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Now and into the future: Modelling and analysis of Danish urban energy systems

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SUMMARY

The global population is growing and so is the urbanisation share - currently over half of the world population lives in urban areas. Urban energy and transport systems are responsible for up to 70% of worldwide greenhouse gas (GHG) emissions, therefore the climate action on the local level is crucial if the objectives of the Paris Agreement are to be fulfilled. Owing to the relatively stable political situation of local governments, as well as their closeness to citizens, cities and towns are recognizing the challenge and increasingly becoming the drivers of sustainable energy transition.

In Denmark, many municipalities implement ambitious climate and energy policy aiming to reach carbon neutrality within next decades. Planners and decision-makers need decision support tools for devising their strategic energy plans. Energy system models could play such a role by helping assess the feasibility of renewable energy and energy savings projects on a system level and identify scenarios for cost-efficient reduction of CO_2 emissions.

Nonetheless, there is still not enough research concerning the identification and evaluation of least-cost sustainable energy scenarios for specific local urban energy systems, the suitability assessment of potential tools to be used and their usefulness from the municipal planners' perspective. Therefore, this PhD thesis investigates the methods for representing urban energy systems and assesses what changes are feasible in urban energy systems in order to reduce CO_2 emissions.

The PhD thesis employs mathematical modelling of energy scenarios for three Danish cases: the Greater Copenhagen area, and two middle-sized municipalities: Helsingør (Elsinore) in eastern Denmark and Sønderborg in western Denmark. The dissertation also examines relations between the technical changes in energy systems caused by increased share of renewables and energy efficiency, and selected economic characteristics, such as system costs. Moreover, it explores the role of energy system modelling in municipal planning using qualitative research consisting of expert interviews and content analysis. The PhD thesis comprises four papers, focusing on climate mitigation actions in the energy infrastructure and the built environment, and improvements of modelling tools and the modelling process of urban energy systems.

This PhD thesis finds that it is possible to significantly reduce CO_2 emissions from urban energy systems in a cost-effective way by implementing a mix of different energy conversion pathways and energy storage, and a balance between district heating expansion and heat savings. Whereas the detailed findings are applicable mainly for Copenhagen, Helsingør and Sønderborg, on a more general level they are indicative for other areas with similar climatic conditions, population and natural resources.

This dissertation considers three different energy modelling tools and three different energy systems as case studies. Out of the modelling tools used, Sifre and Balmorel are found suitable to analyse integrated energy systems, while energyPRO and the spreadsheet tool LCT - to analyse heating and heat savings. Among the weaknesses of quantitative energy scenario modelling is the inability to depict complex and non-linear stakeholder interactions. Therefore, to better portray sustainability transitions, energy system modelling should be, and often is, supplemented by other types of analysis.

The qualitative analysis shows that municipalities are not active model users, but are involved in the modelling process together with consultancy firms, heat supply companies or academia. Yet still, the modelling process can be improved by putting more effort into sharing data, assumptions and models, inter- and cross-municipal collaboration, as well as a constant dialogue on how to make tools useful for planning and implementing sustainability measures.

Overall, the findings of this PhD thesis can support planners and decision-makers in the transition towards a more sustainably-planned energy system of a city, allowing achieving technical, environmental, social and economic benefits.

RESUMÉ

Den globale befolkning vokser og det samme gør urbaniseringen - i øjeblikket bor over halvdelen af verdensbefolkningen i byområder. Energi- og transportsystemer i byområder er ansvarlige for op til 70% af verdensomspændende drivhusgasemissioner, derfor er klimaforanstaltninger på lokalt plan meget vigtige, hvis målene af Parisaftalen skal opfyldes. Byer anerkender udfordringen og takket være den lokale regerings relativt stabile politiske situation såvel som nærheden til borgerne bliver byerne i stigende grad drivkraften for en bæredygtig energiomstilling.

I Danmark implementerer mange kommuner ambitiøs klima- og energipolitik der sigter mod at nå kulstofneutralitet inden for de næste årtier. Planlæggere og beslutningstagere har brug for beslutningsstøtteværktøjer til udarbejdelse af deres strategiske energiplaner. Energisystemmodeller kunne spille en sådanne rolle ved at hjælpe med at vurdere muligheden for projekter inden for vedvarende energi og energibesparelser på et systemniveau, og med at identificere scenarier for en omkostningseffektiv reduktion af CO_2 emissioner.

Ikke desto mindre er der stadig ikke tilstrækkelig forskning omkring identificering og evaluering af bæredygtige energiscenarier til laveste omkostninger for specifikke lokale energisystemer, egnethedsvurderingen af potentielle værktøjer, der kan bruges, og deres anvendelighed fra kommuneplanlæggernes perspektiv. Derfor undersøger denne ph.d.-afhandling metoderne til at repræsentere byens energisystemer og vurderer, hvilke ændringer er gennemførlige i byernes energisystemer for at reducere CO_2 udledningen.

Ph.d. afhandlingen anvender matematisk modellering af energiscenarier i tre danske casestudier: Storkøbenhavnsområdet, og to mellemstore kommuner: Helsingør i det østlige Danmark og Sønderborg i det vestlige Danmark. Afhandlingen undersøger også forholdet mellem de tekniske ændringer i energisystemerne forårsaget af en øget andel af vedvarende energi og energieffektivitet, og udvalgte økonomiske egenskaber, såsom systemomkostninger. Derudover bruger den en kvalitativ forskning bestående af interviews og indholdsanalyse for at undersøge rollen af energisystemmodellering i kommunal planlægning. Ph.d. afhandlingen består af fire artikler, der fokuserer på klimaforebyggende handlinger i energiinfrastruktur og det byggede miljø, og forbedringer af modeller og modelleringsprocessen for energisystemer i byer.

Denne ph.d. afhandling finder, at det er muligt at betydeligt reducere CO_2-emissioner fra energisystemer i byer på en omkostningseffektiv måde ved at implementere en blanding af forskellige typer af energiomdannelse og lagring og en balance mellem fjernvarmeudvidelse og varmebesparelser. Mens de detaljerede konklusioner hovedsageligt finder anvendelse på København, Helsingør og Sønderborg, på et mere generelt niveau er de vejledende for andre områder med lignende klimatiske forhold, befolkning og naturressourcer.

Denne ph.d. afhandling betragter fire forskellige energimodelleringsværktøjer og tre forskellige energisystemer som casestudier. Ud fra de anvendte modelleringsværktøjer findes Sifre og Balmorel egnede til at analysere integrerede energisystemer, mens energyPRO og regnearkværktøjet LCT - til at analysere varme og varmebesparelser. Blandt svaghederne ved kvantitativ energiscenariemodellering er en manglende evne til at skildre komplekse og ikke-lineære interaktioner mellem aktører på energiområdet. Derfor skal energisystemmodellering suppleres med andre typer af analyse for bedre at kunne vise bæredygtighedsomstillingen.

Den kvalitative analyse viser, at kommunerne ikke er aktive modelbrugere, men er involverede i modelleringsprocessen sammen med konsulentfirmaer, varmeforsyningsfirmaer eller universiteter. Alligevel kan modelleringsprocessen forbedres ved øget indsats for at dele data, antagelser og modeller, inter- og tværkommunalt samarbejde og konstant dialog om, hvordan man kan gøre værktøjer nyttige til planlægning og implementering af bæredygtighedsmål.

Generelt kan resultaterne af denne ph.d. afhandling understøtte planlæggere og beslutningstagere i omstillingen til et mere bæredygtigt planlagt energisystem i en by og på den måde opnå tekniske, miljømæssige, sociale og økonomiske fordele.

“There is no logic that can be superimposed on the city; people make it, and it is to them, not buildings, that we must fit our plans.”
— Jane Jacobs, "Downtown is for people", 1958

PREFACE

This PhD thesis has been submitted to the Department of Management at the Technical University of Denmark (DTU), in partial fulfilment of the requirements for acquiring the PhD degree. The work has been supervised by Per Sieverts Nielsen (DTU Management) and Jay Sterling Gregg (UNEP-DTU Partnership). The PhD study has been funded by the Department of Management at the Technical University of Denmark and the Centre for IT-Intelligent Energy Systems in Cities - CITIES (funded by Innovation Fund Denmark, formerly Danish Strategic Research Council, grant 1035-0027B).

The PhD thesis consists of two major parts. The first part comprises introduction, theoretical framework, research design and methodologies, results and discussion, and conclusions and outlook. The second part is a collection of the four research papers that have been written during the PhD study. Three of the articles have been published in peer-reviewed journals and one was under review at a journal as of November 2019.

Kongens Lyngby, November 2019

Sara Ben Amer

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This Ph.D. thesis concludes several years of research on the subject of urban energy systems and smart sustainable cities. Overall, it was a rewarding experience, although some unexpected events on the private life front made the end of this period very challenging. I would like to extend my thanks to all those who supported me along the way.

I would like to express my gratitude to my main supervisor Per Sieverts Nielsen, for his constructive guidance, encouragement and commenting on the dissertation and articles. I would also like to thank my co-supervisor Jay Sterling Gregg for his always valuable comments to my papers and the dissertation and sometimes philosophical discussions on the value of energy systems modelling.

I would also like to thank all of my co-authors for the fruitful collaboration, sharing their knowledge and for providing inputs to the papers.

I would like to express my appreciation to the colleagues at the former Climate Change and Sustainable Development group, where I started my research journey, and to the colleagues at the Energy Systems Analysis group, where I am now. Thank you all for academic discussions and a pleasant atmosphere!

This PhD thesis is dedicated to my parents, thank you for your unconditional love, encouragement and continuous support. And thank you, my lovely daughter Maja, for being my sunshine.

LIST OF PUBLICATIONS

ARTICLES INCLUDED IN THE THESIS

Paper A: Sveinbjörnsson D., **S. Ben Amer-Allam**, A.B. Hansen, L. Algren, and A.S. Pedersen. 2017. Energy Supply Modelling of a Low-CO_2 Emitting Energy System: Case Study of a Danish Municipality. Applied Energy 195: 922–41. https://doi.org/10.1016/j.apenergy.2017.03.086.

Paper B: **Ben Amer-Allam S**., M. Münster, and S. Petrović. 2017. Scenarios for Sustainable Heat Supply and Heat Savings in Municipalities - The Case of Helsingør, Denmark. Energy 137. https://doi.org/10.1016/j.energy.2017.06.091.

Paper C: **Ben Amer S**, Bramstoft R, Balyk O, Nielsen PS. 2019. Modelling the future low-carbon energy systems - case study of Greater Copenhagen, Denmark. Accepted for publication in the International Journal of Sustainable Energy Planning and Management. http://dx.doi.org/10.5278/ijsepm.3356.

Paper D: **Ben Amer S**, Gregg JS, Sperling K, Drysdale D. 2019. Too complex and impractical? The role of energy system models in municipal decision-making processes. Under review in Energy Research and Social Science as of November 2019

OTHER RELEVANT WORK

Conference paper: **Ben Amer S**, Münster M, Petrović S. 2016. Scenarios for sustainable heat supply in cities – case of Helsingør, Denmark. Paper presented at 11th Conference on Sustainable Development of Energy, Water and Environment Systems, Lisbon, Portugal.

Conference paper: **Ben Amer S**. 2014. Scenario modelling as a tool for planning sustainable urban energy systems. Paper presented at Urban Futures-Squaring Circles: Europe, China and the World in 2050, Lisbon, Portugal.

Report: Nielsen PS, **Ben Amer** S, Halsnæs K. 2013. Definition of Smart Energy City and State of the art of 6 Transform cities using Key Performance Indicators: Deliverable 1.2. 23 p.

Conference poster: **Ben Amer S**. 2017. Low-carbon municipalities: modelling of Sønderborg, Denmark. Poster session presented at 4th General Consortium Meeting of CITIES Centre, Aarhus, Denmark.

Conference poster: **Ben Amer S**. 2015. Energy system modelling of Nordhavnen, the sustainable urban district of Copenhagen. Poster session presented at DTU Sustain Conference 2015, Lyngby, Denmark.

Conference poster: **Ben Amer S**. 2014. What is a city? Poster session presented at 1st General Consortium Meeting of CITIES Centre, Lyngby, Denmark.

Magazine article: **Ben Amer-Allam S**., M Münster, L Kranzl. 2017. Key success factors for district heating and cooling for six cases across Europe - lessons learnt from the ongoing progRESsHEAT project. International Magazine on District Heating and Cooling "Hot Cool" No. 2/2017

Magazine article: **Ben Amer**, **S**. 2015. Kopenhaga - miasto wolne od CO_2 (Copenhagen - a CO_2 neutral city), "Czysta Energia" Magazine, June 2015

ABBREVIATIONS

BAU - Business As Usual

CHP - combined heat and power

DH - district heating

GHG - greenhouse gas

HP - heat pump

LCT - Least Cost Tool

P2H - power-to-heat

RQ - research question

SDGs - Sustainable Development Goals

UN - United Nations

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PART I MODELLING AND ANALYSIS OF DANISH URBAN ENERGY SYSTEMS

1 INTRODUCTION

The introduction starts with describing the research context and the energy policy context for this PhD thesis, followed by examining the research gaps and discussing the purpose of the thesis and research questions. Next, the themes and contributions of the papers included in the dissertation are evaluated. This chapter ends with a description of the structure of this thesis.

1.1 RESEARCH CONTEXT

The global population is expected to grow from current 7.7 billion up to 10.1 billion within three decades from now (UN 2019). As of 2018, over half of the world population lived in urban areas[1] and this proportion is estimated to increase to almost 70% in 2050 (UN 2018). The increasing greenhouse gas (GHG) concentration in the atmosphere is among the most pressing challenges for humanity - and need to be addressed in the near future to avoid even more extensive consequences of climate change (IPCC 2018). Up to 70% of worldwide GHG emissions can be assigned to urban areas - mainly their energy and transport systems (UN 2011). Although some scholars (Satterthwaite 2008; Dodman 2009) claim that estimations of cities' GHG emissions may be overstated, a local level action plays a crucial role in climate change mitigation, contributing to the goals of the Paris Agreement (Solecki et al. 2018; Data Driven Yale, New Climate Institute, and PBL 2018). The citywide, exchanging flows of information, people, and resources can facilitate innovation and transition to sustainable lifestyles (GEA 2012). The relatively stable political situation of local governments, as well as closeness to citizens presumably resulting in their easier involvement, allow some cities to implement ambitious sustainability and energy plans and achieve their climate objectives. Conducting energy planning on a municipal scale allows observing interactions between energy, land-use and climate change in parallel and developing relevant policy (Pasimeni et al. 2014).

This dissertation concentrates on modelling and analysis of Danish urban energy systems by evaluating the state of energy systems now and possible future

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[1] There is no universal definition of urban areas, e.g. UN in its Urbanization Prospects applies the definitions used in each country, which in turn are usually based on the national census.

energy scenarios, with the main aim of cost-effectively reducing the local CO_2 emissions. As mentioned, the term "urban areas", although commonly used, is ambiguous. Therefore, in this thesis I define them as municipal boundaries in case of papers A, B and D and as the metropolitan area in case of paper C, targeting primarily networked heating provision (characteristic for densely built areas rather than villages) and electricity.

This dissertation concentrates on Denmark for several reasons. Denmark has a long energy planning history, as well as sustainable planning tradition, see e.g. (B. K. Sovacool 2013; H. Lund 2010). Heat supply plans were introduced in Denmark in the 1970's following oil crises. In the area of urban sustainability, Danish municipalities are quite ambitious: several are striving to become CO_2 neutral[2] within the next decade. In 2017, renewable energy, primarily biomass and wind, covered almost 33% of the Danish final energy consumption (Danish Energy Agency 2017). In these ways, Denmark serves as a case example of what is possible and as an inspiration to many countries. Moreover, the Danish expertise is recognized worldwide, with over 50% of the Danish export of energy technology and services in 2017 encompassing renewable energy and energy efficiency solutions (Danish Energy Agency and Dansk Energi and DI Energi 2018).

However, according to the Danish Council on Climate Change, Denmark may miss its 2030 climate goals with existing policies (Danish Council on Climate Change 2018). While the newly elected government aspires to commit to 70% GHG reduction (compared to 1990) already in 2030 (Socialdemokratiet et al. 2019), the coordinated efforts on a local and national scale should be strengthened (Sperling, Hvelplund, and Mathiesen 2011).

Several Danish municipalities strive to implement ambitious goals for lowering CO_2 emissions, for example within the voluntary strategic energy planning framework, defined by the Danish Energy Agency as: "a planning tool that allows the municipalities to plan the local energy conditions for a more flexible and energy-efficient energy system in order to utilize the potential for conversion to more renewable energy and energy savings in a way that is the most energy-efficient for society" (Danish Energy Agency 2016). These planning

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[2] CO_2-neutrality is defined differently, but often understood as a situation when emissions and mitigation actions in an area even out.

objectives are also among the goals set for the municipalities analysed in this dissertation. By and large, the planning of urban energy systems can be approached from two perspectives: sustainability and complexity.

Achieving sustainability is an overarching goal which can be expressed globally e.g. by implementing UN's Sustainable Development Goals, also mentioned in section 1.2.1. On the municipal level, a vast body of research is amassed on defining urban sustainability. While not directly engaging with the discussions on sustainable and smart city, this thesis deals with aspects important to the overall sustainability of urban areas, i.e. reduced CO_2 emissions via the implementation of renewable energy sources and increased energy efficiency. In general, the "sustainable city" concept usually applies the wider concept of sustainable development, as defined in the report "Our Common Future" (Brundtland Commission 1987): " development that meets the needs of the present without compromising the ability of future generations to meet their own needs", to the urban scale. Often, the notion of "triple bottom line", also known as "three pillars of sustainability" (economic, social and environmental) is used to render the dimensions of sustainability more operational (de Jong et al. 2015).

Out of numerous urban concepts existing in the research and policy discourse, "sustainable city" occurs most frequently in the peer-reviewed literature and is closely interlinked with other concepts such as "smart city" or "low-carbon city" (de Jong et al. 2015). Mosannenzadeh (Mosannenzadeh et al. 2017) provides a definition of a "smart energy city development": " [it] aims at a site-specific continuous transition towards sustainability, self-sufficiency, and resilience of energy systems, while ensuring accessibility, affordability, and adequacy of energy services, through optimised integration of energy conservation, energy efficiency, and local renewable energy sources." Although there is substantial research on theoretical debates about how smart a sustainability city is and vice versa, see e.g. (Yigitcanlar et al. 2019; Haarstad 2017; Appio 2019; Bibri and Krogstie 2017), the discussion so far seems to be inconclusive.

The complexity perspective can be linked to approaching urban energy planning challenges as "wicked" problems, as noticed by e.g. (Cajot et al. 2015). This notion comes after the seminal paper of (Rittel and Webber 1973), who claim: " the problems of governmental planning - and especially those of social or policy planning - are ill-defined; and they rely upon elusive political judgment for resolution". The complexity of urban energy systems is a recognized concept in the literature. According to Basu et al. (Basu et al. 2019), urban energy systems contain many dynamic and cross-sectoral elements: socio-technical, political, environmental and economic. The complexity within urban energy systems is expressed in the multidimensional structure of energy production and consumption, interdependent stakeholders (from the global level to individual prosumers), influence of the local setting and containment within a larger urban systems, which also encompass e.g. waste and water infrastructure etc. (Basu et al. 2019). Kitchin (Kitchin 2015) names, among other, these urban issues as complex: local and regional interrelations, political and financial acceptance of energy initiatives and their practical implementation, interactions among initiatives, effects on systems, economy and population, and cost evaluations.

As the aforementioned definitions indicate, from a technical perspective, to mitigate pollution and climate change, urban energy systems have to become secure, reliable, energy-efficient and fossil fuel-free. Technical solutions for energy production, consumption, "prosumption" (combination of production and consumption) and even "flexsumption" (flexible consumption) in cities are now being developed (e.g. distributed multi-generation systems, low-temperature district heating and district cooling based on renewable energy sources, microgeneration, house insulation, smart metering). Energy systems have been undergoing a constant development, similarly the modelling tools have to increase in complexity to be able to represent more possibilities to extract, convert, store and supply energy (Lopion et al. 2018). As an example, much has changed since in 1903 Denmark´s first waste incineration combined heat and power plants (CHPs) and district heating (DH) network were built in the municipality of Frederiksberg (DBDH, n.d.). The district heating technology, its fuel mix and methods for provision have significantly improved over the last century: from steam systems relying on coal and waste, with pipes in concrete ducts, through pressurised hot water systems based on various fossil fuels and biomass, to the current prefabricated systems, increasingly based on renewables and heat storage, and to the future low-temperature systems, based on renewables and possibly new energy sources (H. Lund et al. 2014).

Devising strategic energy plans is a multistep process in which decision support tools are required. Energy system models can facilitate the feasibility assessment of renewable energy and energy savings projects on a system level and help identify scenarios for cost-efficient reduction of CO_2 emissions. Using mathematics to depict scenarios for urban energy systems in an understandable, simplified way, energy system models can accommodate for assumptions and allow for experimentation. They have also been used for checking the consistency of local and national energy targets, see e.g. (Thellufsen and Lund 2016; Drysdale, Vad Mathiesen, and Lund 2019). Energy modelling tools are commonly used in academia to analyse urban areas, see reviews e.g. by (Keirstead, Jennings, and Sivakumar 2012; Allegrini et al. 2015; Ferrari et al. 2019).

However useful, energy system modelling has several limitations and recent literature has started focusing on pinpointing and addressing these. Some of the limitations occur due to insufficient communication between modellers and users of results (Scheer 2017; Braunreiter and Blumer 2018; Iyer and Edmonds 2018). These considerations fall within the field of evidence-based policy making, with the literature on the practical aspects of energy model utilisation and usefulness being rather limited (Ben Amer, Gregg, et al. 2019).

Although new analytical approaches are introduced, there is still room for progress regarding holistic analysis of the complexities of urban systems (Acuto 2018; Acuto, Parnell, and Seto 2018) and facilitation of cross-optimisation of various components in a strategic planning perspective (Blanco et al. 2009; Mirakyan and De Guio 2013)

It is within this research context that this PhD thesis develops energy scenarios for three Danish localities and uses several modelling tools to model them. This dissertation also explores the value of modelling of urban energy systems for municipalities. Chapter 2 discusses the theoretical framework for the thesis and Chapter 3 describes the methodology used.

1.2 ENERGY POLICY CONTEXT

This section describes the policy environment for sustainable urban energy planning, which influences the scenario development and analysis and the modelling of urban energy systems.

1.2.1 INTERNATIONAL FRAMEWORKS

International policy frameworks are crucial for addressing climate change on many levels, because they often direct the prioritisation of national policies and market conditions. On the global level, the Paris Agreement, which entered into force in 2016, aims to limit the global average temperature increase below 2°C above pre-industrial levels - and preferably to 1.5 °C. The Paris Agreement obliges all signatories to submit their best efforts via "nationally determined contributions" (NDCs) and to regularly report on their emissions and progress towards implementing climate action (UNFCCC 2015).

Other relevant global policy commitments are: The New Urban Agenda concerning sustainable urbanization (UN n.d.) and the 2030 Agenda for Sustainable Development, which comprises 17 Sustainable Development Goals (SDGs) (UN 2015) with the following three most relevant to the subject of this PhD thesis:

- SDG 7: "affordable, reliable, sustainable and modern energy for all"
- SDG 9: "resilient infrastructure, inclusive and sustainable industrialization and innovation"
- SDG 11: "inclusive, safe, resilient and sustainable cities and human settlements"

On the European level, the EU has a vision to achieve climate-neutral Europe by 2050 and to reduce greenhouse gas (GHG) emissions by 40% below 1990 levels, and reach 32% renewable energy share in the final EU energy consumption by 2030 (European Commission n.d.). Several directives have been implemented (relating to buildings, energy efficiency, renewable energy sources etc.) to ensure that the EU members are on the right track to reach the goals. By supporting many projects and initiatives concerning sustainability in urban areas, such as e.g. Covenant of Mayors, the EU also recognizes that the participation of cities is desirable for a successful implementation of climate and energy objectives.

1.2.2 DANISH FRAMEWORKS

Denmark was fully dependent on fossil fuel imports until the oil and gas extraction started in the Danish part of North Sea in 1972. Therefore, the country was highly affected by fuel shortages during World Wars and the oil crises in the 1970s, which meant that energy has been a policy target throughout the years. The first national energy plan was ratified in 1976. Contemporary Danish energy policy is founded on relative stability and consensus, expressed in a series of governmental Energy Agreements. By 2050, Denmark strives to become independent from fossil fuels, with the newly elected government possibly aiming for 70% GHG reduction (in relation to 1990) already in 2030 (Socialdemokratiet et al. 2019). According to the draft Danish National Energy and Climate Plan from 2018, GHG emissions not covered by the EU Emissions Trading System are to be reduced by 39% (in relation to 2005) by 2030 (Energy and Supply and Climate Ministry 2019).

Denmark has several frameworks that concern climate, for example the Danish law requires that municipalities prepare climate adaptation plans as part of their spatial plans. The municipal council coordinates the planning, building and environmental protection legislation and approves collective heat supply projects (Danish Ministry of Energy Utilities and Climate 2018).

1.2.3 MUNICIPAL FRAMEWORKS

1.2.3.1 Copenhagen

In its "CPH 2025 Climate Plan", Copenhagen sets a strategy to become the world's first carbon neutral capital in 2025 (The City of Copenhagen 2012). The "carbon neutrality" is defined as follows: net carbon emissions equal zero, achieved by both reduced emissions and compensation in periods when electricity production e.g. from windmills is greater than electricity consumption (The City of Copenhagen 2012). The plan encompasses: energy consumption, energy production, mobility, and city administration initiatives. Every three years a new Roadmap is issued to keep track of achieving the 2025 goal - the latest Roadmap covers actions up to 2020 (City of Copenhagen 2016).

Moreover, Copenhagen participates in regional strategic energy planning activities (Energi på Tværs 2018), where the objective is the electricity and heat supply free from fossil fuels in 2035 and transport - in 2050.

1.2.3.2 Helsingør

In its Climate Plan from 2010, Helsingør sets a goal of becoming CO_2 neutral in 2050 (Helsingør Kommune 2010), with an intermediate objective of reaching a level of 1.7 t of CO_2 equivalents/inhabitant in 2030[3].

Helsingør, similarly to Copenhagen, is part of the regional strategic energy planning project (Energi på Tværs 2018), where the objective is the electricity and heat supply free from fossil fuels in 2035 and transport - in 2050.

1.2.3.3 Sønderborg

In its Strategic Energy Plan from 2014, Sønderborg sets a goal of becoming CO_2-neutral by 2029 (PlanEnergi 2014). Sønderborg also collaborates on strategic energy planning with three other municipalities in the region of Southern Jutland.

1.3 RESEARCH GAPS

This PhD thesis identifies several gaps in the research concerning modelling and analysing urban energy systems. Generally, they fall within three subjects: identifying and evaluating least-cost energy scenarios for local urban energy systems, assessing the suitability of energy system models for analysing cities, and their usefulness from the municipal planners' perspective.

Recent literature calls for holistic analysis of the complexities of urban systems (Acuto 2018; Acuto, Parnell, and Seto 2018; Basu et al. 2019) and facilitation of cross-optimisation of various components in a strategic planning perspective (Blanco et al. 2009; Mirakyan and De Guio 2013). In the area of local energy scenarios, there is insufficient research on the possibilities for implementation of less common solutions on a municipal level e.g. electrolysers and fuel cells, the trade-offs between heat savings and district heating and between district heating expansion and individual heating supply, as well the significance of energy taxation for energy technology choice. By and large, these aspects are dealt with in papers A-C attached to this dissertation.

The most influential smart cities are often used as examples of "ideal" smart and sustainable cities, omitting the differences among cities (Kitchin 2015).

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[3] According to the author's interview with Helsingør municipality representative, this goal will be part of the new strategy, unpublished yet.

Moreover, comparative analyses of cities located in different areas are lacking (Kitchin 2015; Lamb et al. 2019). Even though this thesis concerns only Denmark, the selected cases are different and thus my research contributes to these topics. Among the municipalities analysed, two have less than 300,000 inhabitants - and small urban areas are largely underrepresented in the analysis of climate mitigation (Lamb et al. 2019).

There are several examples of peer-reviewed literature evaluating the strengths and weaknesses of urban energy system models, e.g. (Keirstead, Jennings, and Sivakumar 2012; Allegrini et al. 2015). However, these reviews are often based on information given by the tools providers or research conducted by others, where not all information may have been given in the articles. This thesis evaluates the advantages and disadvantages of the tools applied by the author on Danish case studies.

Moreover, the research on the actual usefulness and usability of tools for modelling energy systems is scarce (Ben Amer, Gregg, et al. 2019). Improving the understanding of how energy system models and the results generated from them are used in the municipal energy planning process, may help clarify assumptions and reduce errors (Ben Amer, Gregg, et al. 2019). This thesis concerns a specific situation of municipal planners, as depicted in article D. The paper also touches upon the issues of stakeholder involvement in the model development process.

1.4 PURPOSE OF THIS THESIS AND RESEARCH QUESTIONS

This PhD thesis investigates the advantages and disadvantages of methods for representing urban energy systems from the scientific and practical perspectives and assesses what changes in urban energy systems could result in reduced CO_2 emissions. Moreover, it explores the role of energy system modelling in municipal planning. The dissertation comprises four papers, which are discussed in more detail in section 1.5 and 4.1 and appended in Part II.

The PhD thesis analyses a number of energy scenarios for three Danish urban areas and examines relations between the implementation of renewable energy sources and energy efficiency in energy systems and selected economic characteristics, such as total system costs. Characterizing those relations can support planners and decision-makers in the transition towards a more sustainably-planned energy system of a city, allowing achieving technical, environmental, social and economic benefits.

This thesis sets out to answer the following research questions:

RQ1: How can modelling tools be used to determine the least-cost low-carbon technologies in future municipal energy systems?

RQ2: What are the strengths and weaknesses of modelling approaches used?

RQ3: What is the role of energy system modelling in municipal energy planning?

This dissertation contributes to the literature on urban energy scenarios, local energy modelling and the use of modelling tools by bringing together knowledge on the strengths and weaknesses of applying different models for modelling urban areas, thus covering several of the research gaps discussed in section 1.3.

The methodological contribution of this PhD thesis is the application of the mixed-method approach, defined by (Clark and Ivankova 2016) as: "a process of research when researchers integrate quantitative methods of data collection and analysis and qualitative methods of data collection and analysis to understand a research problem". The integration is achieved by linking three quantitative papers A-C and the qualitative paper D via the second research question (RQ2) of the thesis (see above). Besides, the third research question (RQ3) builds upon the experience of previous papers by using the same cases and similar focus on the strengths and weaknesses of energy system models.

1.5 PAPER THEMES AND CONTRIBUTIONS

The PhD thesis employs mathematical modelling of urban energy systems for three cases: the Greater Copenhagen area and two middle-sized municipalities: Helsingør in eastern Denmark and Sønderborg in western Denmark - see Figure 1-1.

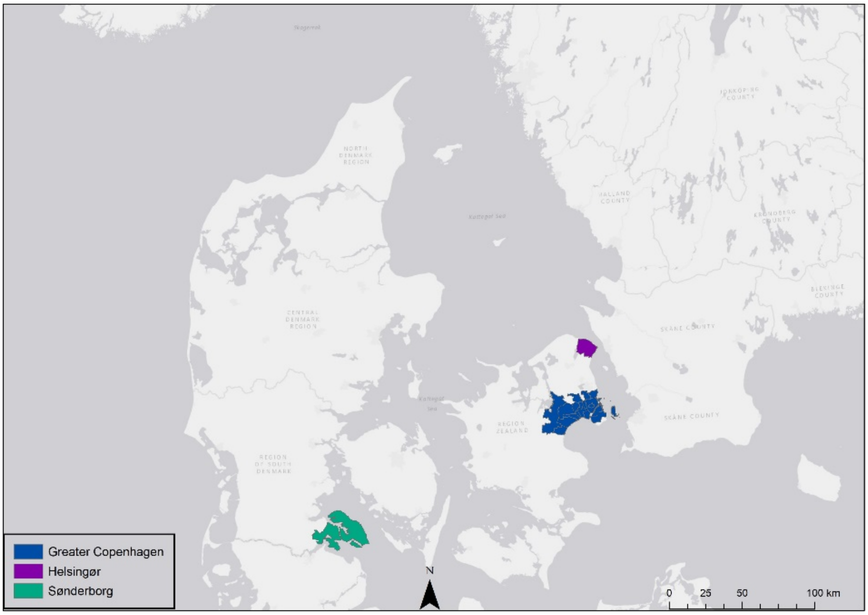

Figure 1-1 Case study locations.

From here, the thesis evaluates the use of energy modelling tools within these municipalities. Table 1-1 shows the location, area and population of the analysed municipalities.

Table 1-1 Location, area and population of the analysed municipalities.

	Copenhagen/ Greater Copenhagen	**Helsingør (Elsinore)**	**Sønderborg**
Location	south-eastern Zealand	north-eastern Zealand, ca. 50 km from Copenhagen	south-eastern Jutland and the island of Als
Area	City of Copenhagen: 86 km^2	119 km^2	497 km^2
Population (2019)	City of Copenhagen: 626,000 Greater Copenhagen: 1.4 million (Danmarks Statistik 2019)	63,000 (Danmarks Statistik 2019)	75,000 (Danmarks Statistik 2019)

In this dissertation, Greater Copenhagen encompasses the City of Copenhagen and 16 other nearby municipalities within the same district heating net (Albertslund, Ballerup, Brøndby, Frederiksberg, Gentofte, Gladsaxe, Glostrup, Greve, Hvidovre, Høje Taastrup, Ishøj, Roskilde, Rødovre, Solrød, Tårnby, and Vallensbæk).

Table 1-2 outlines how the papers analysed in this dissertation deal with the research questions, which themes they belong to, and what methods they use.

Table 1-2 Similarities and differences among the papers included in this thesis (concerning related thesis research question (RQ), subject, method and tool used).

