen, to our knowledge there is no-peer reviewed research on energy planning and investment decision-making for the area of GC, which takes into account the synergies across energy sectors and geographical space. This article's contribution lies in developing and applying a modelling tool, which can be used for local energy planning in a national and regional energy system context – taking the future energy mix, the Nordic electricity market and electricity prices into account. Since the Balmorel tool used allows both investment and operation optimisation, this study also contributes to the area of energy scenario development, providing knowledge background for complex decisions of designing the future heating supply. Wider socio-economic consequences, such as employment, are out of scope of this article and are discussed e.g. in ref. [16].

This paper is structured as follows: Section 2 describes the methodology, Section 3 outlines the input data and assumptions, Section 4 presents the findings, and Section 5 discusses the results. The paper concludes in Section 6.

2. Methodology

2.1. Energy systems modelling with Balmorel

The overall methodology for this paper is scenario development and analysis. We use the energy system model, Balmorel, to model our scenarios. Balmorel is an open-source energy system optimisation tool, implemented in GAMS language [17]. It is a partial equilibrium model, built upon a bottom-up approach. Balmorel simulates the energy system's supply and demand and optimizes the operation of and investments into production units, calculating the most cost-effective mix of technologies for a given scenario [18] by minimizing the total system costs, including annualized investment costs, operation and maintenance and fuel costs, incorporating constraints e.g. heat and electricity coverage for each time period, emission limits. To represent the costs and technical bottlenecks in electricity and heat transportation, Balmorel distinguishes geographical levels (countries, regions and areas) [18]. Using time series, the model represents variation in intermittent technologies such as wind and solar power, demands and storages.

Balmorel is a deterministic model, which allows optimising the energy system with varying yearly foresight, i.e. myopic, partial, and full foresight. Myopic foresight refers to a situation where no information regarding future years is given. In full foresight mode, the model contains detailed assumptions about future energy targets, cost reductions, fuels prices etc., and thus can provide globally optimal solutions. In reality, we have a limited knowledge about the future: policy frameworks, fuel prices, technology costs developments etc. Therefore, in this paper, a partial foresight looking at one simulated period ahead is applied, reflecting a partial knowledge about the future: the situation that decision-makers have perfect foresight only within the simulated year and within the following simulated year.

Except for applications mentioned in ref. [17], Balmorel has been used in the context of Copenhagen in refs. [2,19].

In this paper, we build upon the existing Balmorel model and further extend the modelling framework to include Nordhavn, as a separate part of the GC area. Such an approach allows local energy planning in an integrated national and Nordic energy systems context. Moreover, by implementing specific technological options - energy scenarios, we conduct a comprehensive assessment, supporting future decision making for local energy planning. The modelling framework is adapted to the specific case of GC, but could be applied for other cities around the world.

Energy systems modelling requires the generation technologies, space and time to be aggregated so that the non-linear and complex reality is represented. Due the high computational time of the optimisation in Balmorel, a trade-off between technological details and spatial and temporal resolution is necessary. The geographical area for this paper includes Nordhavn, the GC area, the rest of Denmark, constituted by nine other areas, and countries linked with Denmark via transmission lines and the common Nordic electricity market: Germany, Sweden and Norway. In this study, the temporal resolution is 4 representative seasons (weeks) and 56 time periods (representing every 3rd hour throughout the selected seasons), within each season. Thus, the full year is represented by 224 chronological time-steps. The chronological order of the selected time-steps enables the mathematical model to use stretching methods, ensuring that the production and storage levels i.e. both energy and capacity, are sufficiently replicated, as compared to a time resolution of a full year.

2.2. Energy scenarios

This article focuses on GC: the City of Copenhagen and surrounding municipalities, inhabited by 1.3 million people [20]. Nordhavn is a new district in the City of Copenhagen, expected to have 40,000 new residents and 40,000 workplaces by 2030 [21]. The DH network will be extended in the part of Nordhavn closest to the already existing pipes, but more remote areas may use other solutions, due to the expected low energy consumption of buildings. We model and evaluate the following energy scenarios for GC and Nordhavn, analysing years 2020, 2025, 2035 and 2050:

- Reference: the model chooses freely to invest in Nordhavn in either technology: seawater HP, heat storage, solar heating and ground-source HPs.
- Seawater HP: investing in a large seawater HP with thermal storage in Nordhavn.
- DH extension: extension of Copenhagen’s DH capacity to cover all Nordhavn[1].
- Individual solutions: optimizing investments in Nordhavn in: solar thermal collectors, ground-source HPs, thermal storage and electric boilers.