Paper	**A**	**B**	**C**	**D**
Related thesis RQ	RQ1 RQ2	RQ1 RQ2	RQ1 RQ2	RQ2 RQ3
Subject	electricity, heat and transport in Sønderborg; heat pumps, electrolysis and improved efficiency of biomass utilisation	heating; heat savings and renewable energy implementation in Helsingør's heating network	electricity and heat supply for Greater Copenhagen including the new district Nordhavnen; heat pumps and district heating expansion	use of energy system models by the practitioners within three Danish municipalities
Method used	scenario analysis, energy modelling	scenario analysis, energy modelling	scenario analysis, energy modelling	content analysis of interviews
Tool used	Sifre	energyPRO and Least-Cost Tool	Balmorel	Atlas.ti (text organisation)

Papers A-C contribute to the knowledge within the area of urban energy planning by developing and analysing future local energy scenarios and modelling urban energy systems: specifically, they provide information on how various combinations of technologies can help reaching CO_2 reduction goals from a criterion of cost-efficiency. Such a comprehensive assessment can support future decision making for local energy planning.

The novelty in paper B lies in providing a methodology to derive the optimal mix of district heating (including expansion), individual heating and heat savings. This objective is achieved by linking district heating modelling in energyPRO and heat savings representation via an iterative calculation using the specially developed spreadsheet Least-Cost Tool. Moreover, the analysis is conducted from two perspectives: a simple socio-economic and a private-economic (including taxes and subsidies).

In addition, paper C offers a case study of using the Balmorel tool at the community scale (Nordhavn), which Huang (Huang et al. 2015) define as "a unit of the city, a small-scale area with mixed land use". Such an application of Balmorel is a novelty considering the findings of an earlier review of energy models, where no studies using Balmorel on this scale were identified (Lyden, Pepper, and Tuohy 2018).

For all cases, data on local energy systems and resources was collected, energy scenarios were developed and the energy system was represented in each model. The model development process can be divided into several steps (NRC 2007). Although the models in this PhD thesis were not developed "from scratch", applying them on the specific municipalities required a number of amendments, which are displayed in Table 1-3 (including only the steps where papers contribute). The most important model development contributions included the specification of modelling context, model testing and revision and model use.

Table 1-3 Model development contributions of papers A-C. The classification of development steps (including only the steps where papers A-C contribute) is adopted from (NRC 2007).

	Model		
Development step	**Sifre (paper A)**	**energyPRO and Least-Cost Tool (LCT) (paper B)**	**Balmorel (paper C)**
Definition of model purpose	Scenario comparison from a least-cost perspective	Scenario comparison from a least-cost perspective	Scenario comparison from a least-cost perspective

		and interaction between energyPRO and LCT	
Specification of modelling context	Defining a spatial scale, defining Sønderborg's energy units, evaluation criteria for scenarios	Defining a spatial scale, defining Helsingør's heat supply system, evaluation criteria for scenarios	Defining a spatial scale, including Nordhavn as a new area, evaluation criteria for scenarios
Computational model development	Required inputs for local energy demand and supply	Required inputs for local heat demand and supply; LCT: minor contribution to the full spreadsheet development	Required inputs for local energy demand and supply; seawater heat pumps
Model testing and revision	Corroboration with other literature; sensitivity analysis	Corroboration with other literature; sensitivity analysis	Corroboration with other literature; sensitivity analysis
Model use	Scenario analysis	Scenario analysis; policy analysis and evaluation: the influence of taxation and other regulatory measures	Scenario analysis

According to (B. Sovacool 2014), qualitative research is still lacking in energy studies and paper D aims at filling that void. The paper provides a better understanding of how energy system models are used and what their role is in the larger question of developing energy policy to support the energy transition in Denmark, in this way adding to the little research on this topic. The paper also suggests improvements in the models and the modelling procedure to target the identified challenges.

1.6 STRUCTURE OF THE THESIS

This dissertation consist of two main parts. Part I comprises: introduction, theoretical framework, research design and methodologies, results and discussion, conclusions and outlook, and references. Part II presents the four research papers which form the backbone of the thesis.

2 THEORETICAL FRAMEWORK

There is a myriad of definitions on what consists a theoretical framework. In this dissertation, it is an overview of the main theoretical concepts guiding the thesis and their interlinkages. The theoretical framework of this PhD thesis is primarily based on theories originating from the following major scientific areas: scenario planning, see section 2.1, energy system modelling, see section 2.2 and sustainable urban energy planning, see section 2.3. While sustainable urban energy planning theories provide the general theoretical guidance for how to conduct energy planning in urban areas, scenario planning and energy systems modelling are closely interconnected theoretically and methodologically in this thesis, as chapter 3 shows.

2.1 SCENARIO PLANNING

Energy scenario planning entails a development of energy scenarios, which in turn are modelled and analysed using energy modelling. The scenarios developed and evaluated in papers A-C are described in section 3.3.1. This section, partly based on the conference article of (Ben Amer 2014), presents a theoretical background for scenario planning.

The introduction of the notion of "scenario" in planning in the 1950's is widely attributed to the defence strategist Herman Kahn (Chermack, Lynham, and Ruona 2001). Scientific literature offers numerous scenario definitions, which can be summed up as: a purposeful depiction of possible future energy systems in relation to the present one and pathways to achieve them, including dynamic processes (Nielsen and Karlsson 2007; Ramírez and Selin 2014). No unifying theory exists for scenario planning methodology, so as such it has a rather applied, practice-driven characteristics (Spaniol and Rowland 2018).

This thesis uses mostly quantitative scenarios - entailing techno-economic modelling and analysis conducted using computers. In comparison, qualitative scenarios are more descriptive and concentrate on "softer" aspects e.g. societal, political and cultural transitions (Nielsen and Karlsson 2007). The scenarios analysed in this dissertation can be described as explorative and anticipative/normative, as classified by (Börjeson et al. 2006; Nielsen and Karlsson 2007). The first type depicts many possibilities of future development; the latter is policy-relevant and shows a number of anticipated or undesirable visions and pathways.

Scenario development is largely influenced by uncertainties and resulting assumptions (Nielsen and Karlsson 2007). There are internal and external uncertainties in scenario planning (Witt, Dumeier, and Geldermann 2020). Internal uncertainties deal with how relevant the model is for the analysed problem and the subjective judgement of scenario developers. External uncertainties touch upon economic and social changes beyond the influence of stakeholders, e.g. fuel resources potential and prices, affecting scenario performance assessments such as cost calculations (Witt, Dumeier, and Geldermann 2020). Energy scenarios can accommodate for many external uncertainties in a consistent, systematic manner (Witt, Dumeier, and Geldermann 2020).

Energy scenarios aim to look at consequences of long-term decisions, with sensitivity analyses of e.g. future technology prices and policy (Nielsen and Karlsson 2007). When scenarios are compared, the dissimilarities between them enable to assess various policy measures. Junne et al. (Junne et al. 2019) provide a framework, which can be used to evaluate the transparency of energy scenarios.

Scenarios can increase stakeholder engagement, when used by academia, think-tanks, planners, policymakers, organisations and private firms etc. In Denmark, in addition to influencing the debate among companies, the energy agency, municipalities and central government, energy scenarios have an impact on legislation, presumably thanks to an open political process and a willingness of Danish policy-makers to engage in energy transition. However, energy scenarios often lack the consideration of social characteristics (e.g. importance of lifestyle changes), which may be regarded as a weakness in comparison to the full potential of the method (Nielsen and Karlsson 2007).

2.2 ENERGY SYSTEM MODELLING

This PhD dissertation employs energy system modelling and energy system analysis as the main quantitative analysis methods. The scenario planning approach may have significantly facilitated the development of energy system models (Pfenninger, Hawkes, and Keirstead 2014).

The origin of energy system models dates back to the 1970s' when first power system models were used by utilities for planning purposes. According to (Rath-Nagel and Voss 1981) the following disciplines are applied in energy system models: mathematical programming (depicting the energy quantities flow), engineering process analysis (technically detailed description of energy technologies) and econometrics (energy demands). The usefulness of energy system modelling lies in accounting for dynamic system integration across sectors and borders, and cost-efficient utilisation of storage, allowing coherent optimisation of investment decisions (Ben Amer, Bramstoft, et al. 2019).

Table 2-1 shows the modelling tools that this thesis uses, their optimisation type, implementation and sectoral representation. More information on the mathematical representation of each model is given in section 3.3.

Table 2-1 Modelling tools applied in this thesis (amended from the presentation given by the author at the CITIES 3rd General Consortium Meeting, May 2016).

	Sifre	**energyPRO**[4]	**LCT**	**Balmorel**
Optimisation type	Operation optimisation	User-defined or auto-calculated operation optimisation	Iterative cost optimisation of the heat supply configuration	Investment and operation optimisation
Implementation	Mixed-integer linear programming (MILP) in C#	Delphi	Spreadsheet	Programming in GAMS, solvers e.g. CPLEX
Sectoral representation	Electricity, heat, transport, gas	Flexible: electricity, heat, (transport as "energy plant")	Individual heating and heat savings	Electricity, heat, transport as EVs

Energy system models can be classified as bottom-up (technology-rich) or top-down (focusing on economy). Most of currently developed models are bottom-up, hence are useful in analysing aspects such as least-cost energy mix, but require high amount of data and computational time (Lopion et al. 2018). Detailed temporal resolution allows more in-depth analysis of e.g. flexibility measures, while methods of time aggregation are also developed in order to reduce the computational time (Lopion et al. 2018).

The long-term planning entails two main tasks: operation and investments. Although many of the tools available are able to calculate an optimised operation of the production portfolio, in addition some also aim to determine optimised, as compared to simulated, investments. In optimisation, the mathematical program maximises or minimises an objective function, subject to constraints such as CO_2 emissions. Out of the three energy system models, Balmorel is able to conduct both investment and operation optimisation, whereas energyPRO and

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[4] energyPRO can also be considered a project appraisal tool.

Sifre[5] - only operation optimisation. The main theoretical perspectives relevant here are thus: partial equilibrium optimisation and simulation. See e.g. Wagner (Wagner 2014) for more theoretical insights on decision theory and equilibrium modelling.

Optimisation can be conducted with different types of foresight: myopic, partial and full foresight. The first one is a situation when no information about the future other than the analysed year is known, the second when only the currently optimised year and the next period is known and full foresight: all the information about the future is known. The myopic approach is dominant within the optimisation tools reviewed by Lopion (Lopion et al. 2018).

Energy system models are simplified representations of the energy system, which leave out many of the complexities of the real world. They assume an idealized world of fully rational people with perfect knowledge. However, examples of analyses of historical results of optimisation models reveal deviation in the total system costs of up to 23% depending on assumptions (Trutnevyte 2016). Lund (H. Lund et al. 2017) claim the superiority of simulation over optimisation models regarding stakeholder engagement, because they present several options along with their consequences - and not just one "optimal" solution.

Models are useful in many ways, but carry many assumptions and the subjectivity of modeller in choosing them, as empirically illustrated by e.g. (Laes and Couder 2014). Assumptions in modelling may cause bias and in effect decrease the quality of conducted assessments, so frameworks capturing them quantitatively and qualitatively could potentially improve the knowledge base in modelling processes (Kloprogge, van der Sluijs, and Petersen 2011; Pye et al. 2018).

Several ways of tackling the aforementioned uncertainties exist. While sensitivity analysis to check how sensitive the results are to altering of main assumptions is often used, it is slightly subjective due to the necessity of selecting some assumptions out of many. Local sensitivity analysis - changing one parameter at a time - is a common approach for sensitivity analysis, also applied

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[5] The version used in this thesis; an investment optimisation module is under development.

in this thesis. As an alternative, for analysing price sensitivities, a range of fluctuating price levels could be used (H. Lund et al. 2018). Efforts are currently made to develop methods for global sensitivity and uncertainty analysis, able to represent interactions among many different parameters which is relevant especially in energy systems with high shares of intermittent sources, such as Denmark (Pizarro-Alonso, Ravn, and Münster 2019).

Optimisation models are criticised for their simplification of societal and political issues and of actor interactions. To develop successful policy measures more aspects of energy transitions should be represented and socio-technical energy transition (STET) models are being developed with this purpose in mind (Li, Trutnevyte, and Strachan 2015; Li and Strachan 2019). Some scholars (McDowall and Geels 2017) argue that, although such improved models are useful, they cannot entirely replace qualitative analytical approaches.

The increasing efforts for open-source and freely available tools expressed by e.g. (Wiese et al. 2014; Pfenninger et al. 2018) originate from a shared understanding that energy system modelling and its impact can also be improved by collaborative modelling. Methods for engaging stakeholders in the energy modelling process are shown by e.g. McKenna (McKenna et al. 2018).

This dissertation concerns local energy systems. Although this scale is gaining interest in the modelling community (Keirstead, Jennings, and Sivakumar 2012), most of energy system models have been developed for the national or even global scale, which is due to the power systems historically being developed and operated nationally. Urban energy systems are highly complex and carry uncertainties (Basu et al. 2019), so these aspects should be considered when developing urban energy models and assessing the modelling results.

2.3 SUSTAINABLE URBAN ENERGY PLANNING

The very vast and diverse discipline of (land-use) planning is constantly on the outlook for a defining theory - different theories have always existed in parallel and have their advantages and disadvantages (Allmendinger 2017). Some planning researchers even doubt whether a theory for planning is necessary (Talvitie 2009; Lord 2014). According to Friedmann (Friedmann 1987), planning is “the attempt to connect scientific knowledge to actions in the public domain”. The field of energy planning relies mainly on systems and rational planning, because energy systems have traditionally been distanced from the users, entailing primarily the technical aspects. Rational planning assumes that societal goals can be easily achieved if all think rationally (Baum 1996) and planners analyse the situation, establish goals, formulate actions and comparatively evaluate their consequences (Banfield and Meyerson 1955). Rational planning has been criticised for failing to represent stakeholders rather than experts (Lawrence 2000) and for the assumption of linearity (Noble and Rittel 1988) and purely rational decision-making.

Only recently, with climate change and sustainability challenges gaining importance, have the human aspects been considered to such a great extent as they are today. In particular, communicative planning (Innes and Booher 2015) and collaborative planning are gaining interest (Lawrence 2000), expressed for example in an increasing need for open-source and freely available modelling tools e.g. (Pfenninger et al. 2018; Wiese et al. 2014) and engaging the users and people affected by energy policies.

General definitions and methods for energy planning on all scales are reviewed by (Prasad, Bansal, and Raturi 2014). (Mirakyan and De Guio 2013) define integrated regional/urban energy planning as: "an approach to find environmentally friendly, institutionally sound, social acceptable and cost-effective solutions of the best mix of energy supply and demand options for a defined area to support long-term regional sustainable development. It is a transparent and participatory planning process, an opportunity for planners to present complex, uncertain issues in structured, holistic and transparent way, for interested parties to review, understand and support the planning decisions". To a large extent this definition is relevant to the topic of this dissertation.

In Denmark, municipalities such as Copenhagen and Sønderborg are well-known for their commitment to low-carbon strategies. Strategic energy planning frameworks for Danish municipalities are proposed and applied by (Krog and Sperling 2019; Krog 2019). As reported by (Sperling, Hvelplund, and Mathiesen 2011) the results of activity of Danish cities could even be better if they gained more freedom in establishing local planning frameworks and access to new planning instruments, for which coordination with the central government would be required.

3 RESEARCH DESIGN AND METHODOLOGIES

This chapter starts with an overview of the research design used in the thesis, followed by presentation of the methods used for data collection and data analysis.

3.1 RESEARCH DESIGN

Three of the papers analysed in this dissertation concentrate on modelling of urban energy systems, and the fourth one explores the use of energy system models within municipalities. In order to fully understand the role of modelling in achieving sustainable municipalities from a perspective of researchers and practitioners alike, the research design contains elements of mixed method research, see also section 1.4. According to (Flick, Kardoff, and Steinke 2004), conducting qualitative research improves the knowledge of the social phenomena, which is hidden for outsiders or even insiders busy with their daily activities. Therefore, the three research questions (RQs) in this thesis span between the RQ1 touching upon technology and RQ2 and RQ3 - usability.

In this dissertation, data was collected using document study and semi-structured interviews. It was then analysed using scenario analysis, energy system modelling or content analysis. The case study method is used as delimitation of the results. The cases are: the Danish municipalities of Helsingør and Sønderborg and Greater Copenhagen area. Single case studies are conducted in papers A-C and a comparative analysis of three cases in paper D. Single cases have a value for learning even though generalisation from single cases is difficult, if impossible (Steinberg 2015; Flyvbjerg 2006). The analysed cases share similar institutions and governance types (for example, the areas of policy over which cities have executive power; their available municipal budgets), social priorities (for example, infrastructure or service access) and political constraints (for example, the balance of private and corporate interests). The cases differ in size, location and local energy resources.

3.2 DATA COLLECTION METHODS

3.2.1 LITERATURE AND DATASET SEARCH

For all the papers and the thesis, a literature and dataset search was performed to collect secondary data (journal articles, conference proceedings, books, reports, webpages, databases, policy documents), concerning urban energy planning initiatives, policy backgrounds and techno-economic data on energy supply and consumption in the analysed municipalities.

3.2.2 INTERVIEWS

Primary data in the form of semi-structured expert interviews with the representatives from Copenhagen, Helsingør and Sønderborg was collected in connection with paper D. The interviewees were identified using purposive sampling (Silverman 2010) and expert sampling. Interviews, although not as generalizable as questionnaires, often allow to get many insights (Rowley 2012), e.g. due to the possibility to adjust and rephrase questions (with various levels of flexibility, depending e.g. on the interview structure).

3.3 DATA ANALYSIS METHODS

3.3.1 SCENARIO DEVELOPMENT AND ANALYSIS

In papers A-C, the scenario analysis method is applied on the urban scale, entailing improvements of the energy efficiency of supply systems and buildings, and increasing the deployment of renewable energy sources. Alternative energy scenarios are determined and evaluated concentrating on reducing CO_2 emissions. The timeframe for scenarios is up to 2050, recognized as the year when carbon neutrality has to be achieved in order to prevent global warming of 2°C. The scenarios are modelled and analysed using energy system modelling and assessed with indicators concerning fuels used and CO_2 emissions.

Figure 3-1 depicts the methodology of scenario analysis used in papers A-C of this thesis. It is divided into the following iterative phases: background analysis, scenario development, conducting and modelling scenarios and scenario outcome comparison and sensitivity analyses.

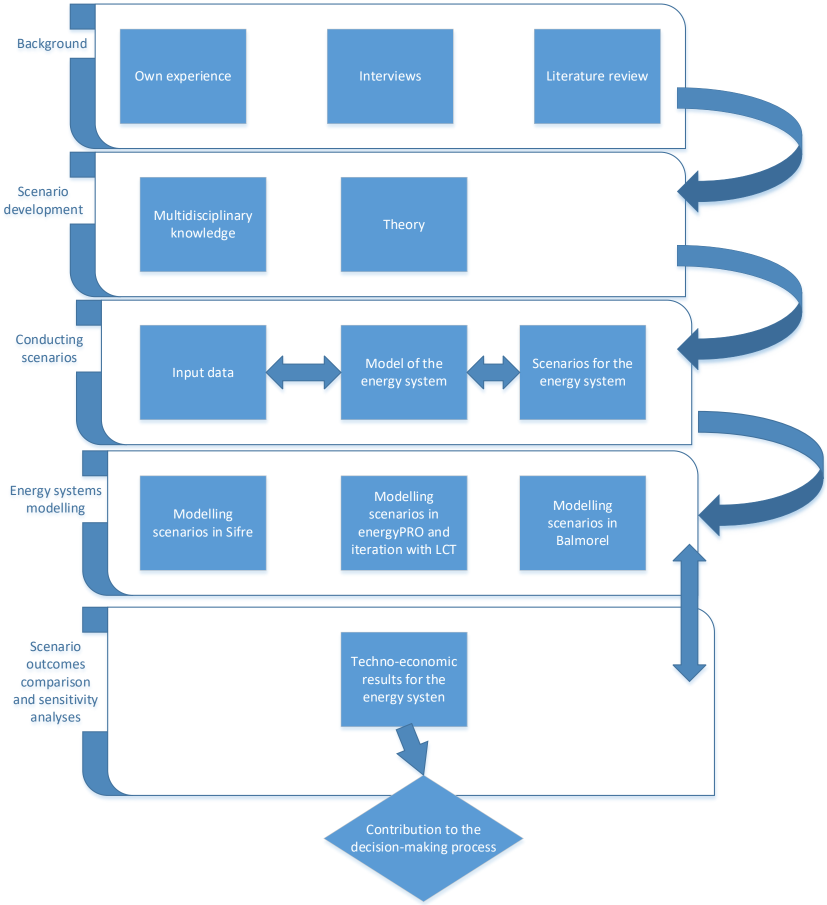

Figure 3-1 Phases of scenario analysis, adapted from (Ben Amer 2014), inspired by (Fontela 2000; Karlsson and Meibom 2008).

The background analysis consisted of literature review, informal talks and semi-structured interviews with the utilities and municipalities, conducted by the author of this thesis and co-authors of papers. This phase formed a backbone for scenario development, where knowledge on scenarios and theory (e.g. economic aspects) contained in each of the models was used. Input data was collected and scenarios were conducted in an iterative process of modelling and adjustment. Finally, the outcomes were techno-economic results of modelling of energy system (different components depending on the paper), which hopefully influenced the planning and decision-making process. In this way, the aforementioned definition of a scenario as purposeful depiction of possible future energy systems and pathways to achieve them is applied.

In each paper A-C different scenarios are modelled, according to the local situation. The scenarios are described below and their details: types of analyses, assessment criteria and sensitivity analyses, presented in Table 3-1.

Paper A models the following scenarios for electricity and heating (transport is kept constant) in Sønderborg:

a) Municipal plan: Production capacities as in Sønderborg's strategic energy plan

b) Biomass: Biomass replaces fossil fuels, no significant electrification

c) Electrification: Significant electrification, biomass consumption kept close to the local limit

d) Electrolysis: Same as c) and addition of gasification and solid oxide electrolysis

e) Reversible electrolysis: Same as d) and addition of reversible solid oxide cells

Paper B models the following scenarios for heating in Helsingør:

a) BAU2030 (Business As Usual): Woodchip CHP and boiler

b) RES2030: as in b) and a policy of forbidding individual heat supply using fossil fuels

c) HP2030: Large-scale heat pumps and heat storage

d) BAU2050: Woodchip CHP and boiler

e) Combi2050: Heat pumps, heat storage, solar heating and woodchips

Paper C models the following scenarios for Nordhavn:

a) Reference: optimisation among: seawater HP, heat storage, solar heating and ground-source HPs.

b) Seawater heat pump: large heat pump using seawater as heat source, and thermal storage.

c) District heating extension: extension of Copenhagen's district heating capacity to Nordhavn.

d) Individual solutions: optimisation among: solar thermal collectors, ground-source heat pumps, thermal storage and electric boilers.

Table 3-1 Type of analysis, assessment criteria, and sensitivity/uncertainty analysis applied in papers A-C.

Paper	**A**	**B**	**C**
Analysed years	2029	2030, 2050	2020, 2025, 2035, 2050
Type of analysis	socio-economic (4% interest rate, taxes and subsidies excluded)	private (0.99-4.46% interest rate, depending on the investor type, taxes and subsidies included) and socio-economic (2% interest rate, taxes and subsidies excluded)	socio-economic (4% interest rate, taxes and subsidies excluded)
Assessment criteria	total system cost, total system CO_2 emissions, total biomass consumption, total system energy conversion efficiency	heat supply mix, heating costs, share of district heating and heat savings, CO_2 emissions	electricity and heat generation, electricity and heat price, CO_2 emissions
Sensitivity/uncertainty analyses	+/-30% price changes of biomass, electricity and fossil fuels	+/-50% price changes of biomass and electricity	Seawater HP COP=2.8 instead of 3, ground-source HP COP=3.5 instead of 4; 2% and 6% discount rate

The main similarities lie in assessment criteria, which encompass CO_2 emissions, fuel mixes and total system costs. The sensitivity analyses cover primarily fuel prices, with an exception of paper C, where changes in COP and discount rates are included. The most important difference is that paper B focuses only on heating and conducts both socio-economic and private-economic analysis, which significantly influence the final results.

3.3.2 ENERGY SYSTEM MODELLING AND ANALYSIS

The applicability of energy modelling is investigated, using the following tools: Sifre, energyPRO, Least-Cost Tool (LCT) and Balmorel. The tools were chosen in order to observe the technical influence of changing the share of renewables and energy efficiency in the energy system and the related changes in costs. Balmorel and Sifre both have a detailed representation of technologies and already include an up-to-date data set for the existing plants and storage capacities. Moreover, they have all been used in Danish contexts before, so are able to depict e.g. the Danish district heating system.

Paper A: Sifre

Sifre was used to model Sønderborg, since it can handle electricity, heat and transport. It is developed by one of collaborators in paper A, Danish electricity and gas transmission systems operator, Energinet.dk, who was interested in strengthening their competence in urban energy analyses and checking the applicability of a wide range of technologies. The model represents energy flows and energy prices in all sectors in discrete time steps. Sifre uses mixed-integer linear optimisation, the objective function minimising the total operating expenses of the specified energy system over a period, while fulfilling the specified energy demand during all time steps in the same period. In paper A, the calculation period was one year with a time resolution of one hour. Capital expenses were excluded from the model, but added to the results after optimisation. Eq. 1 displays the objective function in Sifre. It is to minimise system operation cost Z (Energinet.dk, n.d.), where:

$$\min Z = \sum_{t\in T}\left(\sum_{i\in N}\left(C_{a,t}^{fuel} + C_{a,t}^{over} + C_{a,t}^{under} + \sum_{(a,p)\in A} C_{a,p}^{mcons} + \sum_{(p,a)\in A} C_{p,a}^{mprod}\right)\right.$$
$$\left. + \sum_{(a)\in A^{ICL}} C_{a,t}^{ICL} + \sum_{p\in H} C_{p,t}^{startup}\right) - \sum_{t\in T}\sum_{i\in N}\sum_{f\in D(a)} C_{t,f}^{flex} \tag{1}$$

$C_{a,t}^{fuel}$ is the cost of external fuel supply in time *t* in area a, $C_{a,t}^{over}$ the cost of overproduction, $C_{a,t}^{under}$ the cost of underproduction, $C_{a,p}^{mcons}$ marginal cost of consumption in unit p, $C_{p,a}^{mprod}$ marginal cost of production in unit p, $C_{p,a}^{ICL}$ the cost of the flow on interconnections, $C_{p,a}^{startup}$ the start-up and operating costs of production units, $C_{t,f}^{flex}$ coverage of flexible demand *f* for area a.

Paper B: energyPRO and Least-Cost Tool (LCT)

Among the aims of the project was to encourage municipalities and local energy agencies to use the tool after the project ended. EnergyPRO, a commercial software for techno-economic analyses of energy projects, was used to model Helsingør's district heating due to its versatility and user-friendliness as also stated by (Ferrari et al. 2019). EnergyPRO was used iteratively with the specially-developed spreadsheet tool LCT, analysing heat supply and heat savings costs. The objective function for energyPRO is to minimise *NHPC*:

$$NHPC = FC + FIXOM + VAROM - ELSAL \tag{2}$$

where *NHPC* is net heat production cost of the modelled plant, *FC* fuel cost, *FIXOM* fixed operation and maintenance cost, *VAROM* variable operation and maintenance cost, *ELSAL* electricity sales

The heating cost is calculated by LCT according to the following Eq. (3):

$$HC^{(i)} = \frac{\sum_a \sum_c \sum_u \sum_h HD_{a,c,u,h}^{(i)} \cdot AR_{a,c,u,h} \cdot \left(INV_{a,c,u,h}^{(i)} + O\&M_{a,c,u,h}^{(i)} + FUEL_h\right) \cdot (1+VAT)}{\sum_a \sum_c \sum_u \sum_h HD_{a,c,u,h}^{(i)} \cdot AR_{a,c,u,h}} \tag{3}$$

The criterion for stopping the iteration is: $HC^{(i)} - HC^{(i-1)} < 0.001 \frac{EUR}{kWh}$

where: *HC* is heating cost, *a, c, u, h* geographical area, construction period, use and heating source of the buildings, respectively, *HD* specific heating demand, *AR* heated area of buildings, *INV* investment cost*, O&M* operation and maintenance costs, *FUEL* fuel cost, *VAT* Value Added Tax

Paper C: Balmorel

Balmorel was used to model Greater Copenhagen, because it has a detailed representation of Danish district heating network and Nordic power system. It is a bottom-up linear programming energy system optimisation modelling tool. It enables incorporating data on current and future electricity and heat system and simulating it according to the scenarios chosen. The optimisation targets most cost-effective mix of technologies bounded by e.g. emission limits.

Eq. 4 displays the objective function of Balmorel. It is the sum of all the costs in a given year, where c is country, r is region, $C_{a,p,t}^{fuel}$ are the fuel costs at time t on plant p in area a, $C_{a,p,t}^{OM}$ the operation and maintenance costs, $C_{a,p,t}^{trans}$ transmission costs, $C_{a,p,t}^{inv}$ investment costs, and C^{Ap}costs of add-on contributions.

$$V_{obj} = \sum_{c,r,a,p,t} \left(C_{a,p,t}^{fuel} + C_{a,p,t}^{OM} + C_{a,p,t}^{trans} + C_{a,p,t}^{inv}\right) + C^{Ap} \qquad (4)$$

3.3.3 QUALITATIVE CONTENT ANALYSIS

Content analysis allows to notice patterns in data by systematically classifying it into identified categories and finding themes or deriving theory from it (Moretti et al. 2011; Cho and Lee 2014). The qualitative content analysis (Hsieh and Shannon 2005) was applied in this thesis. Instead of using frequency counts, the step-by-step technique (Erlingsson and Brysiewicz 2017) was found to generate valuable insights from the data. As Figure 3-2 illustrates, the following procedure for data analysis was used: first, interview excerpts carrying a meaning relevant for the subject of the study were selected and condensed, then codes, categories and themes were generated in an iterative process. The Atlas.ti tool was used for managing and organizing the interview data.

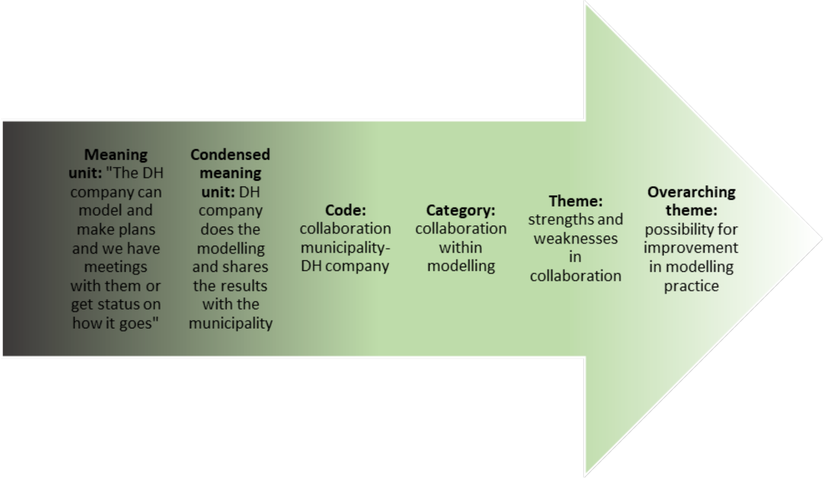

Figure 3-2 Example of an analysis leading from a lower (left-hand side) to a higher (right-hand side) level of abstraction, using an excerpt from an interview conducted for paper D, the graphical representation inspired by (Erlingsson and Brysiewicz 2017).

4 RESULTS AND DISCUSSION

This chapter presents the summary of the results from papers A - D and the contributions of this dissertation. It also discusses the implications and limitations of the obtained results.

4.1 RESULTS FROM PAPERS A-D

For each case, the identified feasible low-carbon energy mixes vary, due to different sectoral foci, local resources, timelines and other scenario details. A general result from papers A-C is that the CO_2 emissions originating from urban energy systems can be reduced by implementing heat savings in buildings, large-scale heat pumps and heat storage in district heating and expanding district heating. The results concerning heat pumps are in line with e.g. (R. Lund, Ilic, and Trygg 2016; Bach et al. 2016), who also find a high potential for large-scale heat pumps in the Danish district heating.

Paper A entails modelling of electricity, heat and transport in Sønderborg. It demonstrates that implementing electrolysis and reversible electrolysis on a municipal level instead of biomass boilers allows achieving least CO_2 emissions at the least cost. The results hold even if higher or lower electricity and fossil fuel prices are applied, the only exception being a case of lower biomass prices, which would decrease the system costs for a scenario primarily based on biomass. For comparison, electrolysis is considered a part of future transport e.g. by (Ridjan, Mathiesen, and Connolly 2014; Ridjan et al. 2013).

Paper B concentrates on modelling of heating and heat savings in Helsingør. It finds that the inclusion or exclusion of taxes in the analysis makes a large difference regarding which technology appears as most cost-efficient, because of the asymmetric fuel taxation. Whereas from the socio-economic perspective individual heat pumps and district heating expansion are more cost-competitive, from the private-economic perspective individual biomass boilers and heat savings, especially in remote areas, are more feasible. The sensitivity analyses reveal that the change of electricity and biomass prices affects mainly the heating costs and CO_2 emissions, because the heat savings levels and the supply types chosen differ from those in the main scenarios. For example, a biomass price increase means that individual natural gas and heat pumps are selected, resulting in higher average heating cost in Helsingør municipality.

Paper C analyses options for the future electricity and heat system in Greater Copenhagen. It demonstrates that the optimised future energy system in Greater Copenhagen is likely to rely on heat pumps, municipal waste, heat storages and excess heat. In the Nordhavn district, either expanding the Copenhagen's district heating network, as also suggested by (HOFOR 2013), or implementing a seawater heat pump could be feasible. As expected, the model outcome is highly sensitive to the discount rate: a lower discount rate of 2% results in a lower heat price in analysed areas, the opposite happens for a higher discount rate of 6%.

Paper D shifts the focus from technologies to users, concentrating on whether energy system models are used by municipal planners and whether models actually help facilitate urban sustainability. The paper finds that the active users of energy system models are consultancies, heat supply companies and universities - municipalities actively use CO_2 calculation or evaluation tools instead. Both models and spreadsheet tools serve visualisation, strategy calculation and progress evaluation. The study identifies several weaknesses of models as perceived by practitioners, e.g. complexity, silo-thinking and insufficient depiction of policy options. Moreover, the paper finds that the staff in analysed municipalities lack the modelling skills, as also identified by (Petersen 2018), and question the usefulness of undertaking modelling themselves. (Krog 2019) observes that the benefit of involving outsiders to conduct analyses is that they can supply additional insights. Paper D recommends increasing the efforts to exchange the data, assumptions and models, and strengthening of inter- and cross-municipal collaboration.

4.2 CONTRIBUTIONS OF THE DISSERTATION

The overall objective of this PhD thesis is to investigate the methods for representing urban energy systems and to assess which changes in urban energy systems could reduce CO_2 emissions. The thesis analyses a number of energy scenarios for three Danish urban areas and examines relations between the implementation of renewable energy sources and energy efficiency in energy systems and selected economic characteristics, such as electricity and heat prices.

In general, research findings of this PhD thesis contribute to the ongoing research and policy debates on the transformation to sustainable energy in cities and modelling of energy transitions - by bringing insights on which investments are least-costly and providing tools for various aspects of urban energy planning. The contribution of the thesis can be divided into four main elements: use of modelling tools for determining future low-carbon urban energy mixes, analysis of strengths and weaknesses of the selected modelling approaches, role of energy system modelling, and mixed method research and stakeholder involvement.

4.2.1 ENERGY MODELLING FOR DETERMINING LOW-CARBON URBAN ENERGY MIXES

The results of this thesis show that a mix of storage and different energy conversion pathways, including those less often applied on a large scale e.g. electrolysis, is feasible if cities are to reduce their CO_2 emissions. A balance between district heating expansion and heat savings is important to consider for achieving cost-efficient solutions. For each case the identified least-cost low-carbon energy mixes are different, due to different scenario details.

The municipal framework conditions play a role in what constitutes an ambitious CO_2 goal and which actions are targeted. Out of the cities analysed, Copenhagen plans to reach CO_2 neutrality first (in 2025), then Sønderborg in 2029 and Helsingør in 2050. Obviously, the 98% share of heat demand covered by district heating in Copenhagen makes it possible to decarbonize this sector faster, in addition Copenhagen has a high share of electrified transport (metro, local trains), which is not the case in the smaller municipalities. Whereas citizen involvement in Copenhagen is important especially regarding switching to fossil-fuel free modes of transport, in Helsingør and Sønderborg, the collective climate action targets all energy sectors and services.

The thesis demonstrates that the exclusion or inclusion of taxes has a bearing on the final modelling results. Heavily taxing electricity in comparison to exempting biomass from taxes encourages investments in the latter, which in long term is not always the most sustainable solution, especially in countries heavily dependent on biomass imports, e.g. Denmark. According to the IPCC, excessive land use for bioenergy should be discouraged, in order to free up land for food production and avoid threats such as desertification and land degradation (IPCC 2019). Moreover, the use of residues for bioenergy ought to take the negative influence on soil quality into consideration (IPCC 2019). Furthermore, a high dependence on biomass may be risky in case of price increase which indeed is likely considering the globally growing demand for biomass.

The choice of scenario assumptions on future fuel and technology prices and CO_2 emission reduction policies may affect the final results. To address this concern, the majority of price projections is based on the reports from the International or Danish Energy Agency and ENTSO-E, some of which are validated with stakeholders, and to some extent they are covered with sensitivity analyses. Nonetheless, technology costs are not part of sensitivity analysis, and considering the changing market trends e.g. solar photovoltaics prices falling unexpectedly fast, it cannot be excluded that some other technology in the mid and long run also will be cheaper than the projections assume.

As demonstrated by (García-Gusano et al. 2016), interest rate levels in scenarios can influence both the resulting costs and technology choice. In this thesis, the assumptions about inflation and discount rates within the private-economic analysis could potentially also affect the fuel mix in Helsingør, because higher cost of borrowing could results in less investments. Although the trend regarding low discount rates has been quite stable in recent years, the possibility of a drastic change in financial markets cannot be excluded.

The case of biomass CHP in Helsingør shows that from a private-economic perspective the cost-effectiveness of district heating expansion is dependent on the price setup (including administrative costs) and biomass taxation. The implementation of heat savings is also highly dependent on how energy taxes are shaped, because high input fuel taxation makes them more cost-competitive than heat supply technologies that are taxed on input fuel.

The modelling frameworks used in the thesis are adapted to the specific cases, but could be applied for other cities around the world. Due to time and data access constraints, it was only plausible to include a limited number of case studies and scenarios. Whereas the detailed findings are applicable mainly for Copenhagen, Helsingør and Sønderborg, they are indicative for other areas with similar climatic conditions, population and natural resources. Obviously a full replication to the cities of the global South is impossible due to different climatic conditions, immediate challenges and higher population and urbanization rates. In all cases, due to the changing character of energy systems, a follow up is necessary to accommodate for the changing energy system and ever decreasing costs of renewable energy technologies.

4.2.2 STRENGTHS AND WEAKNESSES OF SELECTED MODELLING APPROACHES

Energy systems are becoming increasingly complex: new energy conversion and storage technologies, smart metering and flexibility measures are being implemented. As such, energy modelling is a systematic and comprehensive approach aiming to accommodate for this complexity. This dissertation considers three different energy models and three different energy systems as case studies, thus discussing the strengths and weaknesses of applying different models for modelling urban energy systems from the author's perspective is among this thesis' contribution to the literature on local energy modelling. Please note that since different models were used for different cases, a direct comparison is impossible, hence the results below are merely indications. Modelling every case with all the models could bring more insights and stronger conclusions.

In general, out of the modelling tools used, Sifre and Balmorel were found suitable to analyse integrated energy systems based on high share of renewables. EnergyPRO and the spreadsheet tool LCT are found suitable to model heating and heat savings.

By and large, the modelling of the selected urban areas was addressed in two ways: investment optimisation and simulation. This implies differences in how energy scenarios were defined and how installed production capacities were determined. Since investment optimisation in Balmorel, especially in case of partial foresight optimisation, costs computational time, only selected representative hours (time aggregation) were used. Hourly simulation with Sifre was much faster, but more scenario options had to be developed to be able to compare system costs. Similar observations on simulation tools are mentioned by (H. Lund et al. 2017)

There are differences between modelling the whole Nordic region (paper C) and only one specific municipality, connected to the rest of Denmark via electricity prices (papers A and B). In the first case, the model better represents the reality - so Nordhavn is connected to Copenhagen and further on to Denmark and the countries within the common Nordic electricity market. Supposedly, these differences would also be reflected in results - however the research setup conducted does not allow for direct comparisons. According to (Østergaard 2009), modelling an area in a connected mode allows to represent the real-life situation of balancing across areas. In an island mode, no interconnectors to other areas are allowed, and keeping such system in balance is more challenging, but it shows the possible weaknesses in how flexible the analysed system is. The "connected island" mode aims to unite the two perspectives by keeping connections, but limiting electricity exchanges (Østergaard 2009).

Papers A-C range from representing the overall energy system, including transport, to just showing the heating sector. Presumably, the more integration, the better, because it allows for cross-sectoral flexibility measures. On the other hand, targeting the sector with highest municipal influence in Danish context, i.e. heating, can make the results more relevant for the municipal planning processes.

In this thesis, heat savings are explicitly handled for the case of Helsingør (paper B); they are assumed as lower future heat demand for the two other cases, where district heating has a higher share than in Helsingør. The differences in heat savings levels occur depending on the age and location of buildings and their proximity to the collective heat supply, thus assuming an average heat savings share hides a full picture of all possibilities for increasing energy efficiency. The explicit incorporation of heat saving options in the modelling framework generates numerous insights for the municipality, including which building types to target with energy checks and information campaigns.

Among the findings from the interviews, an inability of analysing measures using energy system models was named. This issue touches upon the general difference between a target (e.g. carbon emissions reduction) and policy measure (e.g. tax rebates on electric vehicles). While the first one is the endpoint, relatively easy to implement in models, the latter is more challenging to depict with energy system models and implement in real life. Monetary and non-monetary policy measures could be divided into "sticks" and "carrots" and they may aim for example at influencing behaviour towards more sustainable choices, hence it is the measures that can influence the transitions. However, most of models depict the targets, where the model optimises the energy system setup to fulfil them. The possible steps and measures to accomplish the goals are not shown, in a way relying on the free market solutions. The rational cost efficiency approach assumes perfectly rational actors, but the fields of behavioural economics and psychology find other motivations of human behaviour than monetary, see e.g. (Kastner and Stern 2015; Frederiks, Stenner, and Hobman 2015).

4.2.3 ROLE OF ENERGY SYSTEM MODELS IN MUNICIPAL ENERGY PLANNING

Energy system models can be used to systematically assess the feasibility of renewable energy and energy savings implementation and to help determine scenarios for cost-efficient reduction of CO_2 emissions. This subject is relevant not only in Denmark, but also e.g. for cities belonging to the Covenant of Mayors, because energy system modelling is often among the methods they use to design their energy strategies. Nonetheless, there is insufficient research on the usefulness and usability of tools for modelling energy systems (Ben

Amer, Gregg, et al. 2019). Focusing on a concrete situation of municipal planners, this thesis brings new insights into the practice of creating urban energy strategies.

The role of energy system models and spreadsheet tools in energy planning on the municipal level in Denmark is to provide visualisation, strategy calculation and progress evaluation - which are often the tasks conducted within the framework of strategic energy planning. However, municipal planners find models too complex, inflexible and insufficiently depicting policy options. These weaknesses, connected to the admitted lack of expertise may mean that the potentials of models are underutilized. Municipalities deal with this challenge by collaborating with consultancies, heat supply companies and universities. The status quo can be also improved by more efforts to share the data, assumptions and models, inter- and cross-municipal collaboration and constant dialogue on how to make tools useful for planning and implementing measures towards sustainability.

4.2.4 MIXED METHOD RESEARCH AND STAKEHOLDER INVOLVEMENT

Academics researching cities use quantitative and qualitative methods alike (LeGates 2011) as a means to achieve a holistic picture of cities. Section 1.5 and section 3.1 explain how mixed method research is used in this dissertation. The second research question (RQ2) of the thesis, which focuses on strengths and weaknesses of various modelling approaches, aims to link the three quantitative papers A-C and one qualitative paper D. The thesis also attempts to involve municipal stakeholders in the research through interviews conducted for paper D.

4.3 LIMITATIONS

For the purpose of clarity, several aspects equally important for achieving sustainability had to be excluded from the scope of this thesis due to their vastness.

Biomass is assumed as CO_2 neutral in this analysis, complying with the prevailing approach so far and the UN and EU recommendations. However, there is an ongoing heated debate in Denmark and elsewhere regarding the true impact of biomass cultivation, transport and combustion, in the short and long term. However, this debate is beyond the scope of this thesis.

Detailed modelling of demand response has been excluded from this dissertation, but should be analysed in future work, since it is an element of a flexible energy system, allowing for incorporating more intermittent renewable energy.

Air pollution is another grand challenge linked to energy and transport in urban areas, especially considering the particulate matter and NOx emissions. However, these aspects have also been excluded from this thesis.

For the results concerning district heating expansion, reasons other than costs may be relevant, e.g. comfort and easiness of access, but they are excluded from this thesis. Moreover, governance, social and political aspects as mentioned by e.g. (Grandin et al. 2018; Späth and Rohracher 2014; Gabillet 2015) and a detailed modelling of behaviour needed for transition to sustainability as well as a detailed analysis of urban planning, albeit important, are out of scope of this thesis.

5 CONCLUSIONS AND OUTLOOK

This chapter presents conclusions of this PhD thesis and their significance, as well as discusses possibilities for further research.

The overall objective of the thesis was to investigate the methods for representing urban energy systems, their advantages and disadvantages from a scientific and practical perspective, and to assess which changes in urban energy systems could result in reduced CO_2 emissions. The dissertation analyses a number of energy scenarios for three Danish urban areas and examines relations between the implementation of renewable energy technologies and energy efficiency in energy systems and selected economic consequences, such as total system costs and electricity and heat prices.

In pursuing these goals, the contribution of this thesis can be divided into four main elements: use of modelling tools for determining urban energy mixes, strengths and weaknesses of the selected modelling approaches, the role of energy system modelling, and stakeholder involvement and mixed method research. This thesis has also contributed with four journal articles, three on modelling of urban energy systems and one on the use of energy modelling tools within municipalities. The methodological contribution of this thesis is the application of the mixed-method approach, expressed by linking three quantitative papers A-C and the qualitative paper D through the same case study municipalities and a similar focus on the strengths and weaknesses of energy system models. This dissertation contributes to the literature on urban energy scenarios, local energy modelling and the use of modelling tools, thus covering several of the research gaps discussed in section 1.3.

The research and policy debate on transformation to sustainable energy in cities is ongoing. Within this field, the PhD thesis finds that it is possible to significantly reduce CO_2 emissions from urban energy systems in a cost-effective way by implementing a mix of different energy conversion pathways and heat storage, and a balance between district heating expansion and heat savings. In Sønderborg, installing electrolysers and fuel cells on the municipal level instead of biomass CHPs allows achieving least CO_2 emissions from the energy system at the least cost, if taxes and subsidies are not considered. In Helsingør, from the socio-economic perspective individual heat pumps and district heating expansion are more cost-competitive in the heating system, whereas from the private-economic perspective individual biomass boilers and heat savings, especially in remote areas, are more feasible. The Greater Copenhagen's district heating network is likely to rely on heat pumps, municipal waste, heat storages and excess heat. In the Nordhavn district either expanding the Copenhagen's district heating network or implementing a seawater heat pump could be feasible.

The thesis also shows that the exclusion or inclusion of taxes has a bearing on the final modelling results. Heavily taxing electricity in comparison to exempting biomass from taxes encourages investments in the latter, which from the socio-economic perspective is not always the most sustainable solution, especially in countries profoundly dependent on biomass imports, such as Denmark.

Whereas the detailed findings are applicable mainly for Copenhagen, Helsingør and Sønderborg, on a more general level they are indicative for other areas with similar climatic conditions, population and natural resources. The municipal framework conditions play a role in what constitutes an ambitious CO_2 goal and which actions are targeted, e.g. the 98% share of district heating in Copenhagen makes it possible to decarbonize this sector faster. Obviously a full replication elsewhere, e.g. to the cities of the global South, where most pressing urban challenges occur, is impossible due to e.g. different infrastructural issues, climatic conditions and higher population and urbanization rates. In all cases a follow up is necessary to accommodate for the changing energy system, development of information and communication technologies (ICT) and decreasing costs of renewable energy technologies.

Generally, the modelling of the selected urban areas was addressed in two ways: investment optimisation and simulation. Out of the modelling tools used, Sifre and Balmorel were found suitable to analyse integrated energy systems based on high share of renewables. EnergyPRO and the spreadsheet tool LCT are suitable to model heating and heat savings.

Addressing all energy sectors allows a better integration of flexibility measures, but targeting the sector with highest municipal influence in the Danish context, heating, makes the results more relevant for the municipal planning processes. Moreover, an explicit incorporation of heat saving options in the modelling framework generates numerous insights for the municipality, including which building types to target with energy checks and information campaigns.

Although this thesis does not focus specifically on transport, it was incorporated in Sifre and Balmorel in the form of transport energy demand. Other tools which already have a more detailed transport representation e.g. TIMES or EnergyPLAN could be also suitable, possibly coupled with transport-specific tools.

Nonetheless, several limitations of quantitative energy scenario modelling can be identified. The reliance on statistical data and assumptions means that uncertainties occur in the process. Moreover, least-cost optimisation does not depict complex and non-linear stakeholder interactions, and assumes perfectly rational actors, while the fields of behavioural economics and psychology have other observations. Therefore, energy system modelling should be supplied by other approaches, for example agent-based models (Rai and Robinson 2015;

Snape, Boait, and Rylatt 2015), possibly linked to techno-economic models or qualitative theoretical analyses of the processes behind energy transitions, such as conducted by e.g. (Selvakkumaran and Ahlgren 2017; Schoor et al. 2016; Köhrsen 2018).

Among the findings from the interviews, an inability to analyse measures with energy system models was named, touching upon the general difference between a target (e.g. carbon emissions reduction) and policy measure (e.g. tax rebates on electric vehicles). Most of optimisation models depict the targets, where the model optimises the energy system setup to fulfil them. The possible steps and measures to achieve the goals are hidden. A recommendation could be to couple energy system models with general equilibrium models or use so-called socio-technical transition (STET) models to analyse energy transitions and behaviour.

The thesis agrees with the need to focus on various cities and towns, not only the "role models". While the Danish capital Copenhagen is among the cases analysed, the two other cases are much smaller municipalities, which however have rather ambitious climate and energy goals.

There is insufficient research on the usefulness and usability of tools for modelling energy systems, especially in the municipal contexts. The results of this thesis show that energy system models and spreadsheet tools provide visualisation, strategy calculation and progress evaluation within municipal energy planning. However, municipal planners find models too complex, inflexible and insufficiently depicting policy options. These weaknesses, connected to the admitted lack of expertise may mean that the potentials of models are underutilized. The status quo can be improved by increasing efforts to share the data, assumptions and models, inter- and cross-municipal collaboration and constant dialogue on how to make tools useful for planning and implementing measures towards sustainability. Academia has a big role in facilitating the use of models and knowledge transfer, acting as knowledge intermediaries (Ardito et al. 2019).

Future work could focus on applying the outcomes of the techno-economic scenario analysis in analyses on selected socio-economic impacts (e.g. employment effects, fuel poverty etc.) of urban energy transitions, possibly within the framework of STET models. Moreover, a development of methods for linking the implementation of Sustainable Development Goals (SDGs) and Paris Agreement in the energy system modelling or urban energy planning context could be an option, as also discussed by (Ringkjøb, Haugan, and Solbrekke 2018).

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PART II PAPERS A - D

Paper A: Energy supply modelling of a low-CO_2 emitting energy system: Case study of a Danish municipality

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Energy supply modelling of a low-CO_2 emitting energy system: Case study of a Danish municipality

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HIGHLIGHTS

- Urban energy system scenarios for Sønderborg, Denmark.
- Keeping biomass consumption within the limits of the locally available resources.
- Lowest cost and CO_2 emissions by using heat pumps, solar heating and electrolysis.

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ABSTRACT

Municipal activities play an important role in national and global CO_2-emission reduction efforts, with Nordic countries at the forefront thanks to their energy planning tradition and high penetration of renewable energy sources. In this work, we present a case study of the Danish municipality of Sønderborg, whose aim is to reach zero net CO_2 emissions by 2029. Sønderborg has an official strategic plan towards 2029, which we compared with four alternative scenarios to investigate how the municipality could approach its target in the most energy-efficient and cost-effective way while simultaneously keeping biomass and waste consumption close to the limits of the locally available residual resources.

We modelled all sectors of the energy system on the municipal scale, applying a broad range of energy conversion technologies, including advanced biomass conversion technologies and reversible electrolysis. We constructed five scenarios, each representing a different energy mix for Sønderborg's energy system in 2029. We modelled these scenarios using the mixed-integer linear optimization tool Sifre. We compared the results for the five scenarios using four indicators: annual total system cost, total energy system efficiency, annual net system CO_2 emissions and total annual biomass consumption.

The results show that scenarios with a high degree of electrification perform better on the selected indicators than scenarios with a high degree of biomass utilization. Moreover, the incorporation of advanced conversion technologies such as electrolysis, fuel cells and methanol production further reduces both the total system cost and net CO_2 of the highly electrified energy system. Our sensitivity analysis demonstrates that scenarios with a low biomass consumption and a high degree of electrification are less dependent on changes in energy prices.

We conclude that in order to achieve their CO_2 emission goals in the most energy-efficient, cost-effective and sustainable way, municipalities similar to Sønderborg should compare a wide range of energy system configurations, for example, scenarios with a high degree of electrification and a limited biomass use.

1. Introduction

Energy policy and CO_2 reduction targets on the municipal level play a significant role in the national CO_2 reduction efforts in most countries, being of global importance in the transition to a more sustainable energy supply. Municipal energy planning has gained increased attention in recent years [1–3]. In the EU, initiatives such as Covenant of Mayors encourage exchange of experience among cities working with sustainable energy [4]. In particular, Scandinavia is one of the most experienced regions in strategic energy planning. Following the oil crises in the 1970s non-obligatory

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energy plans were implemented in Sweden [5] and heat supply plans introduced in Denmark [6]. Currently, most Danish municipalities have issued some climate action plans [7] and declared future CO_2 goals, for example Copenhagen [8], Aalborg [9] and Helsingør [10].

In this paper, the Danish municipality of Sønderborg has been selected as a case study of municipal energy supply planning. Sønderborg has a population of about 75,000, located on the Jutland peninsula and the island of Als in southern Denmark (see Fig. 1). In 2009 Sønderborg set itself the target of becoming CO_2-neutral by 2029 [11]. According to the municipality's plans, the target is to be reached by replacing gas-fired turbines and boilers with wind turbines, heat pumps, biomass boilers and solar heating, and by replacing the natural gas supply with locally produced biogas. In Sønderborg's plans, CO_2 neutrality is understood as achieving net zero CO_2 emissions by balancing remaining CO_2 emissions in the region with an equivalent amount of emissions offset, for example, by exporting energy from low-carbon sources out of the municipality. We use the same definition in this study.

This ambitious energy policy makes Sønderborg a highly interesting case. The municipality is very active in realizing its policy and has received funding from several EU and Danish grants to do so. Sønderborg also runs an internal initiative called Project Zero [12], which has provided us with valuable data and validation of our assumptions during this work. In terms of scale, Sønderborg represents a middle-sized Scandinavian municipality with an energy system small enough to make possible a detailed case study, yet complex enough to represent a full urban-scale energy system. The main findings of the case study should therefore be easily applicable or transferable to other similarly sized northern European cities.

Sønderborg municipality's existing strategic energy plan [11] describes the measures the municipality proposes to take to reach its 2029 emission target. The expected results of the plan in 2029 are presented in [11] and favorably compared with a "business as usual" scenario, though no alternative scenarios with different energy supply mixes are investigated. Therefore the plan does not focus on the question of whether Sønderborg's proposed measures are the most suitable pathway towards the municipality's emission target, or whether other, more socio-economically cost-effective and energy efficient pathways for reaching the target could be pursued. Moreover, the strategic energy plan does not address how the amount of biomass consumed for energy purposes in Sønderborg is expected to compare with the locally available residual biomass resources in 2029. To address these issues, in this paper we have developed and analyzed four alternative scenarios for the state of Sønderborg's energy system in 2029 and compared them with the municipality's plan.

In Denmark, as elsewhere, many energy producers currently plan to reduce their greenhouse gas emissions by combusting wood chips or wood/straw pellets instead of fossil fuels in combined heat and power plants. However, if these plans were all to be realized, Denmark would need to import substantial amounts of wood to cover total national demand [13]. The long-distance transport of biomass (straw and wood), which has a very low energy density compared to fossil fuels, may lead to a less sustainable energy supply. It may also be beneficial to prioritize the scarce biomass energy resource for the production of high-grade fuels rather than low-grade thermal energy [13,14]. From a socio-economic perspective, using wind and heat pumps for electricity and heat production in regions such as Scandinavia and northern Germany is often a less expensive solution than biomass [15], and the potential for large-scale utility heat pumps already exists [16–18]. Biomass use can also be reduced in the heating sector by switching to sources such as solar thermal, industrial surplus heat and geothermal heat [19]. In their review of renewable energy system solutions, including electrolysis, heat pumps and sectoral integration, Mathiesen et al. [14] underline the importance of analyzing a wide range of available technologies to facilitate smart energy systems.

The objective of our study is to investigate how Sønderborg can become a low-CO_2 emitting municipality by 2029 in an energy efficient and cost-effective way, while also keeping its biomass consumption close to the limits of the locally available residual biomass resources. This goal is similar to what bioenergy villages in Germany and Austria have been trying to achieve; namely supplying the energy demand of the village solely with regional biomass sources, taking into account the local use of the agricultural and forest area [20]. For this purpose, we investigate the consequences of implementing novel energy conversion technologies such as large-scale heat pumps, biogas production, thermal gasification, electrolysis, biogas methanation and transport fuel synthesis. The modelling was performed using *Sifre*, a mixed-integer linear optimization tool, which optimizes energy flows and energy prices in all sectors of the specified energy system in discrete time steps. The *Sifre* tool is further described in Section 3.1. The results for the five different model scenarios for 2029 were evaluated and compared based on the following four indicators: the total system socio-economic costs, the energy system's net CO_2 emissions, the total biomass consumption (relative to the locally available resources) and the total energy conversion efficiency of the system.

The novelty of our work lies in modelling energy system scenarios containing a large number of different energy conversion

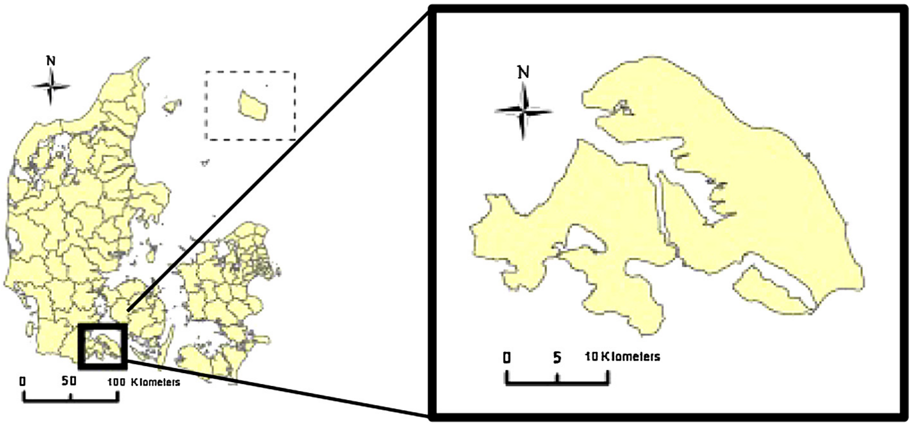

Fig. 1. Location of Sønderborg municipality, Denmark.

technologies on an urban scale, including technologies not commonly employed today, such as electrolysis, fuel cells, thermal gasification and biofuel production. While a large body of literature exists on electrolysis and fuel cells as devices, there is very little discussion about them in a broader perspective of techno-economic energy system scenario analyses [21]. However, in this study we show that these technologies can contribute to future sustainable cities, the results encouraging municipalities not to overlook less common technologies. This work also focuses on the highly relevant issue of the scarcity of biomass resources. We include the comparison of planned biomass consumption with locally available residual biomass resources as one of the indicators used for comparing the outcomes of the scenarios, pointing out any scenarios where biomass imports would be necessary. Moreover, this work highlights the lack of sufficient investigations into whether the strategic plan actually represents the most feasible pathway for reaching the set goals. By expanding the scope of the investigated technologies and scenarios, it may be possible to identify alternative plans that perform better than the official plans in terms of socio-economy, energy efficiency and CO_2 emissions.

In Section 2, we review the literature concerning similar energy system studies and technologies used in the scenarios. In Section 3, the methodology used in this paper is described, including the model, scenarios, indicators and input data. In Section 4, we present the results of the case study. The results are discussed in Section 5, and the main conclusions are summarized in Section 6.

2. Literature review

The current Danish government has changed the previous targets of achieving CO_2-free electricity and heat supply by 2035 and transport by 2050. Besides the target of reaching 30% renewables in final energy consumption by 2020 (according to the EU's climate and energy package from 2008) [22], the policy of the current government is to reduce greenhouse gas (GHG) emissions by 2020 by 20% compared to 2005 in sectors outside the ETS quota scheme (transport, agriculture and individual heating). Denmark is close to achieving these goals already [23]. The targets for 2030 are yet to be stated, but are expected to follow the EU goal of 30% GHG reductions by 2030 in non-quota sectors. The long-term target for 2050 is to become independent of fossil fuels, understood as producing enough renewable energy to supply total Danish energy consumption on an average annual basis [24].

Since nations and cities show different levels of climate ambition, ensuring the consistency of local and national strategies for CO_2 reduction remains a challenge [25]. Thellufsen and Lund [26] address this challenge for the case of Sønderborg municipality by comparing its municipal energy plan [11] to a national scenario with the maximum total biomass consumption set at 67 TWh. While in that case the biomass consumption extrapolated from the local to national level is sufficient, in this paper we have considered the amount of biomass calculated as dry matter, presented in Section 4.4.

As mentioned in Section 1 and 3, among the technologies of interest in this paper is a reversible solid oxide fuel cell, which can operate either in an electrolysis (power-to-gas) or fuel cell (gas-to-power) mode. Hydrogen from electrolysis can be further used for upgrading biogas (see also Section 3.2.2). Graves et al. [27] demonstrate that a solid oxide cell operated in a reversible mode is more stable and not as prone to microstructural degradation as a solid oxide cell operated in constant electrolysis mode, suggesting its flexibility and usefulness in balancing the electrical load. Götz et al. [28] compare several electrolysis technologies and their conversion pathways, focusing on power-to-methane, that is, water electrolysis followed by hydrogen conversion to methane. A recent review of power-to-gas pilot plants shows that the technology is promising, but still has to overcome its high costs and insufficient efficiency [29]. Jentsch et al. [30] demonstrate that power-to-gas technologies are useful elements of an optimized 85% renewable energy system in Germany. Qadrdan et al. [31] show that electrolysis and a subsequent hydrogen injection into the gas grid can reduce wind curtailment and provide operational cost savings for connected electricity and gas systems. The characteristics and assessment factors for various types of fuel cells are reviewed by Sharaf and Orhan [32]. Stambouli and Traversa [33] evaluate solid oxide fuel cells in particular. Dodds et al. [34] discuss the underappreciated possibilities of using fuel cells in the heating sector, and their applications for power generation are examined by Choudhury et al. [35].

Traditionally, energy technologies have been analyzed either on a national or plant/single project level, but together with the increasing role of city-scale climate action, the local focus has been appearing more frequently in the latest energy planning literature. Urban energy methodologies, model types and future research trends are extensively reviewed and critically discussed by [36,37], and a detailed literature review of this topic is out of scope of this article.

The geographical focus of literature dealing with local energy analyses is quite broad: Østergaard and Lund [38] and Sperling and Möller [39] analyze energy scenarios for the Danish municipality of Frederikshavn (of similar size to Sønderborg). Other examples of city scale analysis include energy scenarios for a Hungarian town [40], implementing heat pumps in the Danish municipality of Aalborg [41], energy policy modelling using MarkAL-TIMES [42], the future energy mix for Bologna, Italy [43], urban planning and optimal energy mix for a Chinese eco-city [44], analyzing low-carbon scenarios for Beijing, China, using the LEAP model [45], and using a multi-objective optimization model and time series analysis for energy planning for a town in Brazil [46]. Orehounig et al. [47] describe a method for integrating the energy hub concept at a neighborhood level within a Swiss village, which has a target of becoming fossil-fuel free, and evaluate the resulting energy scenarios on the basis of their penetration of renewable energy and savings of CO_2 emissions [48]. The prerequisites and consequences of energy autarky, i.e. no imports of energy resources are modelled for a rural region in Austria [49]. While different technologies are discussed in these studies, none of them deals with modelling both biomass conversion and reversible electrolysis in a municipality, hence the focus of this paper.

3. Methodology

3.1. The Sifre tool

Sifre is a techno-economic energy system modelling tool, developed by the Danish electricity and gas transmission system operator Energinet.dk [50]. *Sifre* is a mixed-integer linear optimization program, which represents energy flows and energy prices in all sectors of the specified energy system in discrete time steps. A detailed description of the tool and its validation has been published by Energinet.dk [50]. No peer-reviewed work has been yet published based on the results of the *Sifre* tool, though [51] has conducted analyses using data extracted from *Sifre* optimization runs.

The objective of the *Sifre* optimization program is to minimize the total operating expenses of the specified energy system over a period, while fulfilling the specified energy demand during all time steps in the same period. In all optimization runs performed for this work, the calculation period was one year with a time resolution of one hour, resulting in 8760 discrete time steps. The *Sifre* tool relies on the external optimization solver *Gurobi* [52] for solving the optimization problem. Original routines for post-processing and analyzing all *Sifre* model outputs of this work were implemented using the programming languages *Matlab* and *Python.*

Capital expenses are not yet included in the current version of *Sifre*, but they will be incorporated in future model developments. The annualized capital expenses for all new investments (performed after 2014) in energy conversion and storage capacity have been accounted for in this work by adding them to the results post-optimization, based on the installed capacities in each scenario (see Section 3.3.1). Investments performed in 2014 or earlier were assumed to be sunk costs and were not included in the calculation. The scrap value of existing investments was also set to zero. The specific capital costs assumed for each technology are shown in Table A.1 in Appendix A.

3.2. The model of Sønderborg municipality's energy system

Models of Sønderborg municipality's energy system for the years 2014 and 2029 were implemented in *Sifre*. 2029 was chosen because of the municipality's official goal of becoming CO_2 neutral by that year. Five scenarios for 2029, described in detail in Section 3.3, were investigated. Sections 3.2.2–3.2.7 describe all energy conversion pathways that are included in the 2029 scenarios. The structure of Sønderborg's energy system in 2014 was modelled and analyzed in order to compare the results of this modelling scenario with historical data and thereby calibrate the model. A schematic layout of the model for 2029 is shown in Fig. 2. It shows the model structure for Sønderborg's energy system in 2029, depicting the energy sources, conversion units, transmission and distribution networks and energy services and their interconnections. The energy flows within each distribution network are not constrained in the model.