In this study, we exclude air-to-air and air-to-water HPs, because the first one can only cover up to 80 % of the space heating demand and can only deliver heat in the room where it is installed, and the latter is likely to exceed required noise levels in dense city areas [22]. Although expensive, ground-source HPs suit the urban environment best, because they are silent and perform stably over the

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[1] The DH network is assumed here to be already expanded, thus the cost of expansion is not part of the optimisation

year. To reduce the size of area required for drilling, vertical pipes instead of horizontal can be used.

We assess the scenarios with the following criteria: average heat and electricity price and CO_2 emissions.

3. Input data and assumptions

3.1. Energy demand and supply

The Balmorel model contains data for electricity and district heat demand for Denmark, Sweden, Norway and Germany. This article focuses on the Copenhagen area, represented in the model as two areas: GC and Nordhavn. The district heating network in GC covers 17 municipalities and is one coherent system, where heat can be exchanged among different district heating providers. In GC heat is produced primarily in 4 CHP plants (using biomass, natural gas and coal) and 3 waste incineration plants and, if needed, stored in heat accumulators. There are also 30 peak load units [14]. Recently, CHPs in GC have undergone a retrofit to enable burning biomass. The projected heat demand for Nordhavn is based on ref. [17].

Figure 1 shows the yearly values for heat and electricity demand modelled in this paper. The heat demand curves shown in the upper part of Figure 1 (please note the axes) are different because in GC the demand decreases, while no additional heat savings are expected in Nordhavn, which predominantly consists of new energy-efficient buildings.

Figure 1 also depicts the projected electricity demand for the two areas, represented by the demand profile from Eastern Denmark. The electricity demand is contained within Eastern Denmark, corresponding to a bidding area in the power market Nord Pool. This demand covers both the "classical" demand and demand for EVs and is adopted from the ENTSO-E Global Climate Action scenario [23].

We assume that the transportation sector is decarbonised in the future, calling for biofuels especially for long-haul transportation. To simulate this, we have