3.2.1. Solid oxide electrolysis and fuel cells

The electrolyzers and fuel cells in the model are solid oxide cells, because their expected efficiency and costs are projected to be superior to those of alkaline electrolyzers [53–56]. Electrolysis takes place at 650–800 °C. A reverse process is conducted using a solid oxide fuel cell (SOFC), producing electricity, water and heat. It is assumed that the electrolyzer and the fuel cell form a reversible solid oxide cell that can alternate between operating in SOEC and SOFC mode [54]. The energy inputs, outputs and efficiency assumed for the electrolysis and fuel cell processes are listed in Table A.2 in Appendix A. No electrolysis or fuel cell capacity is included in the 2014 scenario. The hydrogen produced in the model is utilized as an input for the fuel cells and for upgrading biogas to synthetic natural gas (SNG) and reforming of syngas to methanol, allowing for a more efficient utilization of the energy obtained from the scarce residual biomass resources [13].

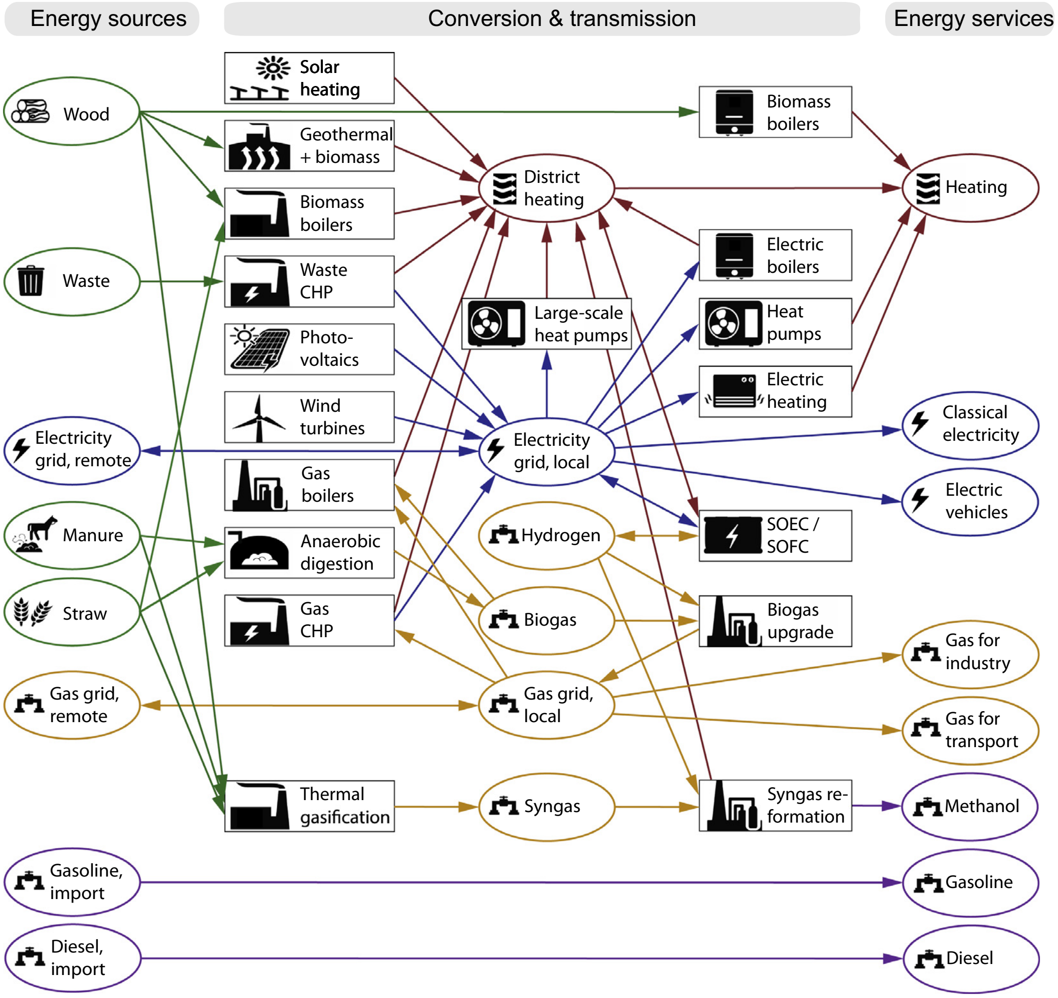

Fig. 2. A schematic representation of the model of Sønderborg municipality's energy system showing the components and energy flows of the model for the 2029 scenarios. Energy sources and imports to the municipality's energy system are shown on the left of the flow chart and energy services (demand) in the municipality are shown on the right. Rectangular fields denote energy conversion units and elliptical fields denote energy carriers and distribution networks. Biomass is indicated in green, electricity in blue, natural gas in orange and petroleum products in violet. For simplification, the schematic excludes energy storage facilities.

Hydrogen is not used as an end-user fuel in the model, since, following the municipal strategic energy plan, the transport fuel mix is kept the same as now.

3.2.2. Biogas production and upgrade

In the model, biogas can be produced using manure, straw and electricity. We assume a wet matter mass input composition of 81% mixed animal manure and 19% straw [57]. The energy inputs, outputs and the efficiency of the biogas production and upgrading processes are listed in Table A.2. In the model, biogas can either be used directly in gas boilers or be upgraded to natural gas quality. The biogas is upgraded through either a conventional CO_2 removal process or a more energy-efficient methanation [13]. The upgraded biogas is injected into the local gas distribution network in Sønderborg municipality. No biogas production or upgrade capacity is included in the 2014 scenario.

3.2.3. Syngas production and reformation to methanol

The model includes the thermal gasification of solid biomass and waste for the production of synthesis gas (syngas), which is reformed to methanol for use as a transport fuel, partly replacing the diesel and gasoline demand in Sønderborg municipality. In principle, methanol could be reformed further to dimethyl ether (DME), but this process is disregarded in this paper, since it is argued that methanol may be more suitable as an electrofuel than DME [21,58]. The energy inputs, output and efficiencies of the gasification and reformation processes are listed in Table A.2. No syngas production or reformation capacity is included in the 2014 scenario.

3.2.4. Individual heating supply

Approximately 428 GWh, corresponding to 53% of the final heat demand in Sønderborg municipality, was supplied by individual heating in 2014 [11]. Five types of individual heating supply are considered in the model; their energy inputs and efficiencies are listed in Table A.3. In the model, individual heat pumps are assumed to operate with a coefficient of performance (COP) equal to 3.0, in line with recommendations from [59].

3.2.5. District heating supply

The district heating system of Sønderborg municipality is composed of five separate district heating networks, which in the model are represented as one fully interconnected network. Approximately 383 GWh, corresponding to 47% of the end-user heat demand in the municipality, was supplied in the form of district heating in 2014 [11]. To satisfy this demand and accommodate the 24% network transmission losses, 504 GWh of heat were generated. The energy inputs, outputs and efficiencies of all district heating production units were obtained from the Danish Energy Agency [60].

The assumed energy inputs, outputs and efficiencies of all heat production units are listed in Table A.4. The largest combined heat and power (CHP) plant in the municipality is located in the city of Sønderborg and consists of two units: a waste incineration unit and a gas turbine unit. The remaining CHP plants are smaller gas turbine units. In addition, several boilers running on natural gas, biomass and electricity exist in the municipality. No biogas boilers were present in the municipality's energy system in 2014, but they are included in some of the 2029 scenarios.

The utility-scale heat pumps are assumed to operate with a coefficient of performance (COP) equal to 3 [61]. Production of the solar heating plants in the model was defined using an hourly time series based on the historical production of an existing solar heating facility in Sønderborg municipality in 2014 [62]. One of the district heating production plants in Sønderborg municipality is a geothermal plant, which is connected to an absorption heat pump and a biomass boiler. Based on [60] it is assumed that the 38% of energy inputs come from the geothermal unit and 62% from the biomass unit.

3.2.6. Electricity production and import/export

In 2014, only 16.3% of Sønderborg's total electricity consumption was generated within the municipal borders, using an incineration CHP plant, natural gas CHP plants, onshore wind turbines and photovoltaics [11]. The municipality is connected to the Western-Danish electricity grid with an effective transmission capacity of 270 MW [11]. In the model, no constraints in electricity flow within the distribution network of Sønderborg municipality are assumed.

The installed renewable electricity generation capacity in Sønderborg municipality in 2014 was 14.6 MW onshore wind turbines and 1.48 MW photovoltaics [63]. For the 2014 scenario, we used historical time series for wind and photovoltaic production in southern Denmark. For the 2029 scenarios, time series for wind and photovoltaic generation were provided by Energinet.dk [64].

3.2.7. Fossil fuel and natural gas import

All natural gas, gasoline, diesel and heating oil is imported in 2014 [11]. Sønderborg municipality is connected to the national gas transmission grid [11]. Natural gas is used in CHP plants and boilers and for industrial processes. In the 2029 scenarios, transport is partly based on natural gas. Diesel and gasoline are consumed by the transport sector and heating oil is only used for individual heating.

3.3. Scenario definitions

3.3.1. Scenario descriptions and installed energy capacities

The modelled scenarios are described in Table 1. The calibration scenario, labelled 0, represents the year 2014 and is based on historical data [11,60,63]. The five remaining scenarios A–E represent alternative options for the state of Sønderborg municipality's energy system in 2029. Scenario A seeks to emulate the strategic energy plan of Sønderborg municipality [11]. Scenario B represents a "Biomass" scenario in which fossil fuel-consuming plants have mostly been replaced by units that combust biomass. Scenario C represents an "Electrification" scenario in which fossil fuels have mostly

Table 1
Modelled scenarios and their descriptions.

Year	Scenario symbol	Scenario name	Description
2014	0	Model calibration	Sønderborg's energy system in 2014 - a comparison with historical data
2029	A	Municipal plan	Future scenario according to the current strategic energy plan of Sønderborg municipality [11,65]
2029	B	Biomass	Future low fossil-fuel scenario where biomass replaces fossil fuels, without any significant electrification (e.g. no utility-scale heat pumps)
2029	C	Electrification	Future low fossil-fuel scenario with a focus on electrification, where biomass consumption is kept close to the locally available limits
2029	D	Electrolysis	Same as the Electrification scenario, with the addition of gasification and solid oxide electrolysis for a more energy-efficient biomass utilization. All biogas upgrade is conducted through biogas methanation instead of CO_2 removal
2029	E	Reversible electrolysis	Same as the Electrolysis scenario, with the addition of reversible solid oxide cells for electrolysis and fuel cell operation

been replaced by electricity-consuming units, such as heat pumps. Scenario D ("Electrolysis") is an extension of scenario C, with the addition of hydrogen production from electrolysis and syngas production from biomass gasification. Scenario E ("Reversible electrolysis") is an extension of scenario D, with the assumption that the electrolyzers are also able to operate in fuel cell mode. Another difference is that natural gas boilers are only used in scenarios 0 and A, but are replaced by biogas boilers in scenarios B, C and D. Gas boilers are not used in scenario E. Please note that scenario A can be viewed as a compromise between scenarios B and C.

The installed capacities for each conversion unit across all scenarios can be seen in Table 2. The capacities in scenarios B–E were chosen by the authors using scenario A and the general scenario descriptions above as guidelines.

The installed capacities for solar heating, photovoltaics and onshore wind turbines equal those assumed in Sønderborg's strategic energy plan. Due to land-use considerations, we have assumed that further expansion of this production capacity is impossible, and the installed solar heating, photovoltaics and onshore wind capacity therefore remain constant throughout scenarios A–E. An expansion of coastal-near wind turbines beyond the strategic energy plan is assumed in scenarios C–E to partially compensate for the increased total electricity demand in these scenarios.

The pathway of biogas production and upgrade to natural gas quality through CO_2 removal is introduced in scenarios A–C. In scenarios D and E, all biogas upgrade is assumed to take place by biogas methanation. The pathway of syngas production, along with reformation to methanol, is only present in scenarios D and E. Hydrogen production is thus only needed in scenarios D and E, and no SOEC production capacity is applied in any of the other scenarios. Finally, the option of operating the solid oxide cells in fuel cell mode is only present in scenario E.

3.3.2. Locally available residual biomass resources

The locally available residual biomass resources in Sønderborg municipality are listed in Table A.5 in Appendix A. In scenarios 0 and A, the biomass consumption was not restricted. In scenarios C–E, the available biomass in the model was restricted based on availability for 2029. In 2014, the waste consisted of both local and imported municipal waste, and it is assumed in all 2029 scenarios that the import of waste can be regulated to match the demand. Table 10 in Section 4.4 shows a comparison of locally used biomass in each 2029 scenario and corresponding national amount of biomass.

3.3.3. Demand for energy services

Demand for energy services in the 2014 model scenario was based on historical data [11,60,63]. In scenario A it was based on Sønderborg's strategic energy plan [11], in scenarios B–E it was decided upon by the authors as an aspect of developing the scenarios, using scenario A and the general scenario descriptions from Section 3.3.1 as guidelines. Table 3 shows the assumed energy demand for each energy service type across all scenarios. The model optimizes operation against the demand for these energy services on an hourly basis according to the hourly demand distribution for each type.

District heating demand is higher in 2029 than in 2014 due to an anticipated conversion of some areas from individual heating to district heating, in line with the strategic energy plan. It remains constant in scenarios A–E. Consumption of individual gas and oil heating is significantly reduced in scenario A compared to 2014. In scenarios B–E gas and oil are not used for individual heating. Individual heating is primarily supplied by biomass boilers in scenario B and by heat pumps in scenarios C–E. Time series for the district heating demand profile were based on measured data for 53 single-family houses in Sønderborg, obtained from the municipality's district heating company [66]. The same heat demand profile was also assumed for individual heating.

Classical electricity demand, which includes all electricity demand except heat pumps, electric vehicles and electrolysis, is lower in 2029 than in 2014 and identical in scenarios A–E, as anticipated in the strategic energy plan. In scenarios A and B, the electricity demand of electric vehicles follows the projection from Sønderborg's strategic energy plan. Electricity demand for heat

Table 2
Total installed capacities for each type of conversion unit in the model, for all scenarios.

Conversion unit	Product	Installed capacity (MW)					
		0	A	B	C	D	E
Natural gas boilers	District heating	160.1	50.0	0.0	0.0	0.0	0.0
Biogas boilers	District heating	0.0	0.0	50.0	10.0	10.0	10.0
CHP (natural gas)	District heating	64.8	64.8	0.0	0.0	0.0	0.0
	Electricity	71.4	71.4	0.0	0.0	0.0	0.0
CHP (waste)	District heating	20.0	20.0	20.0	20.0	20.0	20.0
	Electricity	4.5	4.5	4.5	4.5	4.5	4.5
Geothermal + absorption heat pump	District heating	43.0	43.0	43.0	10.0	0.0	0.0
Biomass boilers	District heating	17.4	25.6	140.4	25.6	25.6	25.6
Electric boilers	District heating	8.0	8.0	8.0	8.0	8.0	8.0
Heat pump (utility-scale)	District heating	0.0	50.0	0.0	187.8	195.3	203.4
Solar heating	District heating	26.1	194.9	194.9	194.9	194.9	194.9
Biomass boilers	Individual heating	17.1	11.4	57.4	11.4	0.0	0.0
Electric heating	Individual heating	25.7	17.1	17.1	17.1	17.1	17.1
Natural gas heaters	Individual heating	57.1	21.2	0.0	0.0	0.0	0.0
Oil heaters	Individual heating	32.8	19.4	0.0	0.0	0.0	0.0
Heat pumps	Individual heating	6.0	11.4	6.0	52.0	63.4	63.4
Photovoltaics	Electricity	14.8	40.0	40.0	40.0	40.0	40.0
Wind turbines (onshore)	Electricity	14.6	30.0	30.0	30.0	30.0	30.0
Wind turbines (coastal-near)	Electricity	0.0	120.0	100.0	140.0	150.0	150.0
Solid oxide electrolyzer cells (SOEC)	Hydrogen	0.0	0.0	0.0	0.0	20.0	40.0
	District heating	0.0	0.0	0.0	0.0	0.4	0.8
Solid oxide fuel cells (SOFC)	Electricity	0.0	0.0	0.0	0.0	0.0	10.0
	District heating	0.0	0.0	0.0	0.0	0.0	1.5
Anaerobic digestion	Biogas	0.0	10.0	10.0	10.0	10.0	10.0
Biogas CO_2 removal	Natural gas	0.0	10.0	10.0	10.0	0.0	0.0
Biogas methanation	Natural gas	0.0	0.0	0.0	0.0	16.0	16.0
Gasifiers	Syngas	0.0	0.0	0.0	0.0	12.0	12.0
Syngas reformation	Methanol	0.0	0.0	0.0	0.0	10.0	10.0

Table 3
The annual demand for each type of energy service in the model.

Energy service	Demand in each scenario (GWh/year)					
	0	A	B	C	D	E
District heating	383	445	445	445	445	445
Individual biomass heating	39	26	187	26	0.0	0.0
Individual gas heating	199	74	0.0	0.0	0.0	0.0
Individual oil heating	116	68	0.0	0.0	0.0	0.0
Individual electric heating	53	41	41	41	41	41
Individual heat pumps (heat prod.)	21	40	21	182	208	208
Electricity (classical)	440	305	305	305	305	305
Electricity (transport)	0.1	19	19	34	34	34
Natural gas (industry)	279	279	279	279	279	279
Natural gas (transport)	0.0	30	30	0.0	0.0	0.0
Gasoline (transport)	230	155	155	155	115	115
Diesel (transport)	270	300	300	300	260	260
Methanol (transport)	0.0	0.0	0.0	0.0	80	80
Total energy demand	2030.1	1782	1782	1767	1767	1767

pumps is not a direct input parameter in the model; it is dictated by the end-user heat demand from individual and large-scale heat pumps. Time series for Danish classical and electric vehicle electricity demand were obtained from Energinet.dk [64]. Classical electricity demand time series for 2014 were based on measured data while time series for 2029 were based on simulations by Energinet.dk. Demand response has been excluded from this study.

The value and profile for industrial gas demand were obtained from Energinet.dk [64]. The industry gas consumption remains unchanged from 2014 to 2029. Some natural gas for transport is consumed in in scenarios A and B. The increase in electric vehicle energy demand in scenarios C–E compared to scenarios A and B comes from the assumption that the vehicles running on natural gas in scenarios A and B, switch to electricity in scenarios C–E, with a double efficiency compared to gas.

We assume that total demand for liquid transport fuels will decrease from 2014 to 2029, due to the increased energy efficiency of the vehicles. Total liquid transport fuel is the same in scenarios A–E. In scenarios D and E, methanol replaces some of the gasoline and diesel.

3.3.4. CO_2 emissions

The CO_2 emission factors recommended by the Danish Energy Agency [67] were used for calculating the total CO_2 emissions arising from fuel consumption for each scenario. The CO_2 emissions of electricity imports and exports from the Western Danish electricity grid are accounted for in the total CO_2 emissions value by adding or subtracting the corresponding amount of average CO_2 emissions in the Danish electricity generation mix: 270 kg/MWh in 2014 and 100 kg/MWh in 2029, in line with data and forecast from the Danish Energy Agency. Any indirect CO_2 emissions, such as those arising from the construction and scrapping of power plants, are excluded from the model, as such life-cycle analysis is outside the scope of this work.

Although CO_2 is not the only gas species responsible for the greenhouse effect, other greenhouse gases including water vapor, methane, nitrous oxide and ozone are excluded from the model. Furthermore, biomass, gasoline and diesel combustion releases NOx, but its quantification is beyond the scope of this paper. As CO_2 emissions are the largest contributor to the greenhouse effect globally, they have been selected as an environmental indicator in this work to enable direct comparison with existing data and climate targets for Sønderborg and with other energy planning literature that uses CO_2 emissions as an indicator.

3.3.5. Electricity, fuel and CO_2 quota prices

The electricity prices, fuel prices and CO_2 quota prices used in the model are shown in Table A.6 in Appendix A. The electricity price time series for 2014 is the historical electricity Nord Pool spot price in Western Denmark. The time series used for the 2029 scenarios come from Energinet.dk's scenario simulations [64]. The 2029 price time series match the wind and photovoltaic generation time series described in Section 3.2.6, as they originate from the same simulation. The prices of fossil fuels were inserted in the form of hourly time series in 2014 and as a constant (average) projected value in 2029.

3.4. Assessment indicators

This study aims to investigate how Sønderborg can become a low-CO_2 emitting municipality in 2029 in an energy-efficient and cost-effective way, given the limited locally available residual biomass resources. The scenario results were compared using four indicators described in Table 4. The total system socio-economic cost is the sum of the fuel cost, operation and maintenance (O&M) costs, the annualized investment costs for investments performed after 2014 and the CO_2 emission quota costs. Taxes and subsidies are excluded. The calculation of total net CO_2 emissions is described in Section 3.3.4. The total biomass consumption is the sum of the energy inputs from wood, straw, manure and waste in the model. The total system energy efficiency is the ratio of the total end-user energy outputs to the total primary energy inputs in the system.

These indicators were selected in order to assess the feasibility of the scenarios in terms of economy (total system socio-economic costs), energy efficiency (total system energy conversion efficiency), greenhouse effect impact (total CO_2 emissions) and sustainability (total biomass consumption relative to the locally available residual biomass resources). Since different indicators may be valued differently depending on a decision-making perspective, rather than determining and presenting performance values for the scenarios by means of an arbitrary choice of weighting

Table 4
Indicators used for comparing the results of scenarios A–E. All values are compared on an annual basis.

Indicator	Unit	Description
Total energy system socio-economic cost	€/year	The sum of the fuel cost, O&M costs, the annualized investment costs and the CO_2 emission costs
Total system CO_2 emissions	ton CO_2/year	Net CO_2 emissions arising from Sønderborg municipality's energy consumption
Total biomass consumption	%	Relative to the total of locally available residual biomass resources
Total system energy conversion efficiency	%	The ratio of the total energy outputs to the total energy inputs in the energy system

factors, we have chosen to present and compare the results in terms of four indicators, thereby treating all indicators as equally important.

The most feasible scenario is the one that best combines the lowest total socio-economic costs, the lowest total CO_2 emissions, a total biomass consumption close to or under the locally available residual biomass resources and the highest total energy system efficiency. Please note that the scenario results, expressed via the indicators, only reflect a comparison of the investigated scenarios and that we make no claim to have found a global optimum for the configuration of Sønderborg's energy system in 2029. The results are thus intended as guidelines for energy policy and energy system planning on a medium-sized northern European urban scale, and not as a manual for the exact configuration of such a system.

4. Results

4.1. Model calibration

A comparison between the results of scenario 0 and historical data for 2014 is shown in Table 5 for the main types of energy flows. A more detailed comparison of the model results with 2014 statistics on fuel consumption for district heating and individual heating can be seen in Tables A.7 and A.8 in Appendix A.

As shown in Table 5 (as well as Tables A.7 and A.8), the results of scenario 0 agree with historical data from 2014. The deviation between the model and the statistics regarding biomass consumption is partly due to the consumption of bio-oil for individual heating, which has not been included in the model. Coal and coke consumption has also been excluded from the model, as this only concerns brick factories and its inclusion would have increased the CO_2 emissions in scenario 0 by an estimated 5 kton/year, corresponding to 1%. The total energy consumption in the model and the statistics deviate by only 1.9%, making the model well calibrated for the present case and suitable for future analyses of the system.

4.2. Energy flows in the 2029 scenarios

Fig. 3 shows a Sankey diagram of all the energy flows in scenario A. Corresponding Sankey diagrams for scenarios B–E are shown in Figs. A.1–A.4 in Appendix A. Table 6 shows annual fuel consumption and electricity imports and exports for all scenarios. Table 7 shows the annual energy outputs of all energy conversion units in the model across all scenarios. A detailed comparison of the scenarios based on the indicators is conducted in Section 4.3.

As shown on the right of Fig. 3, about 33% of final energy consumption in Sønderborg municipality in 2029 is planned to consist of heat, of which 64% will be supplied by district heating. The share of heating in final energy consumption is substantially lower than in the calibration scenario due to anticipated improvements in building insulation and energy efficiency of the heat generation units. In all 2029 scenarios, Sønderborg has transitioned from importing most of its electricity demand to being a large electricity exporter. In scenario A, 49% of all electricity generated in Sønderborg is exported beyond the municipal borders. A significant portion of the electricity generation comes from the coastal-near wind turbines that play a central role in Sønderborg's strategic energy plan. While the total amount of biomass consumption in scenario A is smaller than in scenario 0, new conversion pathways such as anaerobic digestion and biogas upgrade are planned. In scenario A, natural gas imports are reduced by 34% compared to 2014. However, fuel imports for transport remain at the same level as in scenario 0.

As Table 6 shows, the main difference in the resulting fuel consumption among scenarios A–E concerns solid biomass: waste, wood and straw. For waste, it is highest in scenario A and decreases by 10% in scenario B, by 69% in scenario C and by 51% in scenarios D and E. The highest consumption of wood occurs in scenario B and is lower by 85% in scenario A, by 94% in scenario C and by 90% in scenarios D and E. Straw consumption is also the highest in scenario B and decreases by 76% in scenario A, by 94% in scenario C and by 68% in scenarios D and E.

As seen in Table 7, the main difference in the resulting outputs among scenarios A–E concerns wind energy and district heating production. The output of coastal wind turbines is the greatest in scenarios D and E and drops by 20% in scenario A, by 33% in scenario B and by 7% in scenario C. The electricity and heat output of the waste CHP is the largest in scenario A and lower by 10% in scenario B, by 69% in scenario C and 70% in scenario D and E. The geothermal-biomass boiler and the biomass boiler produces heat only in scenarios A and B. Utility heat pumps produce the biggest output in scenario C, and it is lower by 43% in scenario A, and by 2% and 1% in scenarios D and E, respectively. Methanation, SOEC, SOFC, gasification and syngas reformation are only represented in scenarios D and E.

4.3. Indicators

In the following, the results of all scenarios are presented and compared in terms of the indicators introduced in Section 3.4. Fig. 4 shows the annual energy inputs to the system by type and the annual end-use energy outputs by sector. The energy outputs are very similar in all 2029 scenarios, as the energy demands against which the model optimizes system's operation are very similar in all cases, as shown in Table 2. However, these demands are supplied using very different energy inputs in each of the scenarios A–C. The definitions of scenarios C–E differ more subtly and therefore their energy inputs are very similar.

Table 8 shows the results for the total energy efficiency indicator, defined as the ratio between annual total end-user energy outputs and annual total energy inputs. Most scenarios have a total energy efficiency greater than 1, because the heat pumps in the model yield 3.0 units of heat output for every unit of electricity

Table 5
A comparison of the end-use energy consumption between the model calibration scenario and statistics from 2014.

Energy type	Energy consumption (GWh/year)			
	Scenario 0	Historical data	Deviation (%)	Data reference
District heating	383.3	383.0	0.0	[68]
Electricity (classical)	440.0	441.0	0.0	[68]
Natural gas (non-district heating)	474.3	477.4	−0.6	[63]
Biomass (non-district heating)	43.3	48.2	−10.2	[63]
Oil, gasoline & diesel	606.9	622.8	−2.6	[63]
Coal and coke	0.0	13.6	−100	[63]
Total	1947.8	1986.2	1.9	

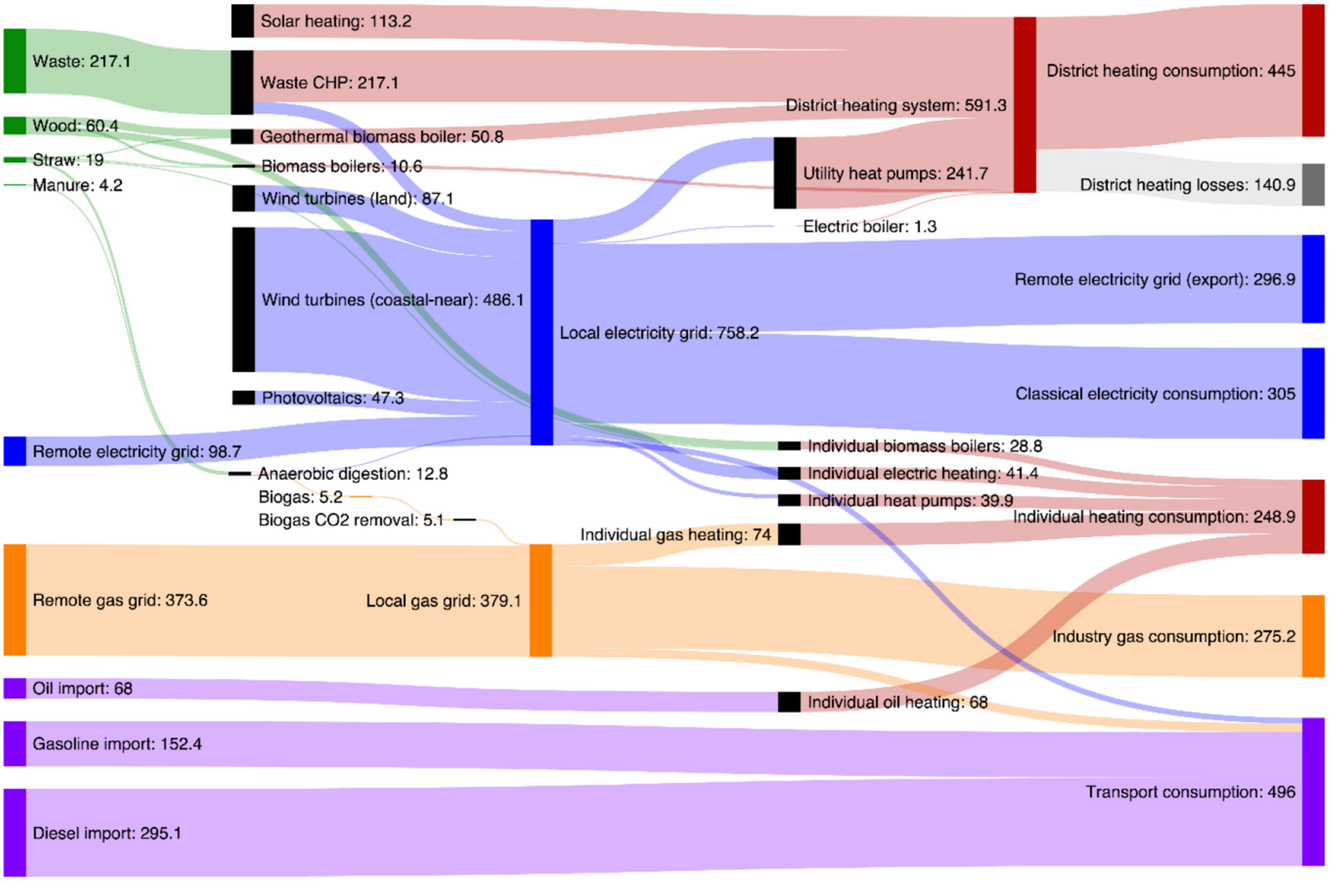

Fig. 3. A Sankey diagram of the model results of scenario A. The numbers denote the total energy outflow from each node. All numbers in GWh/year.

Table 6
The resulting fuel consumption and electricity imports and exports across all scenarios.

Type	Fuel consumption and electricity import/export (GWh/year)					
	0	A	B	C	D	E
Waste	218.0	217.1	194.6	67.2	106.5	105.7
Wood	164.7	60.4	393.2	24.4	40.4	40.4
Straw	32.0	19.0	79.1	4.4	25.4	25.7
Manure	0.0	4.2	4.2	0.0	2.6	2.7
Electricity imports	423.5	98.7	78.8	134.1	134.2	134.7
Electricity exports	0.0	296.9	279.0	265.2	281.6	268.6
Natural gas imports	565.6	373.6	299.5	275.2	270.3	270.1
Oil imports	115.0	68.0	0.0	0.0	0.0	0.0
Gasoline imports	226.2	152.4	152.4	152.4	113.1	113.1
Diesel imports	265.6	295.1	295.1	295.1	255.7	255.7

input. It is clear that scenario B (biomass) has the lowest total energy efficiency, hardly surprising given that this scenario has lowest heat pump capacity out of the 2029 scenarios. Scenario A (the municipal plan) is slightly more energy efficient than the reference scenario. Scenarios C–E, which are those with a high degree of electrification (including heat pumps) and low biomass consumption, are clearly most efficient out of the investigated scenarios and require by far the least energy inputs to fulfill end-user energy demand. Scenarios D and E are slightly less energy efficient than scenario C due to conversion losses in technologies such as solid oxide cells and methanol production from the thermal gasification of biomass.

Fig. 5 gives the annual socio-economic system costs for scenarios A–E. Scenarios D and E achieve the lowest costs (scenario E being less expensive by roughly 60,000 EUR), which is due to savings in fuel expenses and CO_2 emission costs. Moreover, the composition of the costs changes with increasing renewable energy share, electrification and energy efficiency, because the fuel costs become less important and the energy system becomes more capital cost intensive. As a result, scenario B has the lowest capital expenses and the highest fuel expenses, while the opposite is true for scenarios D and E.

Total annual CO_2 emissions are shown in Fig. 6. Emissions are substantially lower in 2029 than in 2014. This is due to large reductions in CO_2 emissions from the heating sector because of a change in the generation mix, and negative emissions from electricity generation in 2029 (as exports of low-CO_2 emitting electricity are assumed to offset Sønderborg's CO_2 emissions). In scenarios C–E, the CO_2 emissions from heat generation are eliminated. Transport and industry remain the main CO_2 emitters, as no large changes in fuel consumption are assumed in these sectors compared to the reference scenario. In scenarios D and E, some fossil

Table 7
The resulting outputs of all energy conversion units across all scenarios. The energy output for each type of individual heating is identical to the demand for the individual heating type, which is presented in Table 2 in Section 3.3.1.

Conversion unit	Output type	Energy output (GWh/year)					
		0	A	B	C	D	E
Wind turbines (land)	Electricity	29.2	87.1	87.1	87.1	87.1	87.1
Wind turbines (coastal-near)	Electricity	0.0	486.1	405.1	567.1	607.6	607.6
Photovoltaics	Electricity	14.0	47.3	47.3	47.3	47.3	47.3
Solar heating	District heating	16.5	113.2	123.1	123.3	123.7	123.7
Waste CHP	District heating	173.7	173.7	155.7	53.8	52.9	52.3
Waste CHP	Electricity	39.2	39.1	35.0	12.1	11.9	11.8
Geothermal biomass boiler	District heating	170.7	50.8	144.0	0.0	0.0	0.0
Biomass boiler	District heating	46.8	10.6	166.1	0.0	0.0	0.0
Gas boilers	District heating	91.4	0.0	0.0	0.0	0.0	0.0
Utility heat pumps	District heating	0.0	241.7	0.0	424.3	414.5	421.6
Electric boilers	District heating	5.2	1.3	1.2	0.0	0.0	0.0
Anaerobic digestion	Biogas	0.0	5.2	5.2	0.0	3.1	3.3
Biogas CO_2 removal	Natural gas	0.0	5.1	5.1	0.0	0.0	0.0
Biogas methanation	Natural gas	0.0	0.0	0.0	0.0	5.2	5.5
SOEC electrolysis	Hydrogen	0.0	0.0	0.0	0.0	17.8	42.1
SOFC fuel cells	Electricity, heat	0.0	0.0	0.0	0.0	0.0	20.5
Gasification	Syngas	0.0	0.0	0.0	0.0	81.3	81.3
Syngas reformation	Methanol	0.0	0.0	0.0	0.0	79.0	79.0

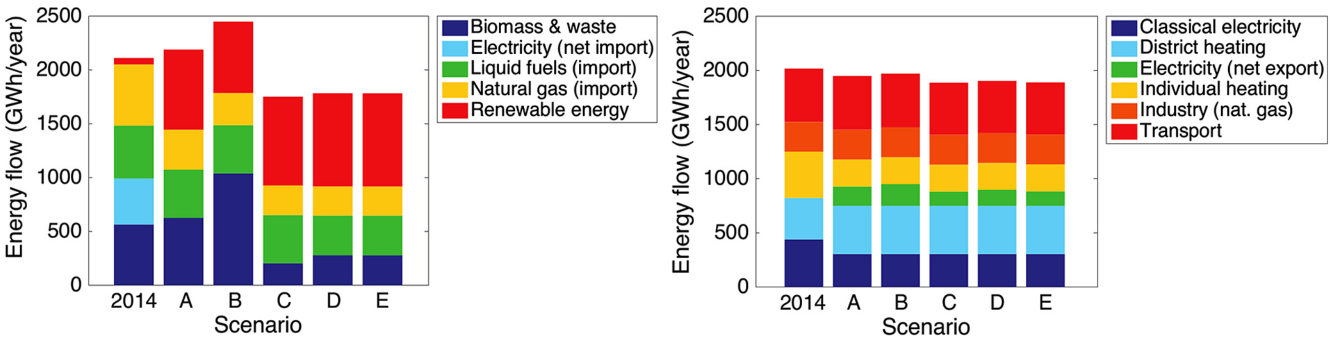

Fig. 4. Total annual energy inputs by energy source (left) and total end-user energy outputs by sector (right).

Table 8
Total annual energy inputs, total annual end-user energy outputs and total system energy efficiency (the ratio between total outputs and total inputs) for all scenarios.

Scenario	Total energy inputs (GWh/year)	Total end-user energy outputs (GWh/year)	Total system energy efficiency
0 (calibration)	1961	2017	1.029
A (municipal plan)	1864	1947	1.045
B (biomass)	2081	1970	0.974
C (electrification)	1643	1887	1.149
D (electrolysis)	1680	1903	1.133
E (reversible electrolysis)	1679	1890	1.126

fuel consumption by transport has been replaced by methanol produced from biomass. This leads to a slight decrease in CO_2 emissions from transport and makes these two scenarios the best ones in terms of minimizing total annual CO_2 emissions.

Table 9 shows total annual biomass consumption for each scenario as a percentage of the locally available residual biomass resources (shown in Table A.5 in Appendix A). In all scenarios, wood constitutes a dominant proportion of biomass consumption and wood consumption in none of the scenarios is strictly within the limits of locally available resources. The requirements regarding the local sustainability of biomass consumption are highly dependent on local and national policies. If the aim is to be completely self-sufficient in using biomass for energy purposes, scenario C is the best, even though it shows very low utilization of resources with better availability than wood: manure and straw. If, however, it is acceptable to supplement the locally available biomass resources with limited imports, then scenarios D and E perform very well, followed by A. These scenarios utilize manure and straw better than scenario C. The best utilization of manure and straw in total occurs in scenario B, though this scenario would require vast imports of wood, thereby decreasing its sustainability.

To summarize, scenario C performs best in terms of total energy efficiency of the system, closely followed by scenarios D and E. Scenario C also performs best in terms of keeping biomass consumption within the locally available limits, again followed by D and E. Scenarios D and E perform best in terms of annual total system costs, followed by scenario B. Scenarios D and E perform best in terms of total annual CO_2 emissions, followed by scenario C. Scenarios C-E perform better than scenario A on all indicators.

4.4. Local versus national biomass consumption

Although the focus of this study is the municipality of Sønderborg, a question arises: if all Denmark was to use the same amount of biomass per capita, that each scenario requires, how great would Danish national biomass consumption for energy purposes be? Table 10 shows the amount of biomass used in each scenario and how it corresponds with the required national level.

Total future Danish biomass production potential was calculated at between 7.2 and 11.1 million tons of dry matter [71]. As Table 10 shows, depending on the assumptions regarding the types

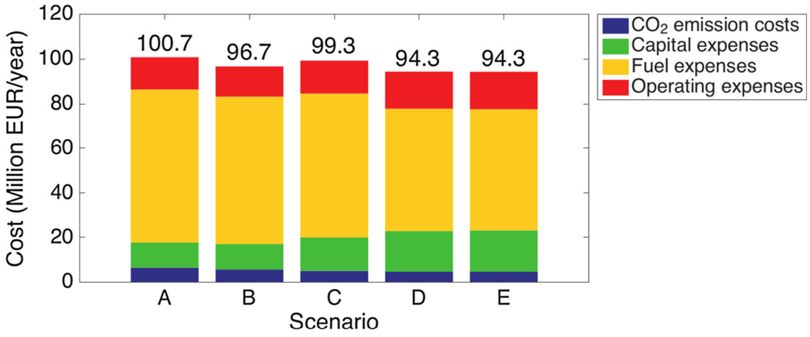

Fig. 5. Total annual socio-economic system costs in scenarios A–E.

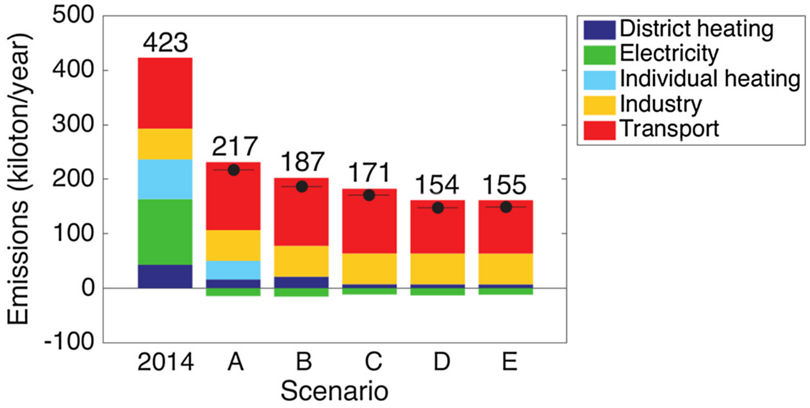

Fig. 6. Annual CO_2 emissions by sector in each scenario. In scenarios A–E, the electricity sector in Sønderborg municipality has negative CO_2 emissions due to its net exports of electricity.

Table 9
Annual biomass consumption as a percentage of the annual local biomass resource of each type (measured in terms of energy content).

Biomass type	2014	A	B	C	D	E
Manure	0.0%	8.1%	5.7%	0.03%	3.5%	3.7%
Straw	36.5%	8.1%	25.0%	1.4%	8.0%	8.1%
Wood	1003%	393.6%	2070%	128.5%	212.8%	212.8%

of biomass used and their energy content, the nation's biomass resource would suffice only in case of scenarios C–E and partly A (only if very high energy content of the biomass used is assumed). Substantial imports would be required to cover the high biomass demand in the case of scenarios A or B. Denmark is rather rich in residual biomass resources, with substantial amounts of residual biomass arising from agriculture and pig farming. If a country such as Denmark is predicted to be unable to meet its biomass demand for energy purposes without imports, therefore it is very likely that the same situation could arise in many other regions and countries that share the Danish municipalities' plans of transitioning to biomass combustion for heat and electricity generation. In the long run, such a development could lead to higher biomass prices and reduced security of supply.

4.5. Heat pump and electrolyzer operation

The hourly resolution reveals the dependency between the prices and the operation of heat pumps, electrolysis and fuel cells. Fig. 7 depicts hourly electricity and district heating prices, excluding taxes and subsidies (socio-economic costs), for the whole of 2029 in scenario E (reversible electrolysis). While electricity prices are an input to the model, district heating prices are calculated based on the fuel cost, the O&M costs and the heat demand. As

Table 10
Comparison of locally used biomass in each scenario and corresponding national amount of biomass. As of 2016, Sønderborg municipality had 74,732 inhabitants [69] out of a total Danish population of 5,717,000 [70].

Scenario	Unit	A	B	C	D	E
Locally used amount	GWh	625	1000	200	250	250
Per capita consumption	GWh/inhabitant	0.008	0.013	0.003	0.003	0.003
Corresponding national amount	GWh	47,813	76,500	15,300	19,125	19,125
Corresponding national dry matter amount (assuming 17.5 GJ/t)	t	9,835,817	15,737,143	3,147,429	3,934,286	3,934,286
Corresponding national dry matter amount (assuming 9 GJ/t)	t	19,125,200	30,600,000	6,120,000	7,650,000	7,650,000

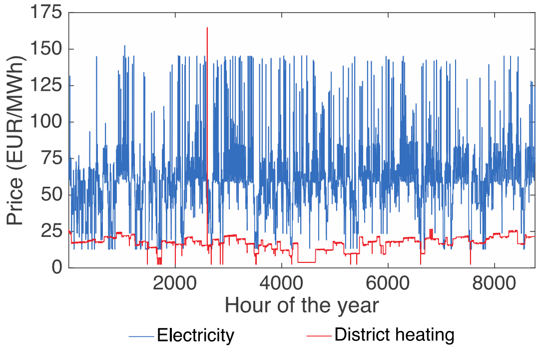

Fig. 7. Electricity and district heating prices (excl. taxes and subsidies) over the year (EUR/MWh).

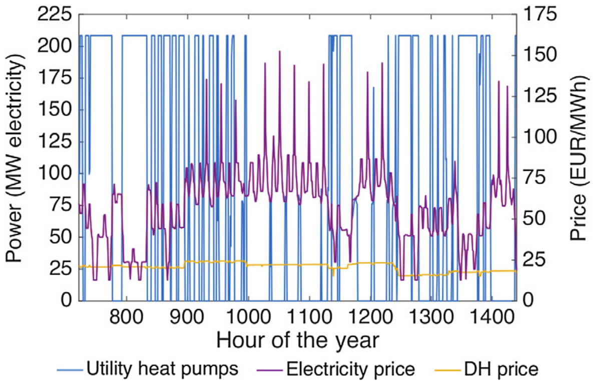

Fig. 8. Hourly operation of heat pumps in relation to the electricity and district heating prices over February. The input power of the utility heat pumps is shown on the left y-axis, while the electricity and district heating prices are shown on the right y-axis.

Fig. 7 shows, the calculated district heating prices are rather stable over the year, slightly decreasing around mid-year, in the hottest months, where only hot water is needed. The reason for this price drop is that the waste incineration plant located in Sønderborg can produce heat more cheaply than other units due to its fuel being free of cost. The electricity spot price varies over the year, with no clear seasonal trend.

Fig. 8 compares district heating heat pump operation with electricity and district heating prices over hours 720–1440 of the year, corresponding to the month of February. While district heating prices are quite stable in the winter season at around 23 €/MWh, electricity prices vary significantly between 12 and 150 €/MWh. The feasibility of operating the heat pumps is mainly governed by the electricity price, with the heat pumps being used when the electricity price falls below 70 €/MWh, but ceasing operation when electricity price rises above that value. In scenarios with heat pumps and electric boilers, the fluctuating electricity prices thus have a large and rapid effect on the merit order of the district heating production units in the system.

A similar effect is observed for the operation of the solid oxide electrolysis and fuel cells. Fig. 9 compares the operation of these units with electricity and district heating prices over hours 720–1440 of the year, corresponding to the month of February. The operation of electrolysis and fuel cells is highly dependent on electricity price, with cells running in electrolysis mode in periods of low electricity prices and in fuel cell mode in periods of high electricity prices. It is, however, not possible to identify exact electricity price for cells starting and stopping operation because it also depends on electricity demand and wind and solar production in the given hour. The great dependence of the operation of heat pumps and SOEC/SOFC on the fluctuating electricity price clearly illustrates the need for advanced smart control mechanisms to achieve a cost-efficient operation of the future energy system not only in the model runs, but also in reality.

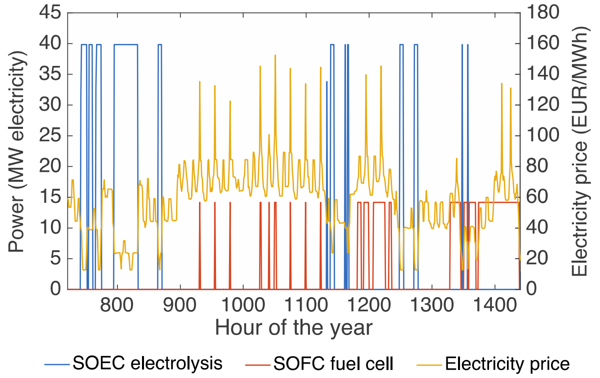

Fig. 9. Hourly operation of electrolysis and fuel cells in relation to electricity price over the month of February. The input power of the electrolysis cells and the output power of the fuel cells is shown on the left y-axis, while the electricity price is shown on the right y-axis.

4.6. Sensitivity analysis

4.6.1. Biomass price changes

Fig. 10 shows how CO_2 emissions and annual system costs change when different biomass prices are implemented in the model. Changing the biomass price does not influence the overall scenario rank order for CO_2 emissions, therefore scenarios D and E still perform best on these criteria. However, it slightly affects scenario B, due to its high consumption of biomass. A 30% decrease in the biomass price would cause a 7% drop in CO_2 emissions in the case of scenario B. This is caused by the large biomass-fired capacity in scenario B, which enables natural gas and waste production capacity to be replaced with biomass capacity in case of lower biomass prices, thus reducing CO_2 emissions. Conversely, other scenarios are not able to change the operation depending on biomass prices, because their biomass-fired production capacity is not as large as in scenario B.

If biomass prices were to increase, the total annual system costs of scenario A would grow by 5%. In scenario B, a 30% biomass price increase would cause 4% higher system costs, while a 30% biomass price decrease would lower the total annual system costs by 3%, making this scenario the most cost-effective choice in the case of lower biomass prices. This again is because of the high dependency of scenario B on the biomass resource. Thus, as increasing the biomass price by approximately 22% or more influences the overall scenario rank order for CO_2 emissions, scenarios D and E would not be feasible in this case.

4.6.2. Electricity price changes

Fig. 11 depicts how CO_2 emissions and annual system costs change when different electricity prices are implemented in the model. Changing the electricity price does not influence the overall scenario rank order for CO_2 emissions, so scenarios D and E still perform best on this criterion. In the case of 30% lower electricity prices, 4% lower CO_2 emissions in scenarios A, D and E, and 3% lower CO_2 emissions in scenarios B and C would occur. 30% higher electricity prices would cause CO_2 emissions to rise by 3% in scenario A and by 6% in case of scenarios C, D and E, due to increasing generation from fossil fuels.

Changing the electricity price influences total system costs in all scenarios to some extent, especially scenarios A and B, where

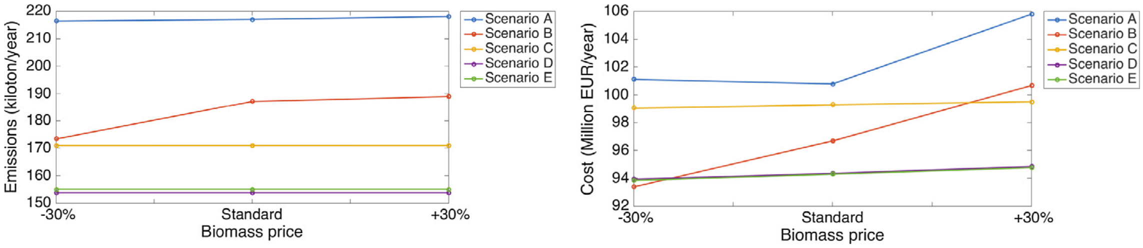

Fig. 10. Changes in total annual CO_2 emissions (left) and total annual system costs (right), depending on the price of biomass.

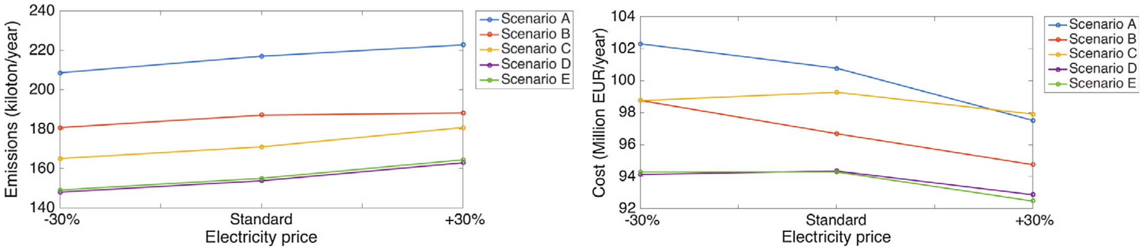

Fig. 11. Changes in total CO_2 emissions (left) and total annual system costs (right), depending on the price of electricity.

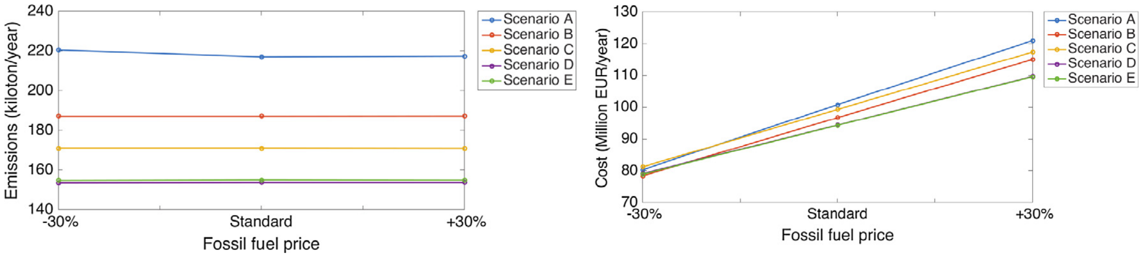

Fig. 12. Changes in total CO_2 emissions (left) and total annual system costs (right), depending on the price of fossil fuels.

electricity exports are the greatest. Sønderborg is a net exporter of electricity in all future scenarios; moreover, the revenue from exported electricity is also higher when the prices are high. The change in system costs is most visible in scenario A: an increase of 30% in the electricity price causes a 3% total system cost reduction.

4.6.3. Fossil fuel price changes

Fig. 12 shows how CO_2 emissions and annual system costs change, when higher and lower fossil fuel prices are implemented in the model. Fossil fuel price changes do not influence CO_2 emission levels, because fossil fuel power plants, individual heating and transport are used in the same way irrespective of price of fossil fuels. Besides, the demand for individual heating and transport fuel has to be satisfied even when fuel prices are high.

The changes in fossil fuel price have a large impact on total system costs. Scenario A results in 20% higher or lower total system costs in the case of fossil fuel price changes, scenario B: 19%, scenario C: 18%, scenario D and E: 16%. Moreover, the scenario rank order changes: with lower fossil prices, scenario B performs best, while with increasing prices, scenario E is more feasible. These cost fluctuations are significant, but clearly scenarios D and E show less dependence on fossil fuel prices, which is a benefit given the unavoidable uncertainty in future prices.

5. Discussion

Municipalities are usually not energy system stakeholders as such, but they have a right to influence their energy mix: for example, in Denmark, municipal heat planning projects have to show socio-economic feasibility before being carried out. While the socio-economic perspective does not mirror actual private economic conditions, by excluding changing taxes and subsidies, it does show the viability of the scenarios and indicates that the results are transferable to other countries with different forms of taxation. In reality, to make investments happen, a private-economic analysis would be required from the point of view of customers and investors. Further work could include taxes and subsidies to develop scenarios in private-economic terms.

We have chosen not to rank the scenarios formally by weighting the indicators and calculating an aggregated performance value for each scenario, in order to treat all indicators as equally important. This approach also increases the transferability of our method, as other municipalities could assess their energy scenarios using these indicators. A quantitative analysis could give a more definitive answer to the case at hand, but it would not necessarily lead to more robust conclusions due to the unavoidable arbitrary assumptions behind the weighting factors in such an analysis. The conclusions of this study are therefore rather qualitative in nature, emphasizing general findings that can be used as guidelines in strategic energy system planning in cities globally.

With lower fossil fuel prices, scenario B (biomass) performs best, while with higher fossil fuel prices, scenario E (reversible electrolysis) is most feasible. Given the volatility of fossil fuel prices, the risk of choosing these scenarios is rather high. The biomass scenario would cost the least if biomass prices were to decrease substantially. Taking into consideration developments on the world biomass market, however, this situation is unlikely.

The world biomass market, especially for wood pellets, is increasing: for example, in 2013 the EU was responsible for 85% of energy-related global wood pellet consumption [72]. Moreover, Denmark is likely to import a substantial part of its biomass consumption, becoming susceptible to changing global market prices [73]. The situation may be similar in other countries with insufficient biomass resources. In the case of less common technologies, for example electrolysis and fuel cells, the dependence on future energy and climate policies may mean that in the short and middle term the investment costs may stagnate or even slightly increase. These possible volatilities show the importance of a maintaining varied energy system where costs and risks are spread equally among the system elements.

Our results point at electrification as a feasible option for future energy systems. As mentioned in the introduction, no other studies analyzing the application of SOEC or SOFC in a city have been identified. However, considering biomass scarcity, electrolysis was deemed an important element of the future transportation sector in [74,21]. Lund [16] has reviewed a body of literature showing the potential of large heat pumps in the Danish energy system and calculated is as being up to 4 GW of thermal capacity. The scenario analyses for a town of Frederikshavn [38] have also found a heat pump suitable for the urban system. Since Denmark is a large wind energy producer, only Danish studies were compared with our results. However, it cannot be excluded that more peer-reviewed work will occur from other regions of the world in the near future, together with increasing share of renewables.

Analyzing benefits of reversible electrolysis in detail could be a topic for further work. For example, the value of the reversibility of the solid oxide electrolysis cell can be quantified as the total cost difference between scenarios D (electrolysis) and E (reversible electrolysis). Scenario E costs approximately 60,000 €/year less than scenario D. The option of operating the electrolyzers reversibly as fuel cells therefore leads to an added value of 1470 €/MW/year of installed electrolyzer electricity input capacity. Moreover, the addition of reversible electrolysis is useful in balancing supply and demand in the electricity system. This value could be estimated either through comparison with an alternative technology or by analyzing current prices for frequency containment reserve. The alternative technology for reserve capacity could be the cheapest peak power technology, for example natural gas turbines. However, they may not be able to provide the rapid frequency reserve service that reversible electrolysis could. Another approach might be to analyze the capacity payments for electricity system performance markets today. For example, current payments on frequency containment reserve (primary reserve) in Denmark correspond to about 60,000 EUR annually [75]. Although this service is the highest paid, there may be many other suppliers to compete with, and cheaper suppliers may enter the market in the future, so this estimate is uncertain. The potential revenues from such grid services were not taken into account when modelling solid oxide cells in this work.

We assumed that the import of waste can be regulated to match the demand. In Sønderborg in 2014, waste came from both local and imported municipal sources. However, with increasing recycling rates and the new waste incineration plants being built in Europe, waste might become a “scarce resource” in the future. Investigating a scenario, in which importing waste from outside a municipality is forbidden could also be a topic for further studies.

The outcomes of the scenario modelling may also be influenced by the relatively high share of district heating in Sønderborg in 2029: 64% of heat supply, which makes the results less applicable to cities where there is no district heating. However, a system consisting of heat pumps, SOEC and SOFC could also be installed on a neighborhood scale, not requiring an extensive district heating coverage.

In all scenarios, changes in heat consumption caused by, for example, heat savings in the form of improved insulation, etc. have been assumed to remain the same as in the municipal plan scenario A, but it could be relevant to assess various shares of heat savings in further work.

Transport and industry remain the main contributors of CO_2, and analyzing these sectors in more detail should be emphasized in further work. The future transportation is likely to be highly electrified, but it will almost certainly also require biofuels. It has been suggested that producing biofuels from biomass, waste (via e.g. thermal gasification) and hydrogen (from electrolysis) could be beneficial [13,14,21,58,76,77]. This work focuses on the use of hydrogen as an input for the fuel cells, for upgrading of biogas to synthetic natural gas and for reforming of syngas to methanol rather than transport fuel, since, according to municipal expectations, transport will be one of the toughest sectors to make sustainable in a short timeframe. Thus, we assume that hydrogen vehicles will not achieve a breakthrough by 2029 and that transport will rather shift towards electricity. However, the possible relevance of hydrogen cars in the remoter future certainly remains open.

6. Conclusion

Unlike national governments, many cities around the globe are currently active on the climate action scene, making the topic of local climate mitigation and ways to achieve it extremely relevant. Since Scandinavia is very experienced in local energy planning, we envisage that our results can serve as guidance for the analyzed case and other municipalities.

This article has outlined how the Danish municipality of Sønderborg can approach its CO_2 reduction goals by 2029 in five different ways. By constructing and modelling energy scenarios, we investigated the effects of selected energy conversion pathways on the energy system, including total system costs, total energy system efficiency, net system CO_2 emissions and total biomass consumption.

While from the private-economic perspective biomass combustion is among the cheapest renewable energy technologies for Danish utilities to invest in at the present time [78], the modelling has demonstrated that a number of other pathways are available if the aim is to achieve low CO_2 emissions in a cost-effective way, if local sourcing of biomass is impossible. Nonetheless, these pathways result in different outcomes in environmental and economic terms. Considering all the indicators, scenarios D (electrolysis) and E (reversible electrolysis) are most feasible from a system cost and CO_2 emission perspective, while providing substantial biomass consumption savings. Moreover, scenario E shows that the addition of reversible electrolysis actually results in decreased total system cost, even when the benefits of balancing supply and demand in the electricity system are disregarded. The sensitivity analysis has shown that scenarios D and E perform best even if changes are implemented in electricity and fossil fuel prices. Only a drop in biomass prices would make scenario B (biomass) the least costly.

These observations lead to the conclusion that the municipal plan (scenario A) is inferior to the electrified scenarios (C–E) when measured on the indicators selected in this study. We therefore suggest that by considering a greater variety of fuel mixes (with more electrification and novel energy conversion technologies), Sønderborg and similar municipalities design a more energy- and cost-effective energy system while keeping biomass consumption close to the locally available limits and substantially lowering CO_2 emissions. Another conclusion is that moving towards an electrified energy system is a better long-term solution than towards a biomass-based energy system. Furthermore, the inclusion of novel and advanced energy conversion pathways such as solid oxide electrolysis and fuel cells, biomass gasification and methanol production help to further decrease the total system costs and CO_2 emissions of an electrified energy system. These conclusions hold true for all municipalities and regions with a similar energy demand to Sønderborg and similar amounts of biomass resources relative to the scale of the energy system.

The significance of this study lies in demonstrating that, by complementing combustion with modern energy conversion technologies, it is possible to achieve climate goals cost- and energy-efficiently. Modelling of different conversion technologies applied within all sectors of the municipal energy system enables their feasibility to be assessed, bridging the gap between R&D and implementation. Although solid-oxide electrolysis and fuel cells are used in industry, our results indicate that their application outside of industry is also worth considering as one of the aspects of a sustainable city in the future. If utilities start experimenting with novel energy conversion technologies more often, we expect that new benefits and challenges will be found, further developing the renewable energy industry.

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Appendix A

See Tables A.1–A.8 and Figs. A.1–A.4.

Table A.1

Economic data for the energy conversion units in the model. The capital expenses for new investments were scaled based on the energy conversion capacity using the following equation for the economies of scale: $c_{scaled} = c_{standard}\left(\frac{P_{scaled}}{P_{standard}}\right)^{\alpha}$, where c denote the capital expenses for the standard capacity and the scaled capacity, P denote the standard capacity and the scaled capacity and α is the scaling exponent. The exponent takes on values from 0 to 1 based on how well the capital expenses for each energy conversion technology scale with capacity.

Conversion unit	Specific CAPEX (€/MW)	Standard capacity (MW)	Scaling exponent	Variable OPEX (€/MWh)	Fixed OPEX (€/MW)	Plant lifetime (years)	Data source
Natural gas boilers	100,000	10	0.7	0.00	3700	35	[61]
Biogas boilers	100,000	10	0.7	3.20	3700	35	[61]
CHP (natural gas)	600,000	100	0.7	0.00	0.00	25	[61]
CHP (waste)	8,500,000	75	0.7	0.00	173,170	20	[61]
Geothermal + absorption HP	800,000	12	0.7	5.40	0.00	20	[61]
Biomass boilers	800,000	12	0.7	5.40	0.00	20	[61]
Electric boilers	75,000	10	0.7	0.50	1100	20	[61]
Heat pump (utility)	575,000	5.0	0.7	2.68	3918	20	[61]
Solar heating	250,512	1.0	1.0	0.57	0.00	20	[61]
Individual biomass boilers	642,308	0.013	1.0	0.00	2000	20	[59]
Individual electric heating	800,000	0.005	1.0	0.00	10,000	30	[59]
Individual gas heaters	480,000	0.013	1.0	0.00	10,800	22	[59]
Individual oil heaters	293,333	0.023	1.0	0.00	1611	25	[59]
Individual heat pumps	1,000,000	0.01	1.0	1.34	0.67	20	[59]
Photovoltaics	1,100,000	0.9	1.0	34.00	0.00	30	[61]
Onshore wind turbines	1,290,000	0.9	1.0	14.00	0.00	20	[61]
Offshore wind turbines	2,430,000	5.0	1.0	19.00	0.00	25	[61]
SOEC electrolyzers	590,000	5.0	0.85	0.00	15,000	20	[61]
SOFC fuel cells	0	0.9	0.85	0.00	2,68	20	[61]
Anaerobic digestion	3,400,000	12.3	0.7	31.00	0.00	20	[61]
Biogas CO_2 removal	292,950	12.0	0.7	0.00	7324	15	[61]
Biogas methanation	674,748	18.9	0.7	0.00	16,869	20	[61]
Gasifiers	555,436	100	0.7	0.00	44,435	25	[61]
Syngas reformation	1,884,966	100	0.7	0.00	56,549	20	[61]

Table A.2

The energy inputs, outputs and efficiencies (defined as energy outputs divided by the energy inputs) of all electrolysis, fuel cell, gas and liquid fuel production processes that are included in the model. The energy input fractions refer to the energy contents. Lower heating values are used. In the processes that yield heat as a byproduct, the heat is utilized in the district heating network.

Conversion process	Energy inputs	Energy outputs	Efficiency	References
Electrolysis (SOEC)	Electricity (85%) Heat (15%)	Hydrogen	82% (total)	[57]
Fuel cell (SOFC)	Hydrogen (100%)	Electricity Heat	60% (electricity) 95% (total)	[57]
Anaerobic digestion	Manure (32.7%) Straw (65.6%) Electricity (1.7%)	Biogas (65% CH_4, 35% CO_2)	40% (total)	[61,79]
Biogas CO_2 removal	Biogas (93%) Electricity (7%)	SNG	92% (total)	[61]
Biogas upgrade	Biogas (59.4%) Hydrogen (40.6%)	SNG	91% (total)	[61]
Gasification	Wood (40%) Waste (40%) Straw (20%)	Syngas Heat	82% (syngas) 92% (total)	[61]
Reformation to methanol	Syngas (100%)	Methanol Heat	68% (methanol) 93% (total)	[80]

Table A.3
The energy inputs and efficiencies for all types of individual heating included in the model. In all cases, the only energy output is heat for space heating and domestic hot water supply.

Conversion unit	Energy inputs	Efficiency	References
Gas boilers	Natural gas (100%)	100%	[59]
Oil boilers	Heating oil (100%)	100%	[59]
Biomass boilers	Wood (85%), straw (15%)	80% (2014), 90% (2029)	[59]
Electric heating	Electricity (100%)	99%	[59]
Heat pumps	Electricity (100%)	COP 3.0	[59]

Table A.4
The conversion units for district heating production in the model. The energy inputs, outputs and efficiency of each type of unit are listed.

Conversion unit	Energy inputs	Energy outputs	Efficiency	References
Biomass boilers	Wood Straw	Heat	100%	[60]
Geothermal abs. heat pump + biomass boiler	Geothermal Wood Straw	Heat	100%	[60]
CHP (natural gas)	Natural gas	Heat, electricity	80%	[60]
CHP (waste)	Waste	Heat, electricity	100%	[60]
Natural gas boilers	Natural gas	Heat	100%	[20]
Biogas boilers	Biogas	Heat	100%	[60]
Electric boilers	Electricity	Heat	100%	[60]
Solar heating	Solar energy	Heat	–	[60]
Heat pumps	Electricity	Heat	COP 3.0	[60]

Table A.5
The locally available residual biomass in Sønderborg municipality. For the 2014 scenario, values corresponding to the year 2009 were used, due to lack of more recent data. The values for 2029 are based on a scenario forecast for the availability of biomass for energy purposes in Denmark [81].