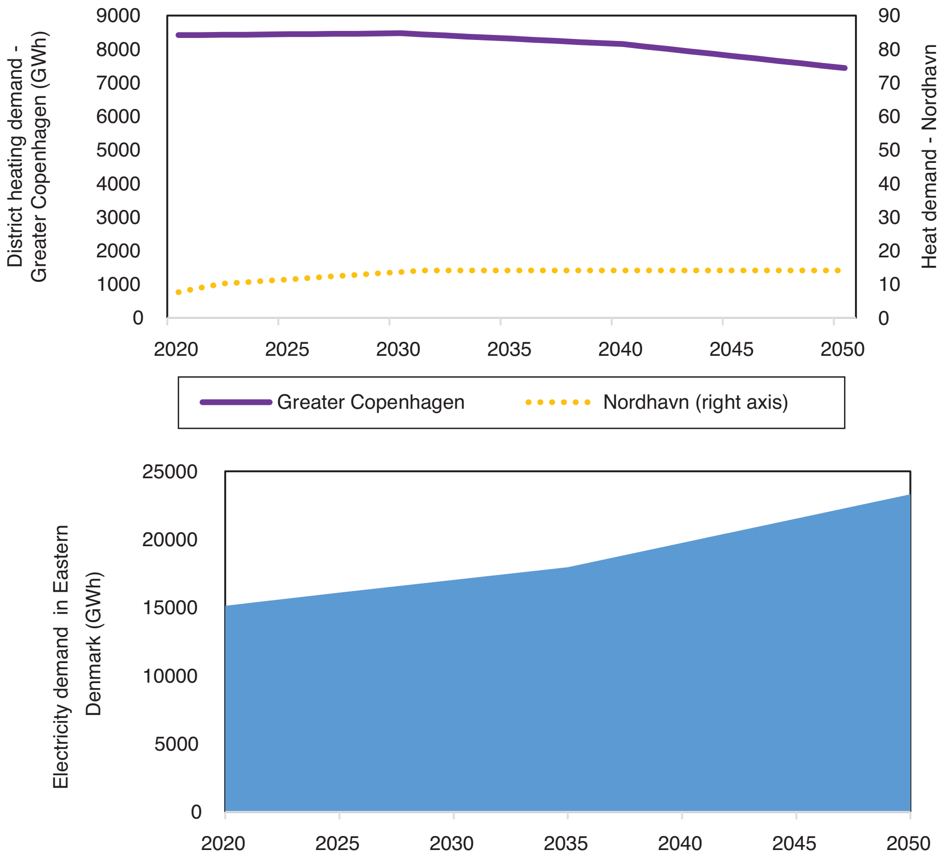

Figure 1: Projected heat demand in GC and Nordhavn (top) and electricity demand (down) in Eastern Denmark (GWh). Please note that heat demand values for Nordhavn are presented on the right axis

implemented excess heat production of 14 PJ for Denmark, which represents the excess heat supply for producing 50 PJ biofuels in Denmark [24]. The transition to electric vehicles is, as mentioned, included in the projected electricity demand.

3.2. Techno-economic data

Ref. [25] describes the data applied in the modelling, except for data on Nordhavn, based on ref. [26]. The investment and O&M costs and efficiencies come from refs. [22, 27], except for the seawater HP, whose investment cost is based on refs. [28, 29]. The COP of 3 is based on ref. [30], O&M costs are the same as the ground-source HP, considering that sea temperature is constant at depth.

Fossil fuel prices are based on ref. [23], biomass prices on ref. [31]. This study is conducted from the socio-economic perspective: excluding subsidies and taxes and applying 4% discount rate over 20 years of investment.

4. Results

4.1. Electricity production

The optimised electricity generation portfolio influences the electricity prices, which are essential for determining the optimised heat production mix, seen from a socio-economic perspective. Figure 2 illustrates the resulting transition of the electricity generation mix over time, for all the simulated countries and for Denmark, with a split between Western and Eastern Danish grids i.e. DK1 and DK2, respectively. The general trend in the decarbonisation pathway of the power system is the increased penetration of the variable renewable energy sources: wind and solar. Moreover, in DK2, where GC is located, an increased penetration of solar and wind power causes biomass to be phased out in 2035.

4.2. Heat production

Figure 3 illustrates the resulting transition of the heating sector in Denmark, GC and Nordhavn. In Denmark and GC, a decrease in DH demand is expected, mainly due to the assumed heat savings, see also section 3.1. Currently, a large share of heat in the Copenhagen DH network is produced using biomass, municipal waste and coal. However, due to CO_2 emission reduction and renewable energy targets, coal is to be phased out. Figure 3, similarly to Figure 2, illustrates that a phase out of biomass in Copenhagen after 2025 is socio-economically optimal. This result complies with the expectation that scarce biomass needs to be freed up for decarbonising the part of transport where electricity is not technically possible yet. The results also show that power-to-heat (P2H) has a promising socio-economic potential.