Biomass type	Availability in 2014 (GWh/year)	Availability in 2029 (GWh/year)	Reference
Wood	39	46	[71]
Straw	207	771	[71]
Manure	180	183	[71]
Total	426	1000	

Table A.6
Electricity and fuel prices used in the model for years 2014 and 2029. The electricity price refers to the Western Danish (DK1) electricity spot price. Time series with an hourly resolution were used as an input for the price of electricity in 2014 and 2029, as well as for the price of fossil fuels in 2014. The 2029 electricity price time series are from a model forecast made by Energinet.dk. In the case of hourly time series, the average price level of the year is shown in parenthesis in the table.

Fuel	Unit	Price 2014	Price 2029	Reference
Electricity	€/MWh	2014 time series (avg. 30.68)	2029 time series (avg: 58.09)	[64]
Wood	€/GJ	6.68	7.71	[82]
Straw	€/GJ	4.40	4.40	[82]
Manure	€/GJ	2.93	2.93	[83]
Natural gas	€/GJ	2014 time series (avg: 6.11)	8.82	[64,82]
Waste	€/GJ	0	0	[83]
Gasoline	€/GJ	2014 time series (avg: 22.36)	34.02	[84,82]
Diesel	€/GJ	2014 time series (avg: 21.32)	30.60	[84,82]
Heating oil	€/GJ	2014 time series (avg: 20.65)	29.64	[84,82]
CO_2 emissions	€/ton	6.04	27.38	[82]

Table A.7
A comparison of fuel consumption for district heating between the model calibration scenario and statistics from 2014.

Type	Scenario 0	Historical data	Deviation	Data reference
Natural gas	91.4	93.5	−2.2%	[68]
Waste	218.0	212.5	+2.6%	[68]
Wood (including bio-oil)	128.2	123.7	+3.6%	[68]
Straw	25.4	24.4	+4.1%	[68]
Solar energy	16.6	15.7	+5.7%	[68]
Electricity	5.3	10.4	−49.0%	[68]
Total	484.9	485.7	1.6%	

Table A.8
A comparison of fuel consumption for individual heating between the model calibration scenario and statistics from 2014.

Type	Scenario 0	Historical data	Deviation	Data reference
Natural gas	199.2	199.4	−0.1%	[65]
Heating oil	115.1	116.1	−0.9%	[65]
Wood	33.0	33.8	−2.4%	[65]
Straw	6.0	6.2	−3.2%	[65]
Heat pumps (thermal output)	21.0	21.2	−0.9%	[65]
Electric heating (thermal output)	53.0	53.5	−0.4%	[65]
Total	427.3	430.2	−0.7%	

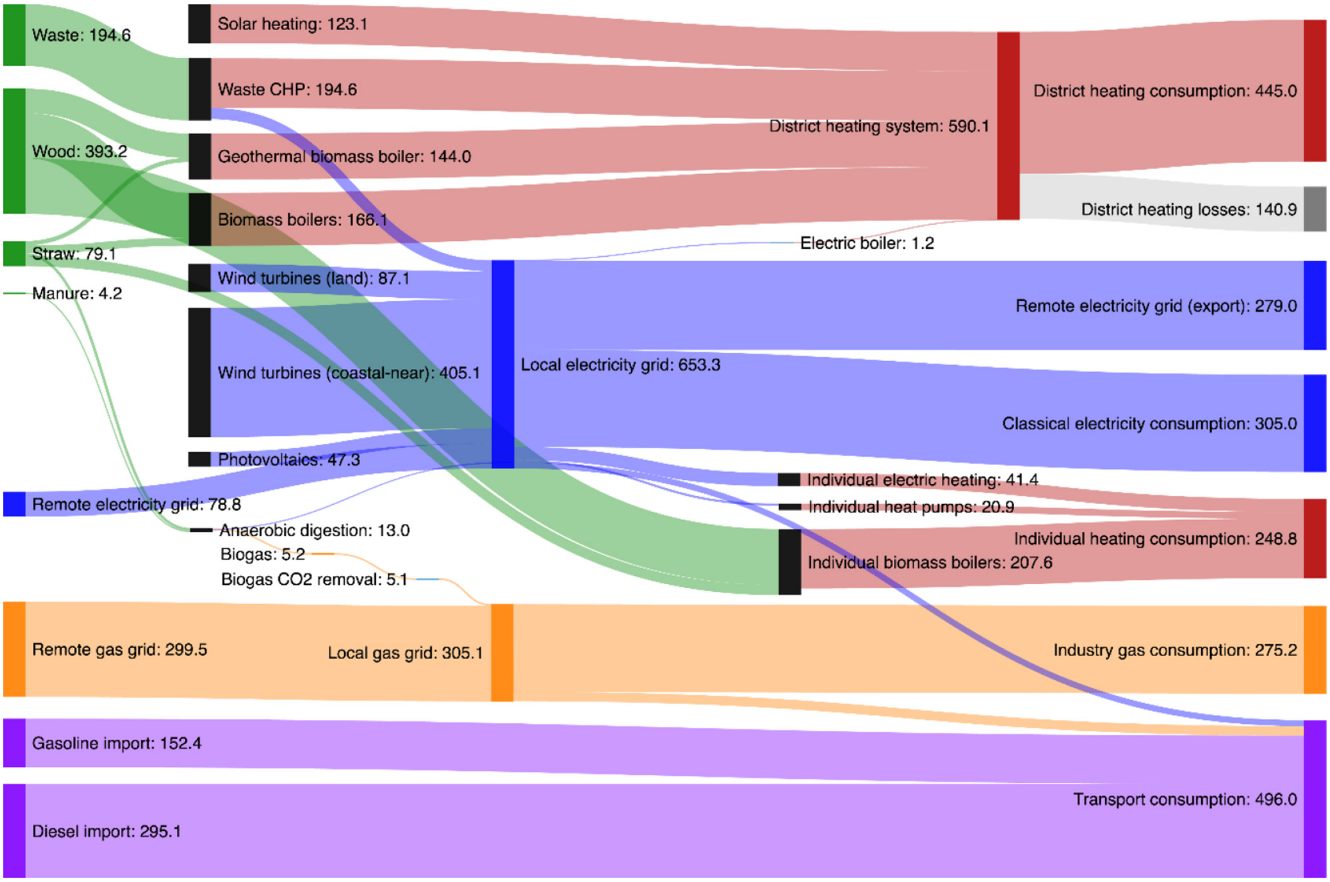

Fig. A.1. Sankey diagram of the model results of the scenario B. The numbers denote the total energy outflow from each node. All numbers in GWh/year.

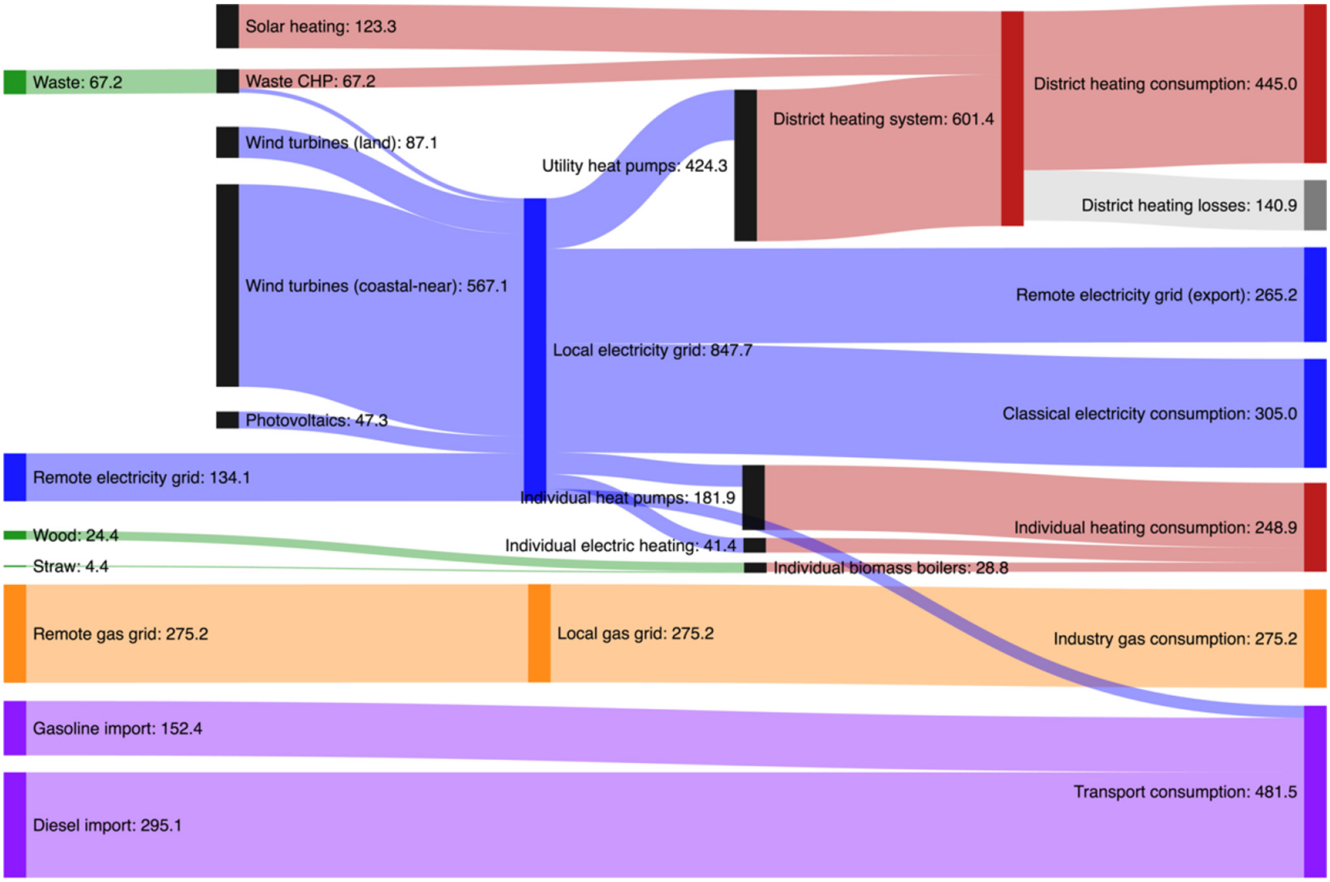

Fig. A.2. Sankey diagram of the model results of the scenario C. The numbers denote the total energy outflow from each node. All numbers in GWh/year.

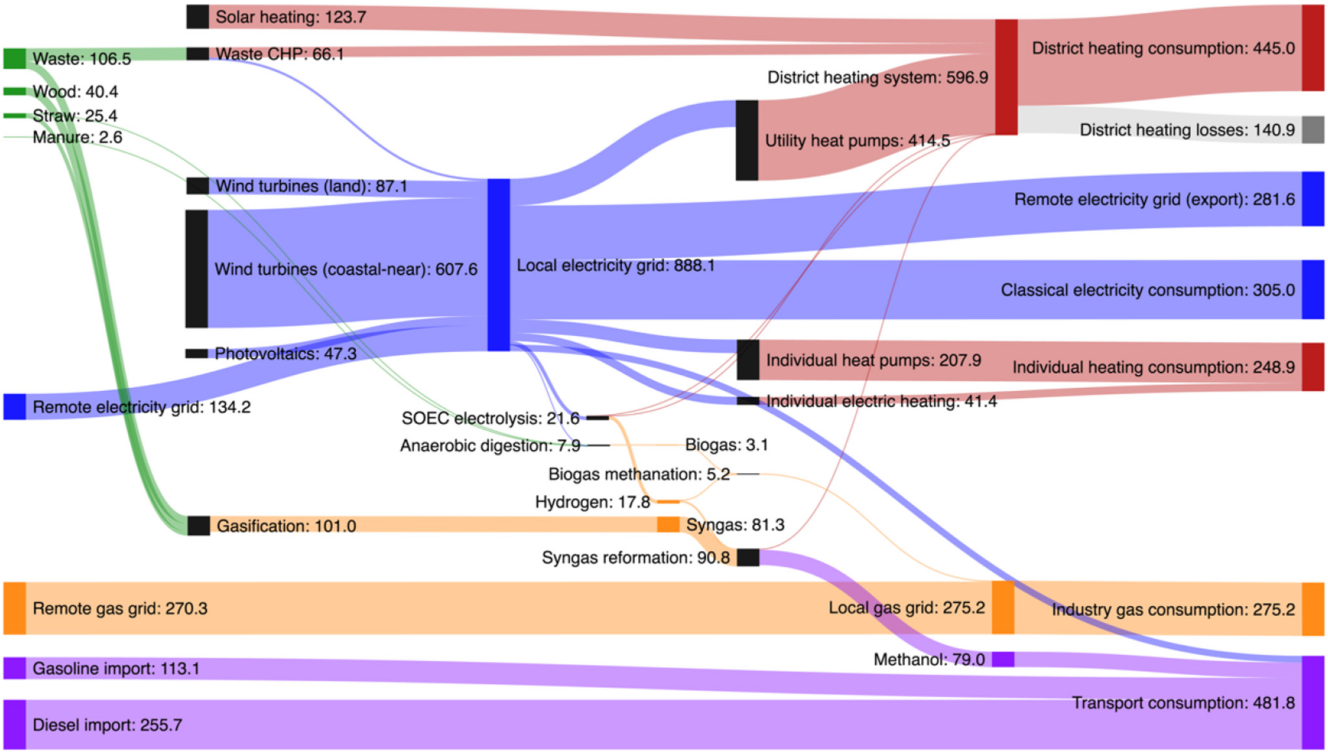

Fig. A.3. Sankey diagram of the model results of the scenario D. The numbers denote the total energy outflow from each node. All numbers in GWh/year.

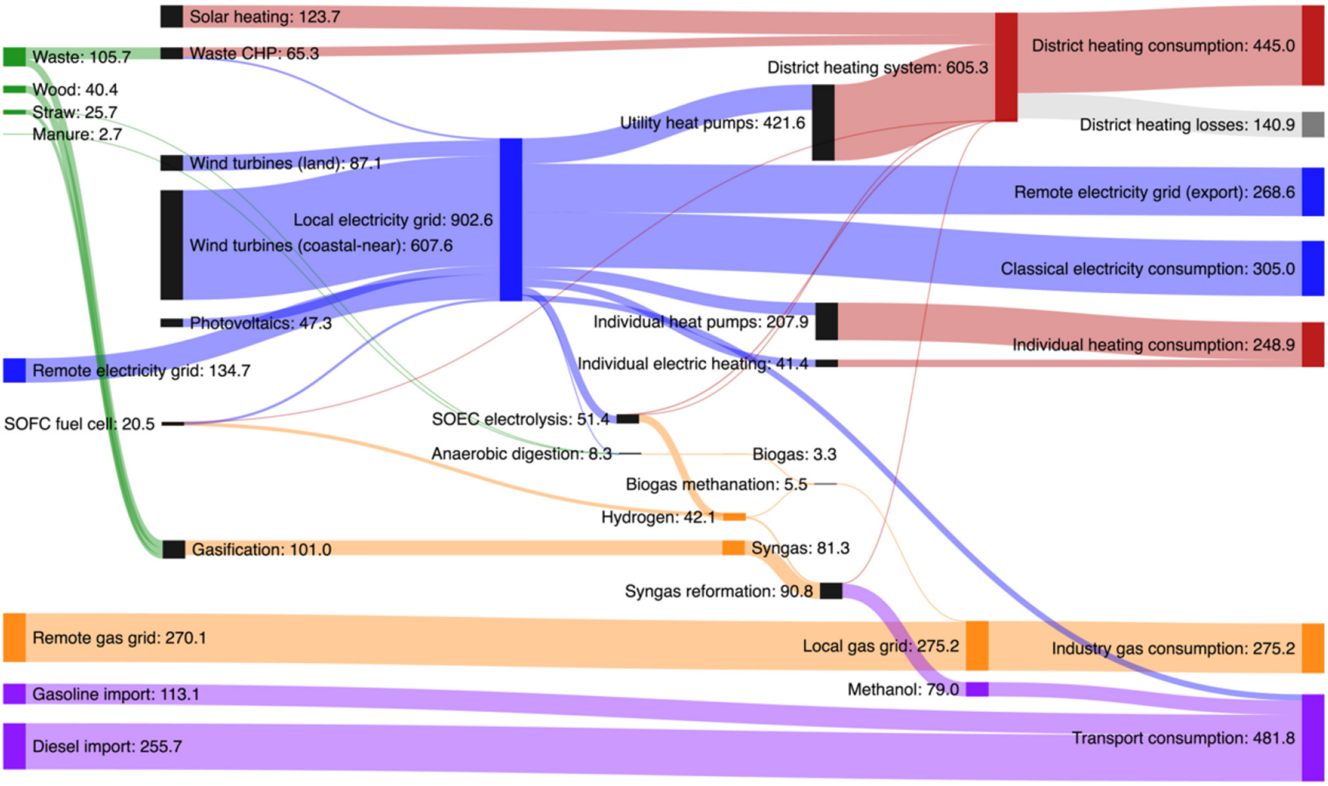

Fig. A.4. Sankey diagram of the model results of the scenario E. The numbers denote the total energy outflow from each node. All numbers in GWh/year.

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Paper B: Scenarios for sustainable heat supply and heat savings in municipalities - The case of Helsingør, Denmark

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Scenarios for sustainable heat supply and heat savings in municipalities - The case of Helsingør, Denmark

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ABSTRACT

Local climate action is not only a domain of large cities, but also smaller urban areas that increasingly address climate change mitigation in their policy. The Danish municipality of Helsingør can achieve a substantial CO_2 emissions reduction by transforming its heat supply and deploying heat savings. In this paper, we model the heating system of Helsingør, assess it from a simple socio- and private-economic perspective, develop future scenarios, and conduct an iterative process to derive a cost-optimal mix between district heating, individual heating and heat savings. The results show that in 2030 it is cost-optimal to reduce the heating demand by 20–39% by implementing heat savings, to deploy 32%–41% of district heating and to reduce heating-related CO_2 emissions by up to 95% in comparison to current emissions. In 2050, the cost-optimal share of district heating in Helsingør increases to between 38 and 44%. The resulting average heating costs and CO_2 emissions are found to be sensitive to biomass and electricity price. Although the findings of the study are mainly applicable for Helsingør, the combined use of the Least Cost Tool and modelling with energyPRO is useful in planning of heating and/or cooling supply for different demand configurations, geographical region and scale.

1. Introduction

Increasingly, urban areas are leading the way for energy efficiency and CO_2 emissions reduction actions. Currently, heating constitutes almost half of the total European energy consumption [1]. In Denmark, heat supply planning is one of the areas, where municipalities enjoy relatively significant influence, especially in relation to district heating [2]. Our case study, Helsingør (also known as Elsinore) is located in the northeastern part of the Zealand island, about 50 km from the Danish capital, Copenhagen. Helsingør has an area of 119 km^2 and has approximately 62,000 inhabitants, resulting in the population density of 522 inhabitants/km^2, which is about 13 times less than Copenhagen (6846 inhabitants/km^2) [3]. Helsingør municipality has been involved in regional strategic energy planning efforts and is currently identifying the range of its local climate action. The municipality aspires to reduce its CO_2 emissions by 20% in 2020, reach a level of one tonne of CO_2 eq./inhabitant in 2030 and become CO_2 neutral in 2050 [4]. Heating in Helsingør emits about one third of the total CO_2, so implementing heat savings in buildings, switching oil- and natural gas-based individual supply to renewables or expanding the district heating network (which in the future is expected to be primarily based on renewable fuels) could help Helsingør achieve its climate mitigation goals.

One of the most common approaches to promoting local climate initiatives is the strategic energy planning (SEP). The Danish Energy Agency defines SEP in the following way: “Strategic energy planning in the municipalities is about long-term planning. The municipality can contribute to a long-term development towards a fossil-free energy supply and other municipal and national climate and energy related goals. SEP encompasses all types of energy supply and demand in all sectors (households, municipal and other public service, private service, industrial production and transport)” [5]. In Europe, Strategic Energy Action Plans (SEAPs) are promoted through the Covenant of Mayors (CoM). SEAPs focus on buildings, equipment/facilities and urban transport, but also on local electricity production and local heating/cooling generation. Industry is on the other hand not a target sector [6]. The first SEAPs show how the Covenant signatories will reach their commitments by 2020. In May 2014, the signatories of the CoM agreed to reduce their GHG emissions with 170 Mt CO_2 eq., which equals 28% of their total emissions and 15% of the EU GHG emissions reduction target

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Nomenclature

Sub- and superscripts

a, c, u, h	geographical area, construction period, use and heating source of the buildings, respectively
i	iteration number

Symbols

ADM	administration costs
AR	heated area of buildings (m^2)
CAP	capacity of a heat supply system (in the case of district heating (DH), including heat exchangers) needed to supply enough heat on the coldest day of the year (at −12 °C)
CO2Q&T	CO$_2$ quota purchase and CO$_2$ tax
CRF	Capital Recovery Factor
DHC_A, DHC_B	district heating costs from perspective A and B, respectively
DHPR	district heating production
eff	efficiency of the heat supply system
ELSAL	electricity sales (in CHP plants)
ENT	energy taxes
HC	annuitized heating costs in the municipality (EUR/kWh)
HD, HS	specific heating demand and reduction of specific heating demand (heat savings), respectively (kWh/m^2)
INV, O&M, FUEL	components of annuitized heating costs related to investments, operation and maintenance, and fuel, respectively
INVC, FIXOM, VAROM, FC	investment costs (EUR/kW heat), fixed operation and maintenance costs (EUR/kW heat) and variable operation and maintenance costs (EUR/kWh heat), and fuel costs (EUR/kWh input fuel), respectively
$INVC_A$, $INVC_B$	annuitized network and capacity investments in DH using discount rate 2% and 0.99%, respectively
MT	methane tax
NHPC	net heat production cost of the modelled plant
NOXT	NOx tax
SUB	subsidies
VAT	Value Added Tax of 25%

Abbreviations

CHP	combined heat and power
CoM	Covenant of Mayors
DH	district heating
GIS	geographic information systems
LCT	Least Cost Tool
MSW	municipal solid waste
SEAP	Strategic Energy Action Plan
SEP	strategic energy planning

[7]. This article identifies cost-efficient and renewables-based heating supply as part of developing a strategic energy plan for the municipality of Helsingør.

Developing a SEAP involves establishing a baseline emissions inventory including an energy balance. However, when focusing on the energy sector it may be beneficial to conduct more detailed system analyses taking into account the fluctuations in demand and production, which we handle here using the energy system analysis tool energyPRO (see also section 3.1).

In the literature, various urban energy models have been reviewed by Refs. [8,9]. The works concentrating specifically on local heat planning include: using statistical methods to determine district heating feasibility in a Russian city [10], using a spreadsheet model and an optimization model for heat supply planning in a Danish housing community [11], modelling design and operation of a distributed energy system and a decentralized district heating network with an optimization model [12], quantitative scenario analyses of the socio-economic feasibility of energy renovations and renewable energy supply in Copenhagen area [13] and determining an optimal dispatch of large-scale heat pumps in Copenhagen using Balmorel model [14].

Modelling of the balance between heat savings and heat supply has been conducted, for example by Merkel et al. [15], who focus on soft-linking models for building stock, decentralized heat supply and energy optimization. Åberg [16] uses a linear optimization model to investigate the changes in CO$_2$ emissions, heat production and electricity co-generation depending on incremental heat demand reductions in Swedish district heating systems. Zvingilaite [17] incorporates heat saving investments into an optimization model of the Danish heat and power sector. Hansen et al. [18] compare the use of levelized costs of heat and an energy system analysis tool to calculate the feasible levels of heat supply and savings in selected European countries.

Geographic Information Systems (GIS) data for Denmark have been applied in peer-reviewed literature before. For instance, GIS data has been used to map Danish heat consumption by Petrović and Karlsson [19], Nielsen and Möller [20] and Sperling and Møller [21]. The energyPRO tool has been used in industry and in several peer-reviewed publications, for example to compare energy storage systems [22], analyse the operation of CHP (combined heat and power) plants on electricity markets [23,24] and their possibilities for balancing services in Denmark [25] and Germany [26]. Moreover [27], has used energyPRO for conducting an energy system analysis of electricity, heat and transport systems of a Hungarian town.

In this paper, we model Helsingør's heating system, assess it from a socio- and private-economic perspective, develop future scenarios, and conduct an iterative process of heating cost curve analysis and energy modelling to derive optimal supply and savings mix. As a result, the following research questions are answered:

- Which future energy systems setups for Helsingør are viable?
- What levels of district heating and heat savings are feasible given various scenarios?
- How sensitive are the results to changes in biomass and electricity prices?

The novelty of this paper lies in linking a detailed representation of heat savings in the building stock and district heating modelling using energyPRO through an iterative calculation conducted in a spreadsheet-based Least Cost Tool. Our methodology allows identifying optimal mix of heat savings, district heating expansion and individual heat supply, given a specific policy scenario. Since this work is part of the progRESsHEAT [28] project, our analyses will also contribute to the municipal energy policy development in Helsingør and other municipalities in Europe.

While a combination of a GIS tool and energyPRO has already been used by Nielsen and Möller [29], our work is novel in the way it provides a holistic methodology to derive the optimal mix of district heating (including expansion), individual heating and heat savings, which are intertwined and modelled dynamically. Moreover, two perspectives are considered: a simple socio-economic and a private-economic (see also section 2.4).

2. Input data

2.1. Current energy system

District heating in Helsingør municipality is currently supplied from a natural gas-fired CHP and several boilers located within its boundaries, and from a municipal solid waste (MSW) incineration plant Norfors and natural gas units located in nearby Hørsholm. In energyPRO, two district heating grids are modelled: one for Helsingør municipality and the other for Norfors (supplying Helsingør and several other municipalities), connected with a bidirectional heat capacity transmission line. Individual heating (modelled in the Least Cost Tool) mainly consists of oil and natural gas boilers and few heat pumps and biomass boilers.

2.2. Local renewable energy resources

The locally-sourced energy crops and forest wood potential for energy production in Helsingør municipality is 44.5 GWh [30]. The solar energy available is up to 162 GWh on roofs and 139 GWh within agricultural area [30]. The possible heat sources for large-scale heat pumps are: a nearby lake, wastewater or seawater [30], as well as low-temperature industrial excess heat, amounting for 100 GWh potential [31]. Additionally, there is potential for air-to-water heat pumps.

2.3. Techno-economic data

The energy content of fuels, based on standard factors from the Danish Energy Agency [32], is shown in Table 1.

In district heating modelling, electricity and heat capacities are derived from the Danish Energy Producers Count and applied efficiencies and costs of similar technologies from the Technology Catalogue developed by the Danish Energy Agency [33]. The investments and O&M costs of individual heating technologies are based on the Technology Catalogue for individual plants [34]. Economy of scale is taken into consideration by having lower capacity costs for large units in e.g. multi-family buildings.

Fuel prices for both DH and individual heating (excluding taxes) are shown in Table 2. For 2030, they are projected by the Danish TSO Energinet.dk [35]. For 2050, they are based on Eurostat's Energy price statistics [36] and European Commission's EU Reference Scenario [37].

The electricity price profile for 2030 is created by scaling the average hourly spot electricity price profile (2011–2015) for Eastern Denmark to the average price (excl. taxes) forecasted by Energinet.dk in 2030: 57.4 EUR/MWh [35]. The electricity price profile for 2050 is created by scaling the average price profile (2011–2015) to the average price (excl. taxes) forecasted for 2050 in Denmark (67.7 EUR/MWh), based on [36] and [37]. The electricity price for individual heat pumps is not represented as hourly time series, but an average yearly price, using the aforementioned values.

Table 1
Energy content of fuels.

Fuel	Value	Unit
Natural gas	0.04	GJ/Nm^3
Wood chips	9.3	GJ/t
MSW	10.6	GJ/t

Table 2
Fuel prices excl. taxes in 2030 and in 2050.

Fuel type	Year 2030	Year 2050
	Price (EUR/MWh)	Price (EUR/MWh)
Natural gas	2.67	3.28
Wood chips	2.16	3.39
Oil	63.0	73.0

2.4. Scenarios and perspectives

This study focuses on two years: 2030 and 2050, representing a mid- and long-term future. For all the scenarios, the following results (indicators) are calculated for the municipality of Helsingør: heat supply mix, heating costs, share of district heating and heat savings, and CO_2 emissions (see section 4).

The scenarios for 2030 are modelled from two perspectives: a simple socio-economic (denoted with “A”) and a private-economic (denoted with “B”). The scenarios for 2050 are evaluated only from a simple socio-economic perspective due to the uncertainty of long-term projections of tax policies. The term “perspective” refers only to the used interest rate and inclusion or exclusion of taxes and subsidies in the heating costs, so the technical system boundaries (district heating and individual heating supply in Helsingør) remain the same. The purpose of examining the two perspectives is to understand whether the cost-optimal results differ if we include or exclude current taxes and use different rates and is a step towards modelling policy interventions for increasing renewables and energy savings in the heat supply.

According to the Danish Energy Agency, socio-economic analyses can be used to determine “the most appropriate way to achieve energy policy objectives” [38], such as CO_2 emission targets. Our analyses do not encompass wider socio-economic consequences, such as employment or public acceptance. We define the simple socio-economic perspective as one used by a policy-maker to assess certain costs for society, i.e. where investments are discounted with a socio-economic rate of 2% [39] and only some costs borne by heat producer are included (see Eq. (1)).

We consider the private-economic perspective as one of a private investor - it includes energy taxes and subsidies and applies the following discount rates: 0.99% for investments in district heating plants and grid, 2.18% for heat savings and heat installations in large buildings (e.g. public offices) and 4.46% for investments in heat savings and heat installations in small buildings (e.g. single/multi-family houses). We assume 1% yearly inflation. In this perspective, discount rates are different for the three categories, because their current conditions for loan taking are also different. Except for district heating, which in Denmark is characterised by a possibility of taking inexpensive municipal loans, the private-economic discount rate is higher than the socio-economic rate, because it includes inflation and industry-specific risks.

The private-economic discount rate for district heating investments is calculated based on the assumption that the investment is financed partly from a municipal loan (currently 1.5%) and partly from a municipal overhead (0.5%) [40]. For the individual heating and heat savings the available private-economic discount rate is adjusted for the effect that part of the investment (33%) is deducted from income tax (assuming income tax of 50%), i.e. the reduction in income tax is reflected in the reduced interest rate. For large buildings, we assume that 80% is a loan based on equity and 20% is the equity. For small buildings, the assumption is that 100% is a loan based on the equity of the house.

Eq. (1) and Eq. (2) show the cost components in district heating cost calculation depending on the perspective taken (A or B). This cost is applied further to the Least Cost Tool (see section 3.2), where the balance between all heating supply types and heat savings in each geographical area is calculated. Heating cost components are somewhat different for individual heating and district heating. While usual costs, such as fuel, operation and maintenance and investment costs are incorporated in both heat supply types, the cost of district heating in Denmark additionally depends on administration costs (e.g. employment), energy taxes and subsidies.

$$DHC_A = \frac{(FC + FIXOM + VAROM + INVC_A + ADM + CO2Q\&T + MT + NOXT - ELSAL)}{DHPR} \tag{1}$$

$$DHC_B = \frac{(FC + FIXOM + VAROM + INVC_B + ADM + CO2Q\&T + MT + NOXT - ELSAL + ENT - SUB)}{DHPR} \tag{2}$$

The VAT (Value Added Tax) is added only in the private-economic analysis, on top of DHC_B (see also section 3.2).

The tax and subsidy rates applied in district heating modelling are shown in Table 3. In the individual heating sector, the private-economic fuel prices are the final prices charged by the fuel distributor, i.e. include fuel taxes and are based on current prices for natural gas, fuel oil and wood pellets.

Table 4 shows the scenarios and perspectives analysed in this study. In 2030, three scenario types are investigated: BAU, RES and HP, each from a simple socio- and private-economic perspective. Due to their age, all currently existing district heating plants are assumed to be decommissioned by 2030 and a biomass CHP will be implemented in Helsingør in 2018, making this technology choice the “business as usual” scenario. Norfors is assumed to have a renewed capacity of the same type of energy units as currently. In the RES scenarios, the basic setup of the district heating production system is the same. The difference comes from prohibiting existing and new individual natural gas and oil boilers, as discussed in the Danish political agreement from 2012 [44] and considering Helsingør's climate goals. In HP scenarios, the district heating production in Helsingør is based exclusively on heat pumps and heat storage, since the locally-sourced biomass is too scarce to cover all the demand.

In 2050, two scenarios are examined, only from a simple socio-economic perspective: BAU and Combi. All district heating plants are assumed to be decommissioned by 2050 and a new biomass CHP is implemented in Helsingør in 2050, making this technology choice the “business as usual” scenario. Norfors has a renewed capacity of the same type of energy units as in 2030. The Combi2050 scenario is based on solar heating, heat pumps, thermal storage and a small biomass boiler.

2.5. Building aggregation

In order to model the heat supply and heat savings in Helsingør, the buildings were aggregated according to their geographical location, age and use.

Geographical location defines the distance to existing district heating grids, thus the cost of district heating (DH). Therefore, we divided Helsingør into four types of areas: DH areas, Next-to-DH areas, Individual areas and Scattered buildings. In DH areas, the majority of buildings are supplied by district heating, but some are not connected to the DH network, requiring investments in connecting pipes and heat exchangers. Next-to-DH areas share a

Table 3
Tax and subsidy rates for the Danish district heating based on [41–43].

Type of tax/subsidy	Tax rate
Energy tax on natural gas consumption for heat	0.37 EUR/Nm^3
Energy tax on natural gas consumption for heat in engines	0.39 EUR/Nm^3
CO_2 tax on natural gas consumption for heat	0.05 EUR/Nm^3
CO_2 tax on natural gas consumption in engines	0.01 EUR/Nm^3
Methane tax on natural gas consumption of stationary piston engines	0.05 EUR/Nm^3
NOx tax on natural gas (per measured emissions)	3.42 EUR/kg NOx
Energy tax on heat produced from waste incineration	3.49 EUR/GJ
Supplementary energy tax on amount of waste used as fuel	4.27 EUR/GJ
Heat pumps: various taxes (PSO, distribution etc.) on large-scale heat pumps (per MWh consumed electricity)	119 EUR/MWh
Subsidy for electricity production using biomass (per MWh electricity produced)	20.13 EUR/MWh

Table 4
Scenarios and perspectives in this study. The scenarios describe the district heating setup - for each of them, the final cost-optimal mix including the individual heat supply and heat savings occurs as a result of the iterative process with LCT (see section 4). In all the scenarios, Norfors area supplies about 15% of heat and is assumed to be based on natural gas boilers and a MSW CHP and a boiler.

Year	Scenario description	Scenario name	Perspective
2030	Helsingør: woodchip CHP and boiler	BAU2030**A** (Business As Usual)	Simple socio-economic
		BAU2030**B** (Business As Usual)	Private-economic
	Helsingør setup as above; additionally, a policy of forbidding fossil fuel fired individual heat supply	RES2030**A** (REnewableS)	Simple socio-economic
		RES2030**B** (REnewableS)	Private-economic
	Helsingør: Heat pumps and heat storage	HP2030**A** (Heat Pumps)	Simple socio-economic
		HP2030**B** (Heat Pumps)	Private-economic
2050	Helsingør: woodchip CHP and boiler	BAU2050**A** (Business As Usual)	Simple socio-economic
	Helsingør: Heat pumps, heat storage, solar heating and wood chips	Combi2050**A** (Combined)	Simple socio-economic

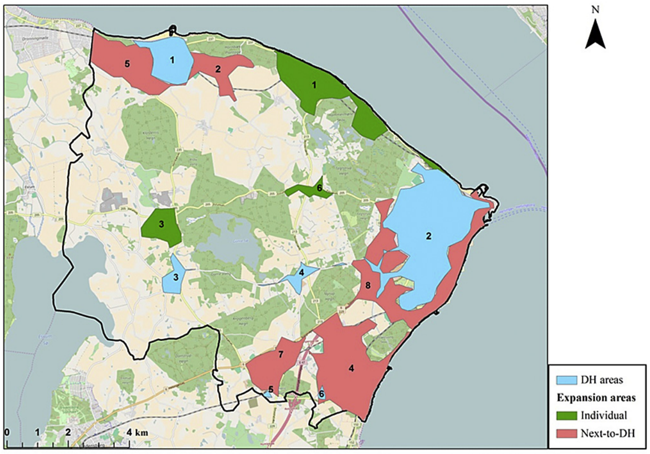

Fig. 1. Administrative boundaries of Helsingør municipality and division into DH areas (blue) and expansion areas: Next-to-DH areas (pink) and Individual areas (green). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

border with existing DH areas, but are not supplied by district heating. To connect the buildings located in Next-to-DH areas to the district heating network, investments in distribution and connecting pipes and heat exchangers are necessary. Individual areas are not supplied by district heating and do not share a border with existing district heating areas. To connect the buildings located in Individual areas to DH, investments in transmission, distribution and connecting pipes and heat exchangers are necessary. Scattered buildings represent individual buildings of low heat density, scattered across the municipality. We exclude the possibility of expansion of district heating to these areas.

Fig. 1 depicts the location of DH areas and areas with expansion potential in Helsingør. Scattered buildings (not shown on the figure) are spread all across the municipality.

As Fig. 2 shows, in Helsingør, the existing DH areas and potential DH expansion areas cover the majority of the building stock.

The heat for buildings located within DH, Next-to-DH and Individual areas can be provided with DH or individual heating. Additionally, their heating demand can be reduced by implementing heat saving measures. The disconnection from DH is not allowed in our analysis. For the Scattered buildings only the individual supply and heat saving measures are possible.

The construction period (age) and the use of buildings

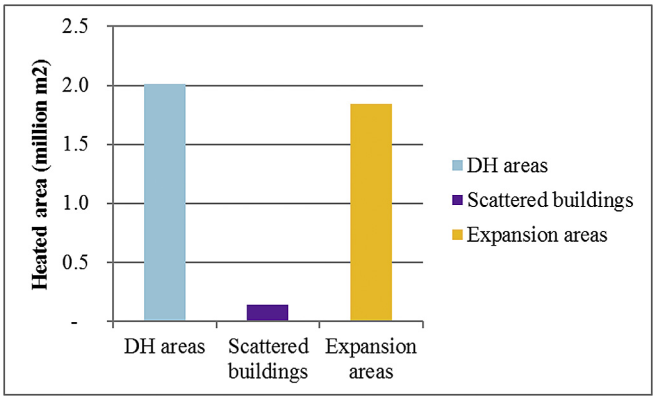

Fig. 2. Aggregation of building stock (heated area) per area type divided into: DH areas, expansion areas (Next-to-DH, and Individual) and Scattered buildings (million m^2).

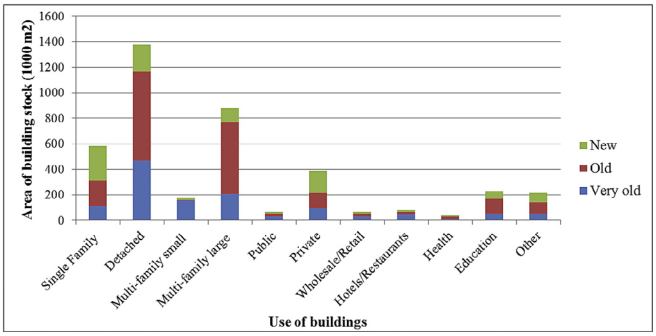

Fig. 3. Building stock aggregated according to use and construction period (1000 m^2). “Very old”, “Old” and “Normal” buildings were built before 1950, between 1951 and 1978, and after 1979, respectively.

determine the annual heating demand and subsequently the costs of heat savings. The aggregation of building stock according to construction period and use is adopted from the Invert/EE-Lab model [45] and presented in Fig. 3.

Buildings of the same use belong to the same use-group; buildings built in the same construction period belong to the same age-group. Buildings within the same age-group and use-group located in the same type of geographical area belong to the same group of buildings. According to the adopted aggregation, there are 3 age-groups, 11 use-groups and 4 geographical areas; in total 132 building groups in Helsingør.

3. Methods

Two main methods are used in this study: district heating modelling with energyPRO and iterative modelling of heat supply and heat savings costs with a purposely-developed spreadsheet-based Least Cost Tool (LCT). The cost-optimal heat supply mix is found by comparing costs of heat savings, DH and individual supply within the LCT, considering the specific heating demand and the average heated area. The process is dynamic, because if individual or DH supply increases or decreases, new costs are calculated and the iterative process continues until definitive results are found, as shown in Fig. 4 and explained further in section 3.2.

The energyPRO tool (see section 3.1) is used to calculate the costs of district heating (DH) production, depending on changes in

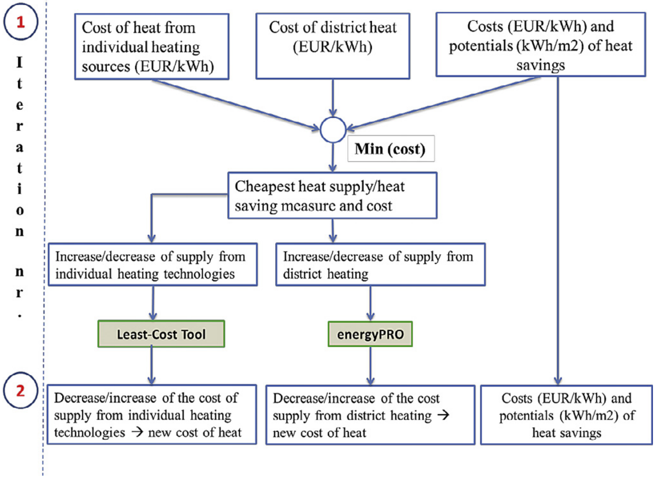

Fig. 4. Least-cost calculation iterations between the Least Cost Tool and energyPRO.

the heat demand, which can increase if DH expansion takes place or decrease if heat savings are implemented. The potentials and costs of heat savings in buildings are adopted from the Invert/EE-Lab model (for its description and methodological details see Refs. [45] and [46]).

3.1. Modelling with energyPRO

In this study, energyPRO is used to calculate the costs of district heating production, depending on changes in the heat demand caused by heat savings. The tool, developed by EMD International [47], is a commercial software for techno-economic analyses of energy projects, which can conduct an operation optimization, accounting for e.g. technical properties of units, maintenance costs, fuel prices, taxes and subsidies etc. [48].

The model only optimizes operation, not investments. Investment capacities were derived by authors in an iterative process of system cost comparison, considering the renewable resources available in Helsingør. The operation optimization is conducted via flexible operation strategy - calculated as in Eq. (3):

The objective function for energyPRO is to minimize *NHPC*, where:

$$NHPC = FC + FIXOM + VAROM - ELSAL \tag{3}$$

The operation strategy is flexible, because additional components can be added to the *NHPC* function, such as those exemplified in Eq. (1) and Eq. (2) in section 2.4. *NHPC* is calculated for each calculation step of 1 h; the length of the optimization period is 1 year. The production units operate non-chronologically within a year, until the heat demand is fulfilled, under constraints such as minimum operation time and capacity of thermal storage [48,49].

3.2. Least Cost Tool (LCT)

Technically, every building can be supplied with heat and domestic hot water either from an individual heating source or from district heating (DH), but when we consider economy, a certain heat density is needed for DH to achieve cost-effectiveness (see also [50]). Similarly with heat saving measures: space heating demand can technically be reduced to very low levels, but the cost of the measures vary greatly within the building stock. With the exception of natural gas boilers, which require grid connection, the cost of heat from individual heating sources does not vary much depending on the geographical position, construction period and the use of building.

Moreover, the choice of a new type of heat supply or heat savings for a building can also influence the costs of other heat supply alternatives; additionally, it can have an effect on the costs of heat supply and heat savings in other buildings. For example, implementing heat saving measures in a building connected to DH will reduce its heat demand, increase the cost per unit of produced district heating and thus increase the cost of district heat for other DH consumers connected to the same grid. Consequently, DH becomes less competitive in the remaining buildings compared to individual heating alternatives and heat savings. However, the impact of this change is only significant in case of substantial heat savings in a larger group of buildings or a part of a city.

Due to these complexities, it is necessary to take into account DH, individual heating options, heat savings and even combinations of heat savings and heat supply to find the least expensive heat supply alternative. To solve this task, we have developed Least Cost Tool (LCT), which calculates the cost-optimal heat supply configuration through an iterative procedure. The iterations are driven by the cost of heat supply, i.e. when the average heat supply cost in the municipality stays below a certain threshold between two consecutive iterations, the iteration procedure stops. The resulting heat supply configuration is optimal, considering the costs and potentials discussed above.

The heating cost is calculated according to the following Eq. (4):

$$HC^{(i)} = \frac{\sum_a\sum_c\sum_u\sum_h HD^{(i)}_{a,c,u,h}\cdot AR_{a,c,u,h}\cdot\left(INV^{(i)}_{a,c,u,h} + O\&M^{(i)}_{a,c,u,h} + FUEL_h\right)\cdot(1+VAT)}{\sum_a\sum_c\sum_u\sum_h HD^{(i)}_{a,c,u,h}\cdot AR_{a,c,u,h}} \tag{4}$$

where the criterion for stopping the iteration is: $HC^{(i)} - HC^{(i-1)} < 0.001\ \frac{EUR}{kWh}$.

The components of Eq. (4) can be expressed with the following Eqs. (5)–(8):

$$INV^{(i)} = \frac{\sum_a\sum_c\sum_u\sum_h INVC_{a,u,h}\cdot CAP^{(i)}_{a,c,u,h}\cdot CRF_u}{\sum_a\sum_c\sum_u\sum_h HD^{(i)}_{a,c,u,h}\cdot AR_{a,c,u,h}} \tag{5}$$

$$O\&M^{(i)}_{a,c,u,h} = FIXOM + VAROM = \frac{\sum_a\sum_c\sum_u\sum_h FIXOM_{u,h}\cdot CAP^{(i)}_{a,c,u,h}\cdot CRF_u}{\sum_a\sum_c\sum_u\sum_h HD^{(i)}_{a,c,u,h}\cdot AR_{a,c,u,h}} + VAROM_h \tag{6}$$

$$FUEL_h = \frac{FC_h}{eff_h} \tag{7}$$

Table 5
CO_2 factors [32].

Fuel	CO_2 factor
Natural gas	56.95 t/TJ
Oil	77.4 t/TJ

$$HD^{(i)}_{a,c,u,h} = HD^{(i-1)}_{a,c,u,h} - HS^{(i)}_{a,c,u,h} \tag{8}$$

3.3. Calculation of CO_2 emissions from heating production

The CO_2 emissions calculated concern only the heat production (including electricity consumption of heat pumps). For each scenario, they are a sum of emissions from district heating relative to the size of production (calculated with energyPRO) and emissions from individual supply, depending on fuels used. The CO_2 emission factors used are shown in Table 5.

We allocate emissions from CHPs proportionally to their heat output. Given the Danish and regional goals for implementation of renewables, we assume that electricity already in 2030 will be 100% based on renewable fuels - thus heat pumps are also assigned no emissions. Moreover, biomass is considered a CO_2-neutral resource.

4. Results

4.1. Heat supply mix

Fig. 5 shows the heat supply mixes in the base year and cost-optimal heat supply mixes for the six analysed scenarios in 2030. The difference between the total heat supplied in the base year and in the alternative scenarios originates from heat savings. In none of the scenarios are oil boilers chosen, due to their high cost.

In the analyses from a simple socio-economic perspective, the heat supply mix is composed of individual natural gas boilers (about 30%), individual ground-source heat pumps and district heating (based on biomass or heat pumps and thermal storage). In the RES2030A scenario the use of individual boilers running on fossil fuels is forbidden, so instead of natural gas, the buildings are supplied mainly by heat pumps and district heating. The reason for the high cost-competitiveness of ground-source heat pumps lays in their high efficiency. In the present analysis, it is assumed that residential heat pumps operate with the average annual electricity price. However, if heat pumps are operated flexibly they can achieve even higher cost-effectiveness.

In the private-economic scenarios, the optimal heat supply mix is dominated by individual biomass boilers, which cover around 56%. The main reason for the high competitiveness of biomass boilers is that biomass is not taxed in Denmark, whereas natural gas and electricity are. The price of biomass for the final consumer can increase in the future, either due to taxation or due to an increase in the world market prices. The influence of increased biomass prices is analysed in Section 4.5.

The results show that in general, individual heat pumps and district heating are more viable from the simple socio-economic perspective, but individual biomass boilers are more viable from the private-economic perspective.

Fig. 6 shows the heat supply mixes in the base year (results from 2030) and cost-optimal heat supply mixes for the two analysed scenarios in 2050. The cost-optimal heat supply mix in both socio-economic scenarios is composed only of individual heat pumps and district heating (based on biomass or heat pumps, thermal storage and solar heating) - natural gas boilers are not part of the mix. This is the result of the policy restriction that fossil fuels cannot be used in the longer time frame, which corresponds with the Danish target of becoming independent of fossil fuels by 2050 [51].

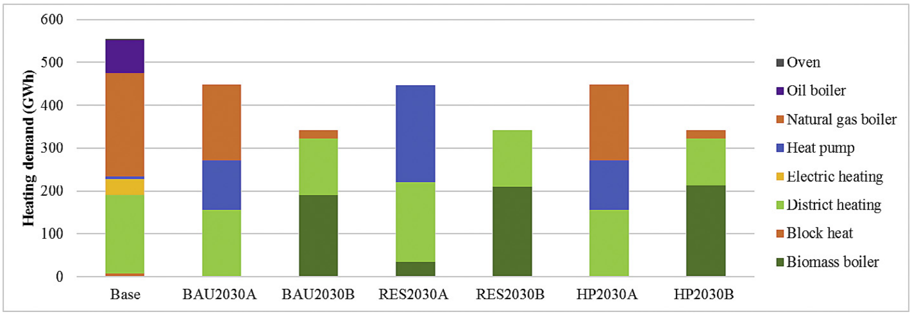

Fig. 5. Heat supply mix in the base and all the 2030 scenarios (GWh).

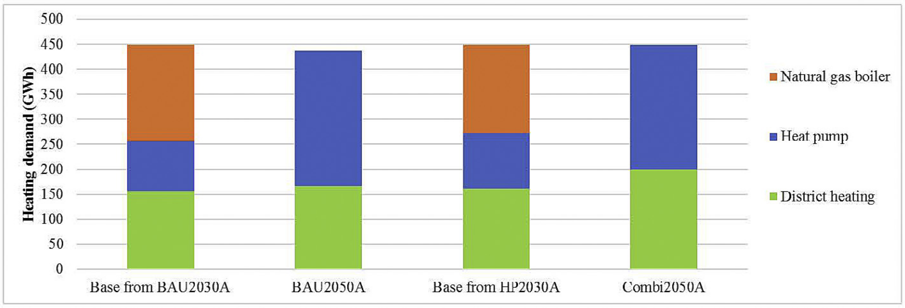

Fig. 6. Heat supply mix in the base and the 2050 scenarios (GWh).

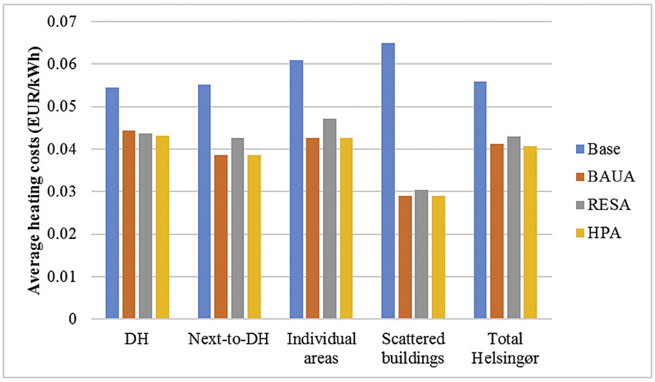

Fig. 7. Average heating costs in the base and in the socio-economic scenarios BAU2030A, RES2030A and HP2030A (EUR/kWh).

4.2. Heating costs

Fig. 7 depicts the calculated average heating costs per area type in Helsingør in analyses from the socio-economic perspective in 2030. The average heating costs represent the average costs for all the buildings located in an area. Heat savings are included in the same way as the heat supply technologies, i.e. annuitized cost of saving 1 kWh of heat is included in the average in the same way as the annuitized cost of supplying 1 kWh of heat. In all areas and all scenarios, costs decrease compared to the base.

The largest decrease in the heating cost occurs within the Scattered buildings due to implementation of around 40% of heat savings. Scattered buildings are relatively old compared to the average age of the building stock in Helsingør. Therefore, the heat savings implemented in Scattered buildings appear to be least expensive. While the difference among 2030 scenarios is minor, the difference between current average heating price (Base) and the average heating price in renewable scenario is rather substantial.

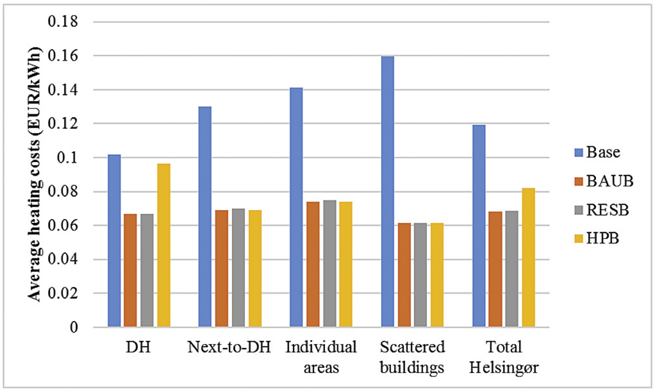

Fig. 8. Average heating costs in the private-economic scenarios BAU2030B, RES2030B and HP2030B (EUR/kWh).

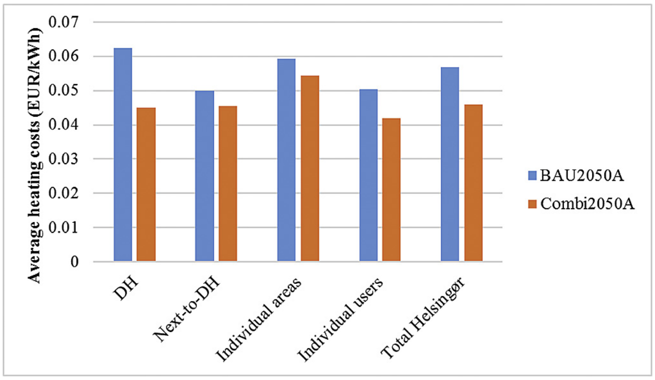

Fig. 9. Average heating costs in the socio-economic scenarios BAU2050BA and Combi2050A (EUR/kWh).

Fig. 8 depicts the calculated average heating costs per area type in Helsingør in the private-economic scenarios in 2030. The decrease of the average heating cost (except in the HPB scenario) is even higher than in the socio-economic scenarios and is around 40%. Moreover, the cost in the RES scenario is almost the same as the BAUB scenario; i.e. forbidding natural gas and oil boilers does not result in a higher cost compared to the BAU scenario. Furthermore, the HP scenario is more expensive than the other alternative scenarios and cannot be recommended from a private-economic perspective with the current taxation in place.

Fig. 9 shows the calculated average heating costs per area type in Helsingør in 2050. The Combi2050 scenario is less expensive both in total in Helsingør and in all areas, mainly because the district heating cost is lower in this scenario, resulting in a higher DH share.

4.3. Share of district heating and heat savings

The share of district heating in Helsingør in the base year is 33%, which corresponds to the current share marked in Fig. 10. The figure shows the resulting cost-optimal shares of district heating in 2030 in the BAU, RES and HP scenarios from the simple socio-economic and private-economic perspectives.

The share of district heating in district heating areas increases in all scenarios. It increases slightly in the BAUA, RESA and RESB scenarios, while the growth of around 10% occurs in the remaining scenarios. The RESA scenario is the most favourable scenario for district heating and this is the only scenario where an expansion to the areas next to existing DH areas is observed. The expansion of district heating within district heating areas was expected, since the investment needs to cover only the substation and connecting pipes. Further expansion, even within district heating areas is limited by the cost of competing technologies. For the municipality as a whole, the share of district heating increases in all scenarios, but only in RESA does it surpass 40%, which is significantly below the Danish average of around 50% or e.g. 98% in the Danish capital, Copenhagen. However, if we consider the population density as a proxy for heat density, Helsingør has a rather small population density, compared to cities like Copenhagen (see section 1), which

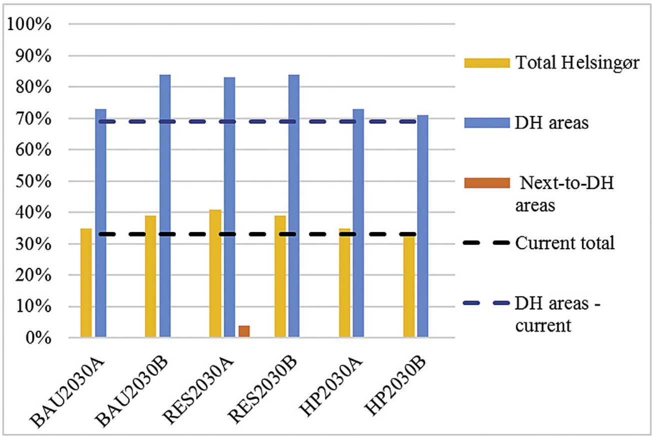

Fig. 10. Share of district heating in the 2030 scenarios (%).

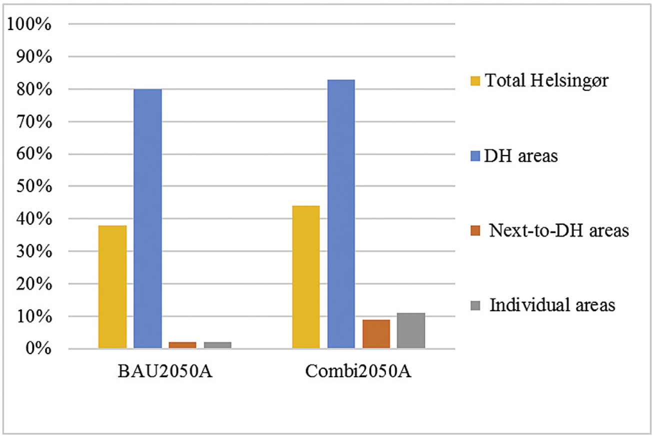

Fig. 11. Share of district heating in the 2050 scenarios (%).

is why reaching high shares of district heating may not be as cost-optimal as in bigger cities.

Fig. 11 depicts the share of district heating in the 2050 scenarios. Due to the lower district heating cost, Combi2050 results in higher shares of district heating than the BAU2050 in each type of area and overall in Helsingør.

The heat savings in 2030 compared to the Base year are presented in Fig. 12 for the six analysed scenarios. Heat savings occur in all scenarios – in the socio-economic ones (BAUA, RESA and HPA) they are around 18%, while in the private-economic scenarios (BAUA, RESA and HPA) the heat savings are around 40%.

The maximum heat savings potential of 58% (blue line in Fig. 12) refers to the share of heat demand that can be reduced in the whole municipality on average; not in every individual type of areas. Two general observations can be drawn from Fig. 12. First, due to the fact that VAT is the only tax applied on heat savings, while the heat supply technologies (except biomass boilers) are also taxed on the input fuel (natural gas, oil, electricity, etc.), heat savings are more cost-competitive from a private-economic perspective than from a simple socio-economic one. Second, scattered buildings are the buildings most affected by heat savings. This is an expected result. On the one hand, these buildings cannot be supplied by district heating and natural gas boilers. On the other hand, these buildings fall into groups of "Very old" and "Old" buildings, i.e. heat savings are relatively cost-effective there.

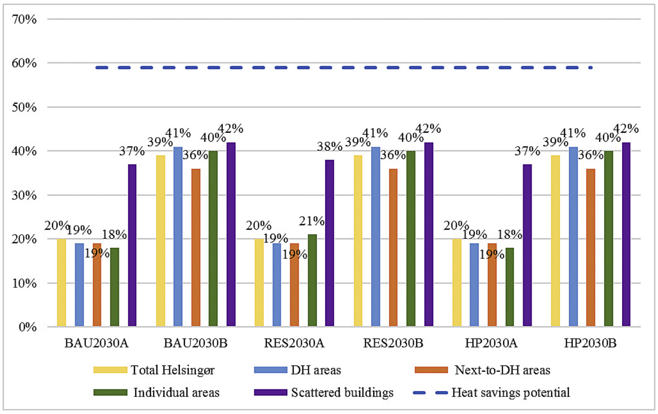

Fig. 12. Share of heat savings in the 2030 scenarios (%).

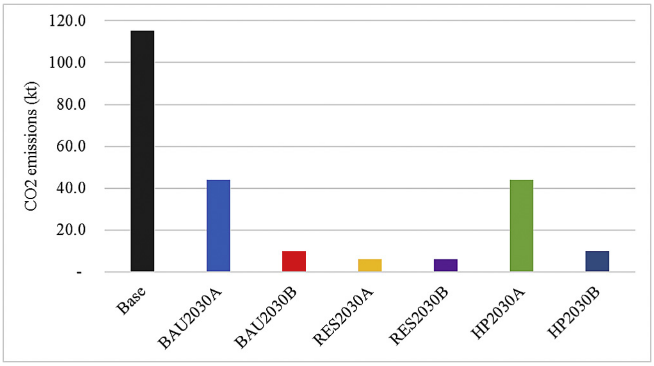

Fig. 13. CO_2 emissions in the 2030 scenarios (kt).

4.4. Heating-related CO_2 emissions

The resulting CO_2 emissions in the heating sector in 2030 compared to the Base year are shown in Fig. 13. Substantial reductions occur in all scenarios; however, RES2030 is the optimal, emitting only 6 kt (95% reduction). The only CO_2 emissions originating from heat supply in this scenario are related to the fixed amount of district heating coming from Norfors area, which is based on natural gas and MSW. These results correspond with the heat supply mixes shown in Section 4.1.

The resulting CO_2 emissions in the heating sector in 2050 amount for 6 kt and are the same in both scenarios, because we assume a constant amount of district heating supplied from the Norfors area. This is also the reason for no further emission reductions compared to e.g. scenario RES2030.

4.5. Sensitivity analyses

Biomass and electricity price are chosen for sensitivity analysis, since the future prices are highly uncertain and the examined scenarios are expected to be highly dependent on these resources. We discuss substantial changes in: district heating and heat savings share, heating costs and CO_2 emissions.

4.5.1. Increase and decrease of the price of woodchips and wood pellets

Table 6 shows the results of the sensitivity analysis on the woodchip price for district heating plants and wood pellet price for individual boilers in the scenarios with a high share of biomass.

Changes in the total district heating share are minor in all scenarios. In the socio-economic scenarios BAU2030A and BAU2050A, a decreasing biomass price causes the district heating share to increase, the overall heating cost to decrease and the heat savings share to decrease as well. This is due to district heating based on biomass being less expensive than other options including heat savings.

In the case of a biomass price increase, both the district heating cost and individual biomass boiler heating cost increase, resulting in selecting natural gas and heat pumps in this scenario and thus higher average heating cost. A 50% biomass price increase does not cause substantial changes in district heating, heat savings share or heating costs, except for BAU2050 scenario, where additional heat savings are not modelled. A remarkable increase in CO_2 emissions occurs in BAU2030B scenario, caused by the large share of individual natural gas boilers.

4.5.2. Increase and decrease of the price of electricity

Table 7 presents the results of the sensitivity analysis on the

Table 6
Changes (%) in DH share, heat savings share, heating costs and CO_2 emissions due to biomass price increase or decrease of 50% in relation to the price used in the main scenarios. Additional heat savings are not implemented in 2050 scenarios.

Scenario	Biomass price change	Change in total DH share	Change in total heat savings share	Change in total heating costs	Change in CO_2 emissions
BAU2030A	+50%	−1%	0%	+11%	+1%
	−50%	+5%	−19%	−10%	−84%
BAU2030B	+50%	−7%	+1%	+12%	+264%
	−50%	−5%	−22%	−15%	−37%
RES2030A	+50%	−5%	+3%	+8%	0%
	−50%	−1%	−19%	−12%	0%
RES2030B	+50%	+11%	+2%	+17%	0%
	−50%	−5%	−22%	−15%	0%
BAU2050A	+50%	−1%	n/a	+18%	0%
	−50%	+8%	n/a	−25%	0%

Table 7
Changes (%) in DH share, heat savings share, heating costs and CO_2 emissions due to electricity price increase or decrease in relation to the price used in the main scenarios. Additional heat savings are not implemented in 2050 scenarios.

Scenario	Electricity price change	Change in total DH share	Change in total heat savings share	Change in total heating costs	Change in CO_2 emissions
HP2030A	+50%	0%	0%	+6%	+56%
	−50%	+5%	−10%	−7%	−67%
HP2030B	+50%	0%	0%	+2%	0%
	−50%	0%	0%	−2%	0%
Combi2050A	+50%	+3%	n/a	+12%	0%
	−50%	−5%	n/a	−10%	0%

electricity price in the scenarios with a high share of heat pumps.

The total DH share does not substantially change due to the electricity price. However, changes in the socio-economic scenarios HP2030A and Combi2030A are more pronounced than in the private-economic scenario HP2030B, where electricity price changes are almost insignificant compared to the taxation levels. In HP2030A, the CO_2 emissions are highly sensitive to the price - an increasing electricity price makes district heating produced using heat pumps and individual heat pumps less profitable, causing more investments into natural gas boilers.

5. Discussion

A number of limitations occur in this study. The costs of heat saving measures adopted from the Invert/EE-Lab model are based on the assumption that heat savings will be implemented when the building is renovated anyway. In this way, the cost only includes the additional renovation costs related to energy savings, not the full costs. While for 2030, this assumption needs to be analysed further, for 2050, it is in line with the Danish experience. Moreover, due to the system boundary definition, we assume the Norfors DH system to remain the same; however, the possibility of new developments (renovations, changes in energy plant capacity) cannot be excluded. Thus, there may not be enough capacity in the system to expand DH as much, due to expansion in the connected system. Furthermore, in calculating individual heating cost for heat pumps, a yearly average electricity cost is assumed, which may not reflect the changes in electricity prices or the possibility to optimise the operation of heat pumps to hours with low electricity prices.

In all the analysed scenarios, the value of investments in new capacities is based on the assumptions about inflation and discount rates, thereby making these parameters crucial for the analysis (see also section 2.4). Our assumptions are based on current rates available for loan-takers, but the possibility of them changing in the future cannot be excluded. Higher rates than assumed would increase the cost of borrowing, which could theoretically discourage investors from taking loans and as a result could e.g. decrease or delay the investments in heat supply options, leading to different supply setups than those resulting from our assumptions.

Since no further implementation of fossil fuels is planned in the municipality, a substantial decrease of CO_2 emissions in the heat supply is very plausible, no matter which scenario will be chosen. However, in the case of the biomass CHP the feasibility of district heating expansion depends very much on which prices the future district heating will be able to offer and how taxation (including tax exemption for biomass) will be shaped. The importance of energy taxation is also significant in our results concerning e.g. heat savings. Other examples are: future fuel and technology prices, as well as policies including CO_2 targets.

The viability of the scenarios proposed depends also on the availability of the locally available renewable energy resources. Scenarios not based on biomass may benefit from better security of supply and from avoiding the risk of biomass price increases. Besides, looking from an overall sustainability perspective, it could be argued that biomass should rather be used in sectors such as heavy transport, which currently does not have other CO_2-free solutions.