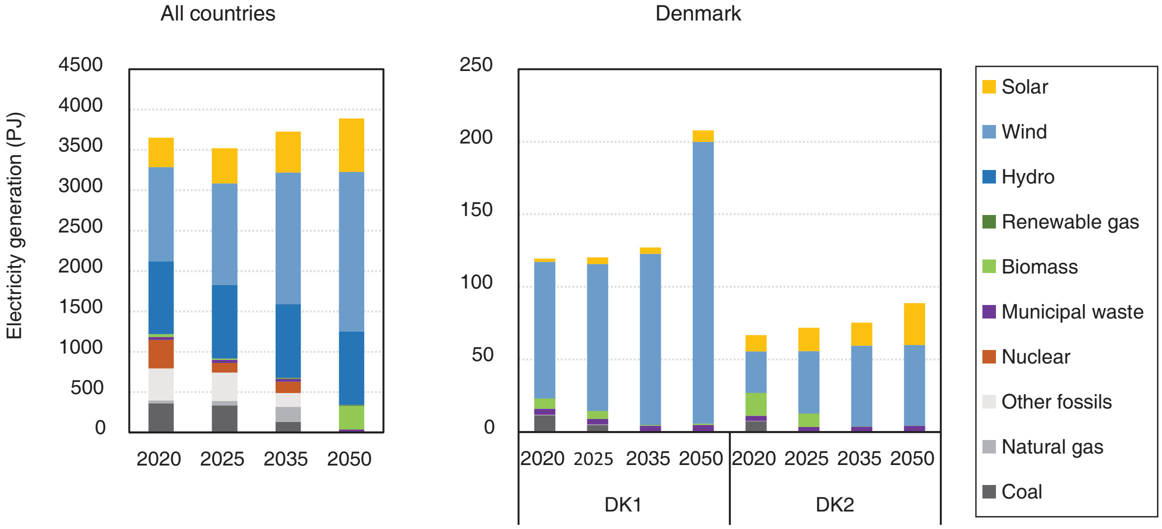

Figure 2: Electricity production per fuel in 2020, 2025, 2035 and 2050 in all the simulated countries (left) and in Denmark (right), divided into Western (DK1) and Eastern Denmark (DK2) (PJ)

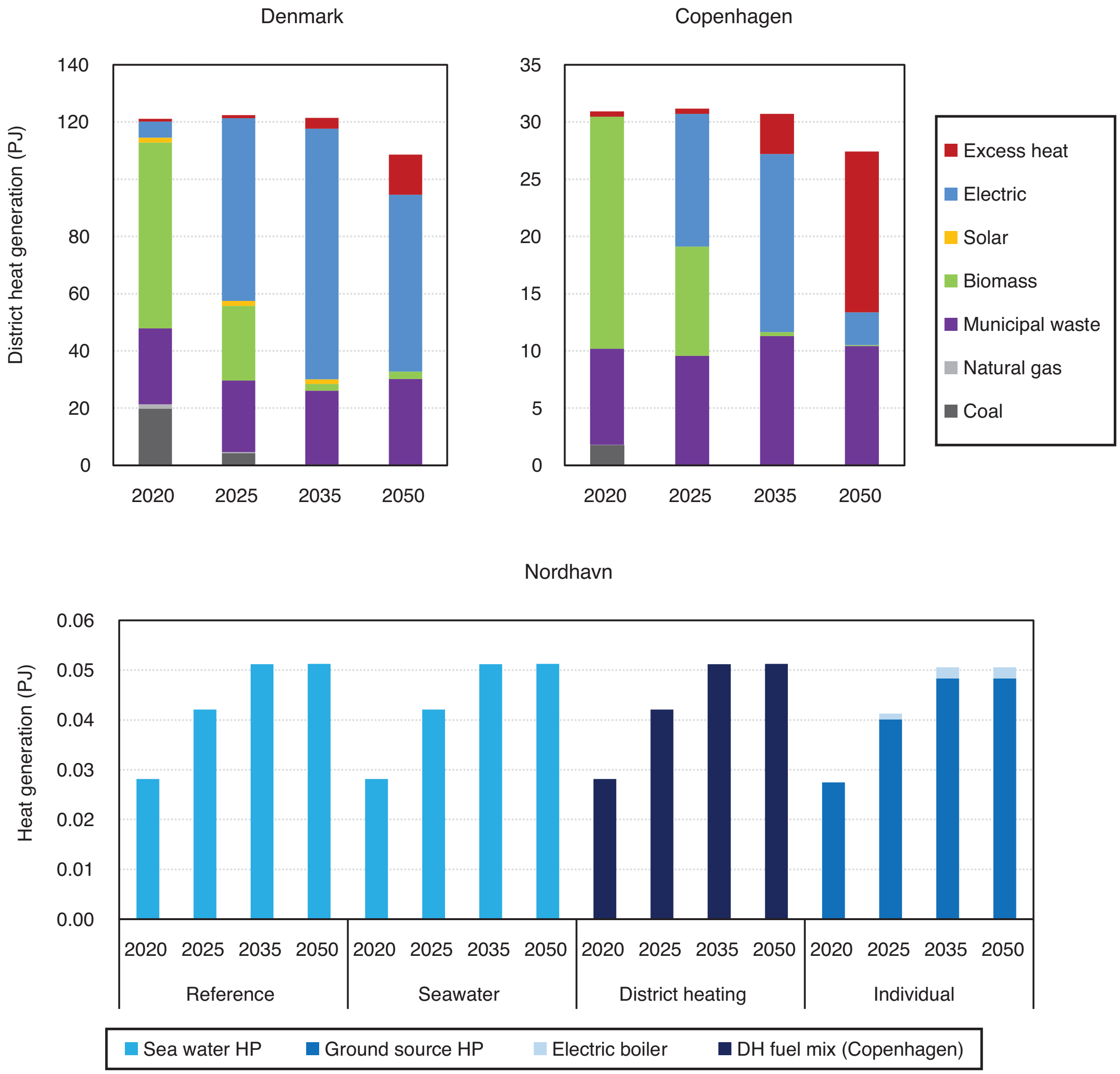

Figure 3: Heat production mix in 2020, 2025, 2035 and 2050 in Denmark, GC and Nordhavn (PJ)

Focusing on Nordhavn, a local seawater HP seems to be a promising technology in case the Copenhagen's DH network is not extended there. Local HP technologies are socio-economically viable if the area is not connected to the Copenhagen DH network, however, in case a connection is possible, the model finds this solution more feasible than installing HPs.

As discussed in section 3.1, transport is expected to use biofuels in long-haul transportation. We simulate this by implementing excess heat production (biorefineries) in the model. The GC area has highest potentials for cost-efficient utilisation of the excess heat in the DH network, so all of the Danish excess heat capacities are located here, see also ref. [32].

4.3. Heat and electricity price

Table 1 shows the simple annual average heat and electricity prices obtained from the modelling and indicates that prices vary over years. Since the excess heat production covers a high share of the DH demand in Copenhagen, the annual average heat prices are lower in Copenhagen than Nordhavn in all modelled years except for 2035. This indicates that DH expansion to Nordhavn could be a relevant solution. Moreover, P2H technologies are

Table 1: Annual average heat in Copenhagen and Nordhavn (EUR/GJ) and electricity prices in Eastern Denmark (EUR/MWh)

		Average heat price (EUR/GJ)		**Average electricity price (EUR/MWh)**
		Copenhagen	**Nordhavn**	**Eastern Denmark (DK2)**
Reference	2020	1.5	1.9	22.5
	2025	1.8	1.9	21.7
	2035	4.1	3.7	38.1
	2050	1.5	6.0	62.1

heavily invested in, so the correlation between electricity and heat prices is visible and the rise in the price of heat in Nordhavn follows the projected increase in the electricity price.

To provide a deeper understanding of this correlation, Figure 4 illustrates the dynamics between heat production and electricity and heat prices for Copenhagen and Nordhavn in 2035. Figure 4 shows that waste incineration plants and excess heat are supplied continuously as base load production throughout the year in Copenhagen. Moreover, P2H technologies generate heat at periods with low electricity prices, and heat storages are used when economically feasible. The correlation between P2H generation and electricity prices is evident when focusing on Nordhavn in 2035.

4.4. CO_2 emissions

The pathway of CO_2 reduction in Denmark and Copenhagen shows a steep reduction already between 2020 and 2025 in the electricity and district heating systems, followed by the transition to carbon-neutrality. In the simulations, the CO_2 emissions by 2020 are calculated to be 4860 ktons/y in Denmark, where GC contributes with 640 ktons/y. Compared to the 2018 data from the City of Copenhagen, which shows 925 ktons from electricity and DH sectors [33], the calculated number (encompassing all municipalities in GC) is low. However, the recent conversion to biomass is expected to reduce the CO_2 emissions from DH and electricity substantially. The model shows that GC can reach zero emissions in the DH and electricity sectors in 2025, whereas Denmark still emits 1200 ktons CO_2/y in 2025. Copenhagen achieves its target by phasing out fossil fuels. By 2035 the model projects Denmark to be nearly carbon-neutral regarding electricity and district heating production.

4.5. Sensitivity analyses

We have conducted sensitivity analyses to examine how results change depending on altering the COP of the seawater HP to 2.8, and of the ground-source HPs to 3.5, and changing discount rate to 2% and 6% instead of 4%. Table 2 shows the resulting differences in heat and electricity prices.

Overall, changes occur both in average heat and electricity prices. The influence of COP is mainly visible in Nordhavn (where a seawater HP would be installed) and is within the range of 5-9% increase in average heat price.

As expected, a lower discount rate results in a lower heat price in both Copenhagen and Nordhavn. The opposite happens for a higher discount rate. This effect is especially visible in 2025 and 2035, where many new investments take place. This result shows that our findings highly depend on the choice of discount rate.

5. Discussion

In this paper, we find that the expansion of Copenhagen's DH network to Nordhavn shows a promising perspective seen from a socio-economic point of view. In case the heating demand in Nordhavn is supplied by a local source, P2H technologies are chosen. These results are in line with the findings in ref. [26], where analyses of heat supply alternatives for Nordhavn, focusing on changing electricity price, COP of HPs, investment cost and heat demand, were conducted. In that report, almost all the cases showed that expanding the Copenhagen's DH network would pay off from a socio-economic perspective, but lower electricity prices would significantly improve the cost-effectiveness of HPs.

The results in this article are obtained by using the energy system model Balmorel. Although it is a detailed model, it uses a number of assumptions and simplifications. To show how results depend on some of the assumptions, we conducted sensitivity analysis. The choice of heat supply may also depend on qualitative aspects, such as security of supply and comfort, which were excluded in this analysis. Moreover, our socio-economic analysis does not include taxes, while

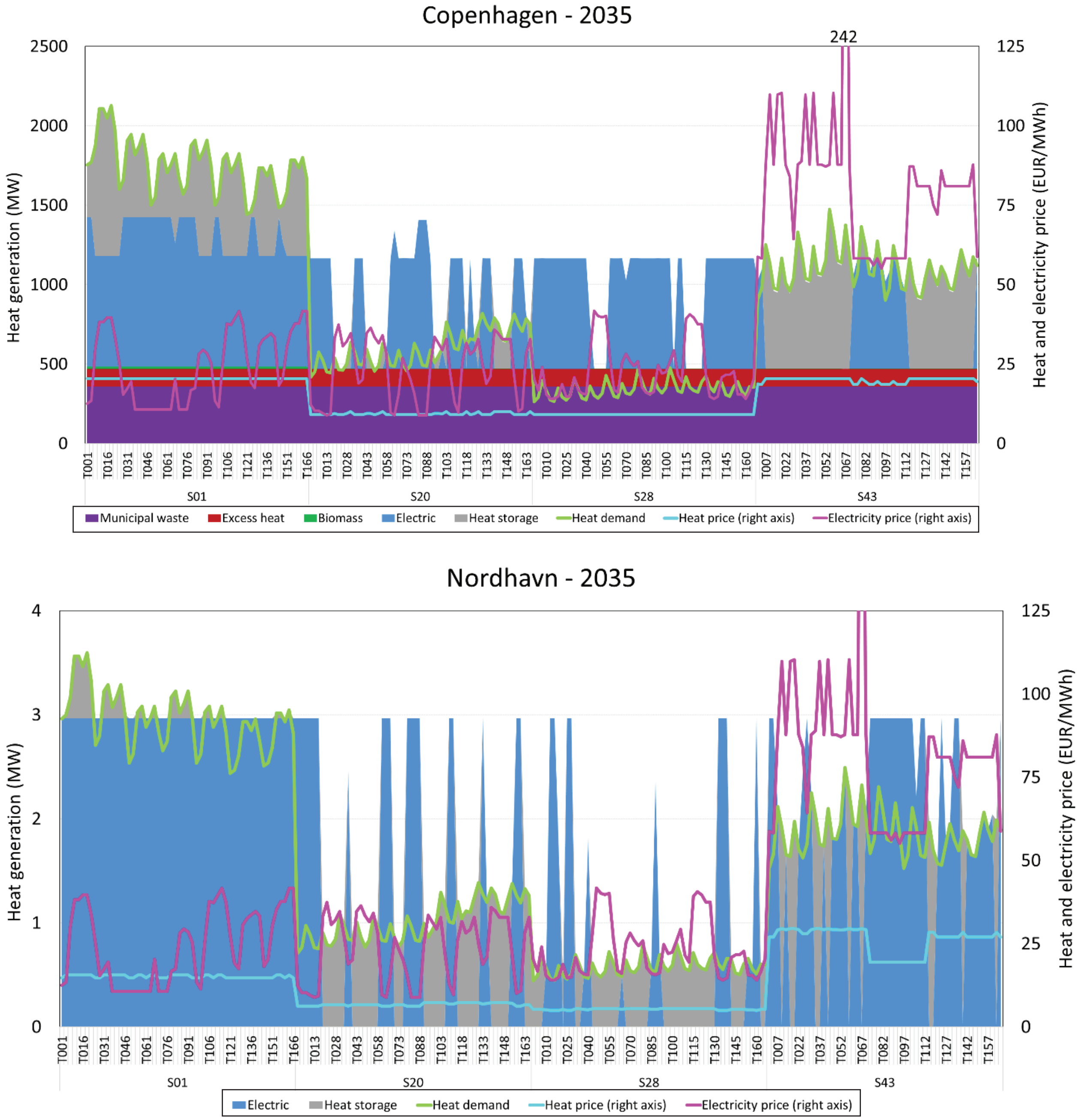

Figure 4: Dynamics between heat production and electricity and heat prices for GC (top) and Nordhavn (down) in 2035 in the reference scenario

the economic attractiveness, seen from a private-economic perspective, may be reduced for e.g. P2H technologies. This is because taxes constitute about 50% of the final electricity tariff for customers. On the other hand, there are exemptions for users that consume more than 4000 kWh electricity for HPs a year. A real-life illustration of the current tax structure is the biomass base power and heating production. The current tax structure, where biomass is free from taxes, means that it is a more profitable solution than e.g. HPs, which are affected by electricity taxes. For comparison, ref. [34] has conducted a detailed modelling of the framework conditions for DH in the Nordics.

Table 2: Changes in average heat and electricity prices due to the lower COP of HP and discount rate, as compared to the Reference (%)

		Average heat price		Average electricity price
	Year	Copenhagen	Nordhavn	Eastern Denmark
Seawater HP COP=2.8; ground-source HP COP=3.5	2020	0%	9%	0%
	2025	0%	9%	0%
	2035	0%	5%	0%
	2050	2%	7%	0%
2% disc. rate	2020	–3%	–6%	–4%
	2025	–36%	–28%	–28%
	2035	–35%	–26%	–24%
	2050	–7%	–9%	–3%
6% disc. rate	2020	0%	9%	5%
	2025	47%	32%	34%
	2035	25%	14%	17%
	2050	–3%	4%	4%

Although this analysis is conducted for Denmark - specifically for GC, the method and tools applied can be used for a similar analysis of other geographical location. In this way, the perspectives can be broadened, creating valuable insights into energy planning in smart sustainable cities.

6. Conclusions

In this paper, we have developed and applied a method for energy system modelling of Greater Copenhagen with the Balmorel model. We consider the developed model a suitable tool to represent an urban area while keeping connections to the rest of Denmark and Nordic electricity market.

We have constructed and evaluated scenarios for energy supply of Nordhavn focusing on heat and electricity generation mixes and prices, and CO_2 emissions. All of the scenarios resulted in a steep reduction in CO_2 emissions already between 2020 and 2025 in the electricity and district heating systems, followed by a transition to carbon-neutrality. We found that DH expansion to Nordhavn and a seawater HP are plausible solutions. P2H technologies, municipal waste, heat storages and excess heat would be main supply technologies in the future energy transition. To examine the sensitivity of the scenarios, we conducted a sensitivity analysis, where we reduced the COP of HP technologies and tested how discount rates of 2% and 6%, influenced the results. Slight changes in COPs of the HPs modelled only have little influence on the results, but our findings highly depend on the choice of discount rate.

Despite the narrow geographical focus, the challenges discussed in this paper and the method developed are relevant for other urban areas in Europe that aspire to have sustainable energy systems. By assessing a number of scenarios for energy supply, their consequences can be compared to provide recommendations for the planning process not only in GC, but also in other similar projects elsewhere.

The method developed could be also used by energy planners in other cities, beyond Copenhagen, especially where a decision on planning with socio-economic perspective has to be made. It is useful for developing sustainable energy plans for new urban developments and, especially in cities with high DH penetration, to decide for a relevant heat supply option. Recently, more and more cities are creating development projects-urban labs, which will encompass residential, commercial and industrial buildings, as well as smart and sustainable infrastructure, including energy systems.

Acknowledgements

This article was invited and accepted for publication in the EERA Joint Programme on Smart Cities' Special issue on *Tools, technologies and systems integration for the Smart and Sustainable Cities to come* [35]. This work is part of the CITIES (Centre for IT–Intelligent Energy System in Cities) project funded in part of the Danish Innovation found. Grant DSF 1305-00027B (Det Strategiske Forskningsråd).

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