Since the possibility of DH disconnection is excluded in this study, high shares of heat savings are implemented even in district heating areas. However, allowing disconnection could affect these shares. Furthermore, the lack of a limit on the speed of implementation of new individual heating technologies also influences the results. We assume that all of the technologies are implemented in the year of focus, while in practice certain implementation delay will occur e.g. due to people's behaviour or technical obstacles.

The sensitivity analysis conducted shows that the change of electricity and biomass prices influences mainly the heating costs and CO_2 emissions, which in turn is linked to different fuel mixes than in the main scenarios.

The goals of Helsingør reaching a level of one tonne of CO_2/inhabitant in 2030 and becoming CO_2 neutral in 2050 are achievable in the heating sector, independently from scenario - but certainly, choosing scenarios with lowest emissions such as RES2030 will allow faster transition to sustainability or offsetting emissions from other sectors, e.g. transport. This will in turn require that a ban on fossil fuel-based individual heat supply is implemented, which may be difficult to get political support for in practice.

6. Conclusions

In this study, we developed a methodology for deriving an optimal mix of heat savings, district heating expansion and individual heat supply, using the spreadsheet-based Least Cost Tool (LCT) and energyPRO modelling tool. We applied this methodology in the municipality of Helsingør, Denmark.

In general, our results show that in Helsingør individual heat pumps and district heating are more feasible from the simple socio-economic perspective, but individual biomass boilers are more feasible from the private-economic perspective - similar conclusions have been presented for several Danish locations by Ref. [52].

From the simple socio-economic perspective, the highest district heating share for the municipality as a whole (41%) and lowest CO_2 emissions (6 kt) occur in the RES2030A scenario, where a policy of forbidding individual oil and natural gas boilers is applied. This share is still below the current Danish average of around 50%. RES2030A is also the only scenario where an expansion to the neighbouring areas is observed. Moreover, the RES2030A scenario has the same low average heating cost as the BAU2030 scenario.

From the private-economic perspective, the scenario resulting in the highest district heating share (39%) and the lowest CO_2 emissions is the RES2030B scenario - it also results in a low average heat cost equal to the BAU2030B scenario. Thus, under our assumptions, RES scenarios are most feasible for Helsingør in 2030, considering both economic and environmental aspects. In 2050, the Combi scenario is more viable than BAU when accounting for the district heating share and the heating cost.

The overall heat demand reduction due to heat savings is the same for each 2030 scenario. However, it is higher from the private-economic perspective, where it is feasible to save almost 40% of the heat demand in each area.

A possibility for substantial CO_2 reduction exists in Helsingør, contributing to fulfilling the municipality's aspirations of reaching the level of one tonne of CO_2/inhabitant in 2030 and becoming CO_2 neutral in 2050. A 95% CO_2 emission reduction occurs in the scenarios RES2030A and RES2030B. Both 2050 scenarios: BAUA and Combi achieve the same CO_2 level as RES2030, due to the assumed fixed amount of heat supplied from the Norfors area, which is based on MSW and natural gas.

Since the Combi2050 scenario is from the simple socio-economic perspective an optimal solution for Helsingør in 2050, we recommend that the operation of an already decided biomass CHP plant is closely monitored and new technologies such as heat pumps and heat storages are considered in the 10–15 years' perspective. The uncertainty connected to future biomass taxation is rather high. If electricity taxation changes in the future, considering large heat pumps is also important. Many district heating companies in Denmark are investing in solar thermal installations now and this technology should be examined as well.

Although the findings of the study are mainly applicable for Helsingør, they can be representative for towns of similar size, climate conditions, access to natural resources and district heating share. Moreover, the iterative method for calculating the optimal heat supply configuration can be useful in energy planning of any heating system type, geographical region and scale. Furthermore, the paper displays solutions that may encourage other cities to conduct local energy planning.

Future work will concentrate on policy analyses such as the influence of tax alternation and subsidies on the profitability of heat supply and heat savings options in Helsingør. It will also address some of the behavioural aspects, such as the practicality of using residential biomass boilers versus e.g. heat pumps and district heating and the rate of implementation of individual heating technologies.

Acknowledgements

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

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Modelling the future low-carbon energy systems - case study of Greater Copenhagen, Denmark[1]

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Keywords
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Keyword/key term 2; local energy planning
Keyword/key term 3; urban energy systems
Keyword/key term 4; energy scenarios
Keyword/key term 5; Balmorel

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.

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

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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.

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[2].
- 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 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.

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

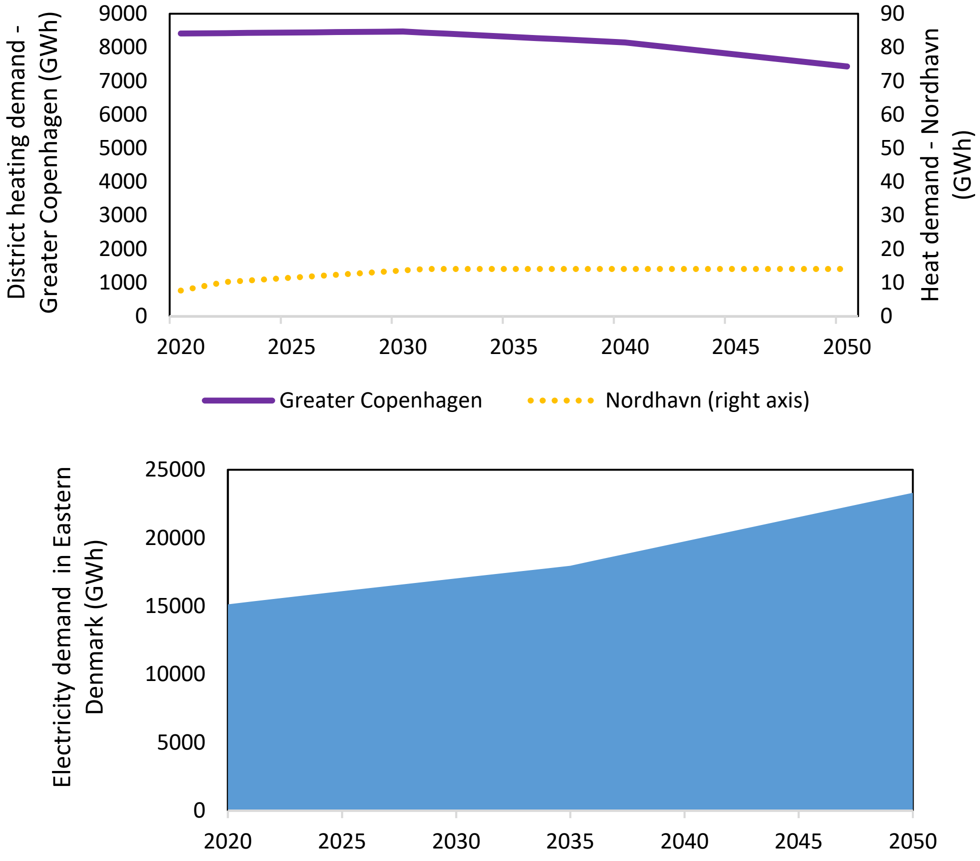

Figure 1. Projected heat demand in GC and Nordhavn (top) and electricity demand (down) in Eastern Denmark (GWh). Please note that heat demand values for Nordhavn are presented on the right axis.

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 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.

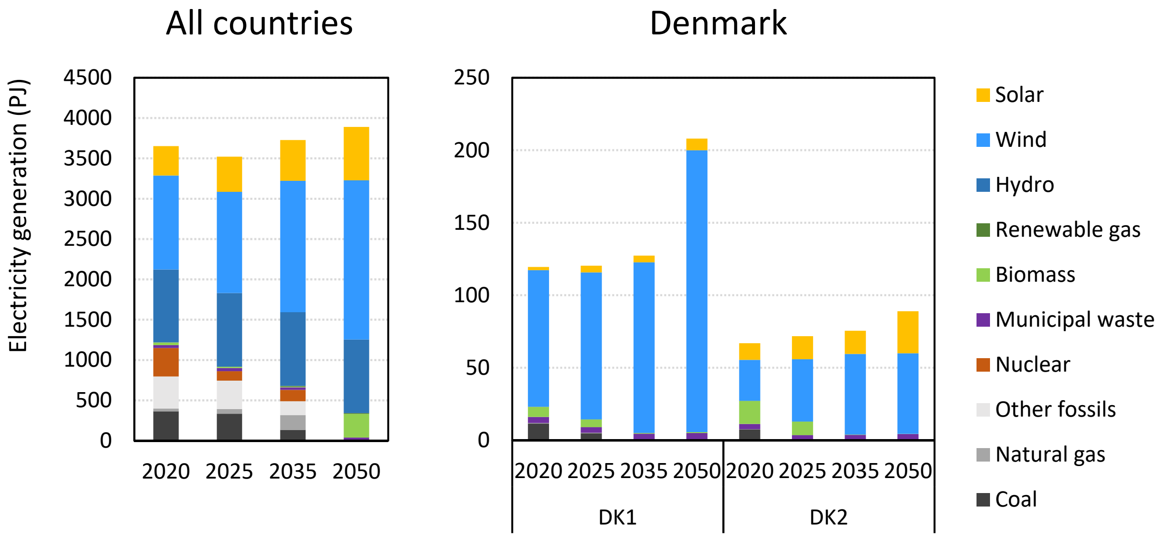

Figure 2. Electricity production per fuel in 2020, 2025, 2035 and 2050 in all the simulated countries (left) and in Denmark (right), divided into Western (DK1) and Eastern Denmark (DK2) (PJ).

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.

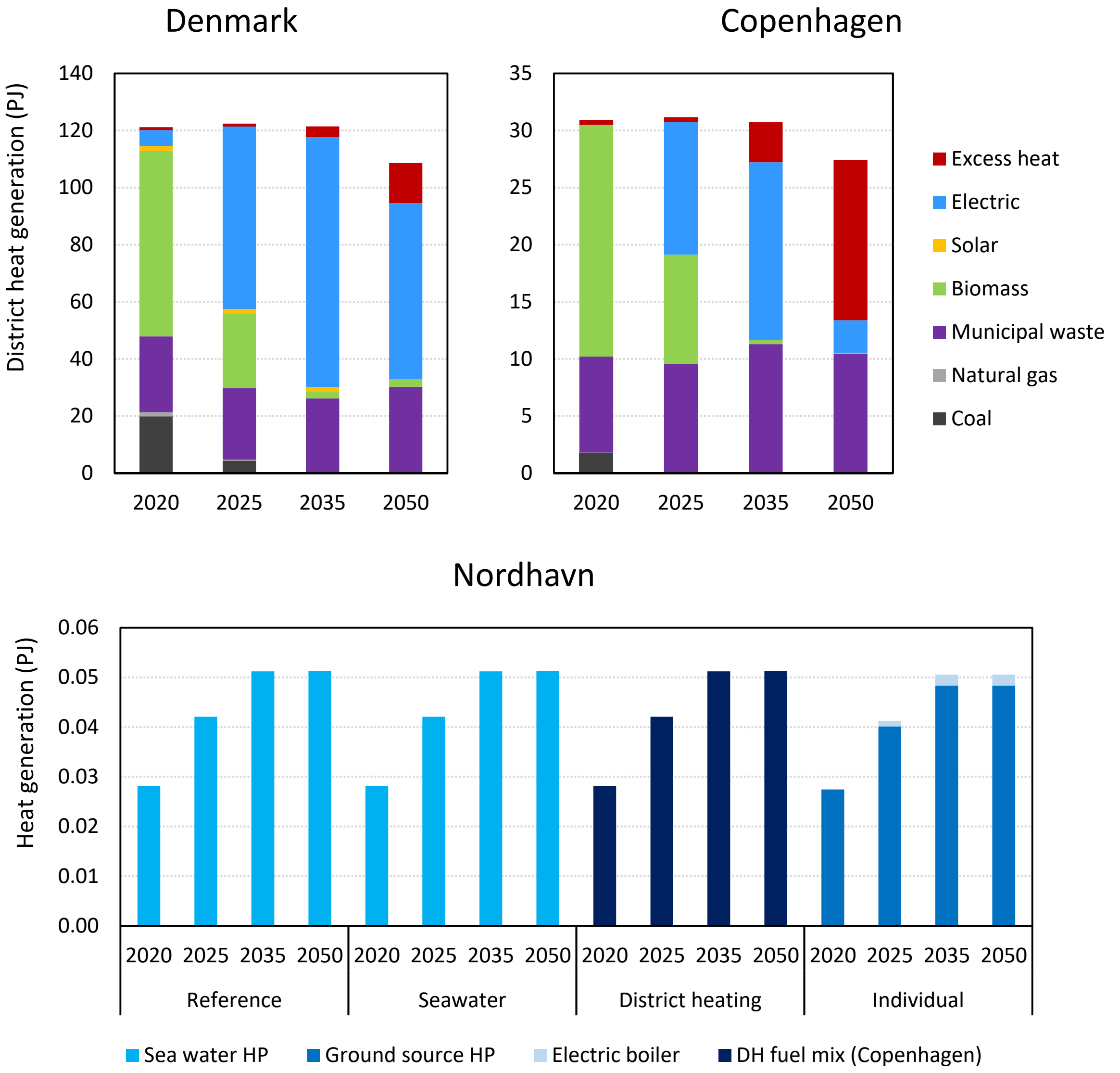

Figure 3. Heat production mix in 2020, 2025, 2035 and 2050 in Denmark, GC and Nordhavn (PJ).

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 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.

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

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.

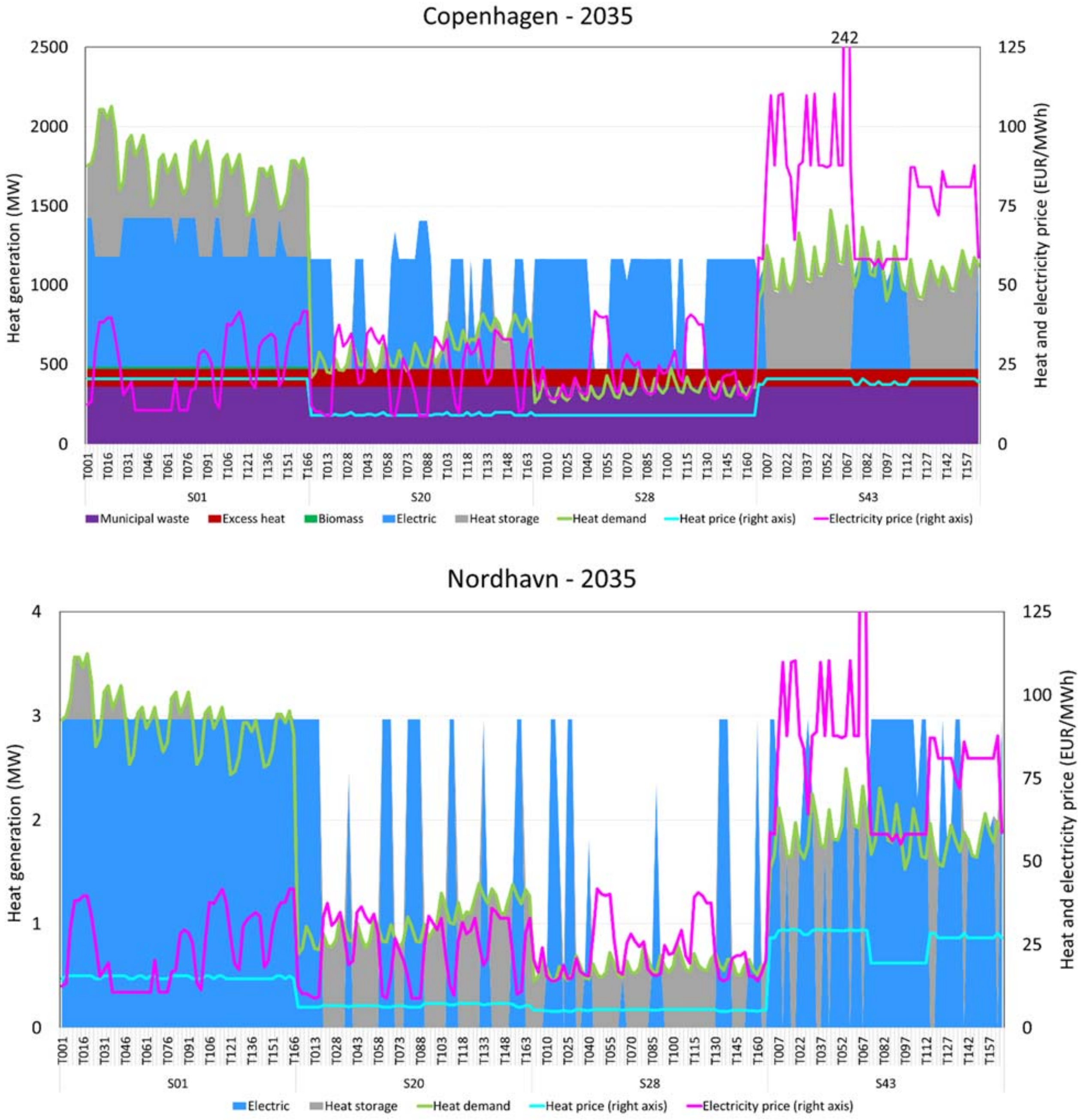

Figure 4. Dynamics between heat production and electricity and heat prices for GC (top) and Nordhavn (down) in 2035 in the reference scenario.

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.

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

	Year	Average heat price Copenhagen	 Nordhavn	Average electricity price 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%

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 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.

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.

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Paper D: Too complex and impractical? The role of energy system models in municipal decision-making processes

Too complex and impractical? The role of energy system models in municipal decision-making processes[1]

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Abstract

Energy system models are designed to support the transition to a low-carbon energy system by calculating pathways and economic costs of various energy policies and targets. As such, they are intended to provide support for decision making and energy planning. However, it is unclear to what extent and how energy system models (often developed and applied outside urban contexts) are used to create urban energy strategies. Moreover, it is unclear who uses energy system models, and whether they are useful in other areas of municipal energy planning. This study aims to clarify these aspects by examining practitioners' use of energy system models in municipalities. Semi-structured interviews with practitioners from three Danish municipalities were conducted and evaluated using qualitative content analysis. We found that municipalities rely on CO_2 calculation or evaluation tools, and not energy system models directly. Energy system models or spreadsheet tools are, however, used by heat supply companies, consultancies and universities, and results are incorporated into the planning and implementation of municipal energy visions and projects. According to the municipalities, energy system models have several limitations. Moreover, the municipalities lack expertise, resources and incentives to use the models. This study finds that energy system models and the practice of modelling can be improved by increasing the openness surrounding data and assumptions, increasing collaboration with local stakeholders and across municipalities, and improving links between technical modelling and practical implementation.

Keywords: energy system models; urban energy transitions; energy modelling; strategic energy planning; municipal decision-making; cities

Highlights:

- Explorative study of the actual use of energy system models in municipalities
- Cities prefer carbon calculators and spreadsheet tools over energy system models
- Results from energy system modelling incorporated in municipal planning
- Open data and models and collaboration can improve modelling practice and process

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[1] Preprint under review at Energy Research and Social Science as of November 2019

- Linkage between technical modelling and practical implementation is needed

1 Introduction

Addressing climate change is among the top policy priorities in the EU, with a vision to achieve climate-neutral Europe by 2050 and binding targets to reduce greenhouse gas (GHG) emissions by 40% below 1990 levels, and reach 32% renewable energy share in the final EU energy consumption by 2030 [1]. The country in focus in this paper, Denmark, aims to be independent from fossil fuels by 2050, with signs of government aspiring to 70% GHG reduction (compared to 1990) already in 2030 [2]. The draft Danish National Energy and Climate Plan (NECP) from 2018 sets a target for GHG emission reduction not covered by the EU Emissions Trading System of 39% in 2030 compared to 2005 [3].

While international and national policy frameworks are crucial, cities have been playing an ever-increasing role in setting climate mitigation goals, see e.g. ref. [4]. Municipalities are potential key implementers of the energy transition, due to their proximity to the local citizens and coordinative role across stakeholders and sectors. Conducting energy planning on a municipal scale allows observing interactions between energy, land-use and climate change in parallel and designing relevant policy accordingly [5].

Several Danish municipalities are active in setting ambitious goals for decreasing CO_2 emissions. They also play a vital role in heat planning [6]. The municipal council by law approves projects on collective heat supply, e.g. district heating and gas, and ensures coordination with planning, building, Environmental Impact Assessment (EIA) rules and environmental protection legislation [7].

To set a framework for municipal energy planning, in 2010 the Danish Energy Agency defined strategic energy planning as: "a planning tool that allows the municipalities to plan the local energy conditions for a more flexible and energy-efficient energy system in order to utilize the potential for conversion to more renewable energy and energy savings in a way that is the most energy-efficient for society" [8]. Although strategic energy planning is optional [9], the majority of Danish municipalities have conducted it or are willing to do so [10]. Nonetheless, creating coherent and implementable urban energy strategies remains a challenge [10]. The lack of coordination between the national and local level of energy planning is also among the issues [11]. Municipalities have to integrate the energy planning knowledge that was collected on national level over many years, with experience only in heating. This task is still relatively new, hence several challenges exist [12] and municipalities need the right tools and competences to avoid making arbitrary or narrow visions and to create and share knowledge of the complex energy system transition.

The use of relevant tools can increase the chances for successful energy strategies. While energy system models are commonly used in academia to analyse urban areas, see e.g. ref. [13], it is not clear what role they play in contributing to the municipal energy strategies or policies. Since policy relevance is the ultimate goal of much of applied research, there is a growing interest in analysing evidence-based policy making, including how knowledge capacity can be improved, how research results are incorporated in policy development and how different tools are used by planning professionals.

Some empirical evidence shows that the use of tools such as energy system models e.g. MARKAL, is rather uncommon in public policy-making [14]. However, another study by ref. [15] discusses how the MARKAL model has helped shape the energy and climate policy in the UK throughout the years. Bush and Bale [16] examined how decision-making tools can facilitate innovation and used strategic niche management theory to develop a heat planning tool. Bolwig et al. [17] investigated how energy system flexibility relates to socio-technical transitions and how it can be represented with system dynamics models. Analysing several different tools (including energy-related models), Kolkman et al. [18] found that the actual use of models in policymaking is influenced by the model and organizational features, infrastructure, reputation and contribution to the development.

Overall, the literature on the practice of using models in decision-making concerning energy is scarce, therefore this study contributes to the field. Valuable insights can be gained through looking at literature on the use of models in related disciplines, such as land-use planning. While in the past the practitioners often lacked modelling expertise and the knowledge on tools available [19], currently the main concerns are: which tools could be used and when, and how practitioners can gain the skill of using them [20]. In order to have a higher impact on planning, the model development has to be better aligned with practitioners' modelling procedures [20]. In traffic planning, the reliance on tacit knowledge, when outdated and in opposition to expert knowledge (e.g. gained through modelling), may hinder the accomplishment of planning targets set [21].

1.1 Energy system models

This article evaluates the use of energy system models within municipalities to examine their role in urban energy transitions. Therefore, we introduce here our definition of energy system models and discuss how models can represent energy systems and sustainability transitions, as well as model challenges.

The Fifth Assessment Report of the IPCC states that the energy system "comprises all components related to the production, conversion, delivery, and use of energy” [22]. Energy system models are similarly structured, and are designed to be used for creation, simulation and/or optimization and analysis of energy systems. As such, these models represent these elements in a simplified, interlinked way and often include technology, demographics, finance, policies, and markets [23] .

We therefore define energy systems modelling as *the process of using computerized mathematical tools to simulate and/or optimize future energy systems,* subject to assumptions about technological development, resource availability, and policy constraints. Herein we use the term "energy system model" - though practitioners often use this term interchangeably with abbreviated "energy model". Energy systems models range in scale from global to household, though this analysis focuses on the municipal scale, since it is on this scale where much of the strategic decision-making about energy systems occurs.

Energy system models:

- offer a simplified representation of a complex energy system;
- allow collecting many formalized assumptions by depicting them e.g. mathematically [24];
- allow to experiment with energy system configurations (e.g. technology types and mixes, timing, location, costs), thereby avoiding the need to test all the possible setups in reality;
- can help determine the feasibility of various goals, estimate their investment costs, and determine whether planned actions are sufficient;
- and can be useful in aligning local and national energy and climate targets e.g. [25].

In general, models have the capacity to depict characteristics of sustainability transitions [26]. While the models of focus in this paper do not fully comply with STET (socio-technical energy transition) models as defined by Li et al. [27], they allow examining issues linked to sustainability transitions. The theory of sustainability transitions assumes there exists a regime, which can be restructured or replaced - and models relate to transitions in three aspects [26]:

- they can depict the dynamics of several domains in "multi-domain interactions"
- they allow examining mechanisms at the core of path dependency and regime stability
- they allow discovering relations among various external and internal factors

Quantitative system (e.g. energy system) modelling is also characterized by a well-established and reliable research method and a focus on system interdependencies and possibilities to identify possible problem areas [28].

Energy system models are constructed to represent a simplified picture of real world energy systems. But they also influence and are influenced by the social world. In this light, models are agents of energy system transitions through their impact on energy policy. Policy makers, on the other hand, can make requests for insights, and in so doing, change the way a model is structured. For example, the MARKAL model helps "rationalise climate and energy policy commitments", "develop a community with shared assumptions and goals" and has a "capacity for facilitating new visions and new scenarios" - and so far little literature has focused on these aspects [15]. Models can be successful in "bringing together supportive epistemic communities with shared assumptions and goals" and, in this way, act as boundary objects (having a common function for a group of people) for actors involved in energy policy [15].

However, the interpretation of energy scenarios used in energy planning is prone to errors [29,30]. The results of energy system modelling may sometimes be misinterpreted, leading to either overreliance or non-usage by those who are outside of the modelling process, because information on assumptions used and guidance for interpretation of results is missing [31]. Empirical studies show that models may hide the modellers' subjectivity, resulting in different policy recommendations if different tools are used [32].

Even still, as discussed by DeCarolis et al. [33], energy system optimization models are often incapable of representing societal aspects, sustainability and the energy transition sufficiently. To handle more complex system transitions, models have become more complex, which may affect the (potential) users, such as municipalities. Furthermore, while cost optimization is a useful way to quantify the possible costs of a transition, it should be considered with caution. Analysing historical results of optimization models focusing on the UK's electricity system, Trutnevyte [34] found that the total system costs resulting from optimization deviated up to 23% depending on assumptions taken. Moreover, simulation models may be better for involving stakeholders in the analysis than optimization models, because they present various possibilities and their consequences, as claimed by Lund et al. [35].

1.2 Hypothesis and research questions

This study evaluates the use of energy system models within municipalities and examines their role in urban energy transitions. In doing so, we explore the nexus between holistic, sometimes theoretical analysis for urban energy systems on the one hand, and the realities of municipal planning (i.e., how a city operates, what makes planners engage, how strategies emerge, etc.) on the other. By drawing from interviews with selected Danish municipalities, we aim to bring new knowledge into the practice of creating urban energy strategies and applying energy system models for urban energy planning. Our hypothesis is that a better understanding of how energy system models (and their output) are used in the energy planning process could potentially help clarify assumptions, reduce errors, and result in energy models becoming better tailored towards the needs of municipalities. Thus, our main research question is as follows:

What is the current practice of energy system modelling in municipalities and which suggestions can be made in order to improve modelling to better support municipal energy transitions?

The following sub-questions guide the study:

> -Which type of energy system models do municipalities rely upon and in what way are they incorporated into the municipal decision-making process?
>
> -What are the limitations of energy system models concerning the representation of municipal energy systems and the use of modelling results in the municipal energy planning process?
>
> -How can the setup and practice of modelling be improved to better suit the needs of municipalities?

1.3 Cases

This article focuses on three Danish municipalities: Copenhagen, Helsingør and Sønderborg, selected due to authors' modelling work recently completed in each of the municipalities. Table 1 presents the geographic characteristics of the analysed municipalities and their urban energy policy frameworks relevant to this study.

Table 1. Location, area, population and urban energy policy goals of the analysed municipalities.

	Copenhagen	**Helsingør (Elsinore)**	**Sønderborg**
Location	south-eastern Zealand	north-eastern Zealand, ca. 50 km from Copenhagen	south-eastern Jutland and the island of Als
Area	86 km^2	119 km^2	497 km^2
Population (2019)	626,000	63,000	75,000
Urban energy goals and strategies	CO_2 neutral in 2025 as described in Copenhagen's Climate Plan [36] and Roadmap [37]	CO_2 neutral in 2050 described in Helsingør's Climate Plan [38] with an intermediate goal of reaching a level of 1.7 t of CO_2 eq./inhabitant in 2030[2]	CO_2-neutral by 2029, described in Sønderborg's Strategic Energy Plan [39]

These municipalities represent a cross-section of different types of communities within Denmark: Copenhagen is the capital of Denmark, Helsingør is a historic satellite city to Copenhagen, and Sønderborg is a rural economic hub. Copenhagen is the largest city with growing population size, while Helsingør and Sønderborg are both average in size and challenged with keeping their population size stable. All of the municipalities have plans for climate action. Additionally, Sønderborg has its own strategic energy plan and is involved in cross-municipal strategic energy planning, while Copenhagen and Helsingør are part of the regional strategic planning.

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[2] This goal will appear in the new climate strategy, unpublished yet. Source: interview with Helsingør representative.

1.4 Structure of this article

This article is structured as follows: Section 2 outlines the methods, Section 3 presents the results, and Section 4 discusses the findings. The paper concludes in Section 5.

2 Methods

2.1 Research design

We used a qualitative research design, where data was collected through interviews. Research and interview questions may originate from theory (inductive), practice (deductive), or from their combination [40]. This study used both theory and practice to generate the research and interview questions. Questions were developed partly based on the authors' own experience concerning the previous collaboration with the municipalities and partly based on the literature discussed in Sections 1 and 2. Table 2 shows the summary of the questions asked at the interviews, in relation to the thematic areas identified.

Table 2. Thematic areas in the interview protocol

Thematic area and explanation	**Focus of the interview questions**
Sustainability transitions - To better understand the context of the modelling practice	Definition and measurement of sustainability in the municipality. The roles of policymakers, communities, businesses, citizens, activist groups etc. The progress of the municipality with respect to energy and climate goals.
Energy system models - To understand the actual role and practice of energy systems modelling in the municipalities	The use of energy system models in the municipality (are they used and how?, by whom?, which models?) and positive and negative user experiences. Possible usefulness of models in providing information, portraying the dynamics of the system and displaying technologies. Limitations of energy systems modelling.
Heat and energy - To gain knowledge of the specific planning processes modelling practices are embedded in	The energy/heat planning process and decision-making in the municipality: objectives, actors, steps, factors, frequency. The role of energy scenarios and energy system models.
Collaborative planning - To develop suggestions for how models and the modelling practice could be improved	Collaborations and stakeholder involvement in the energy system modelling for the municipality. Making energy modelling for the municipality more user-friendly.

2.2 Data collection

The study used purposive sampling [41] and expert sampling to generate relevant answers. The study's first author conducted six face-to-face, semi-structured interviews (five in Danish and one in English), with the representatives from three Danish municipalities: Copenhagen, Helsingør and Sønderborg. The interviews, conducted between February and July 2019, were fully recorded, transcribed and translated to English. The reasons for case choice are discussed in Section 1.3. Table 3 provides an overview of all interviewees: the municipality represented, seniority and the code assigned in this article.

Table 3. Overview of interviewees.

No.	Municipality	Participant code	Participant seniority in the current workplace
1	Copenhagen	C1	3 years
2	Copenhagen	C2	18 years
3	Helsingør	H1	10 years
4	Helsingør	H2	32 years
5	Sønderborg	S1	13 years
6	Sønderborg/Project Zero[3]	S2	6 years

2.3 Data analysis

The Atlas.ti tool was used for managing and organizing the data. We analysed interviews using qualitative content analysis [42]. The step-by step approach was inspired by Erlingsson and Brysiewicz [43]: selected data, i.e. "meaning units" were condensed, then codes, categories, themes and overarching themes were generated in an iterative and non-linear process. Section 3 shows the results of this analysis.

3 Results

3.1 Energy system modelling within municipalities

All of the interviewees stated that the modelling competence does not lie within their respective municipality, but within heat supply companies, consultancies or universities, which actively use energy system models. The analysed municipalities use CO_2 emission inventory or evaluation tools to keep track of CO_2 emissions. Nonetheless, they relate to and use energy system modelling indirectly, for example by collaborating with local district heating companies, consultancies or universities.

Table 4 presents the models and tools used to represent the municipal energy systems and a statement on how each municipality uses the tool, ordered by progressing involvement: "recognizing the tool and/or the study conducted using the tool", "access to results", "influence on results", "actively using the tool".

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[3] ProjectZero is a public-private partnership, driving Sønderborg´s transition to a carbon-neutral community

Table 4. Tools representing urban energy systems analysed in this study and a description of how the tool is used by the municipality. Source: own research. Note: This table is not intended as a guide on model characteristics, for reviews, see e.g. [44–47].

Name of the tool	**Type**	**Typical application area**	**Focus area in relation to this study**	**How is the tool used/not used**
Balmorel see e.g. [48] [49]	investment and operation optimisation tool	international, focus on district heating	City of Copenhagen	access to results
			City of Copenhagen as part of Greater Copenhagen ("Heat Plan Copenhagen" project)	access to results/influence on results
			City of Copenhagen and Helsingør municipality as part of the Capital Region of Denmark ("Energy Across" project)	access to results/ influence on results
CONNIE	spreadsheet tool for CO_2 emissions evaluation	City of Copenhagen	City of Copenhagen	actively using the tool
Energy and CO_2 calculator [50]	Danish Energy Agency's geographically based CO_2 inventory tool	municipal, regional and Danish level	City of Copenhagen	recognizing the tool, used within the Energy Across collaboration
			Helsingør municipality	recognizing the tool, used within the Energy Across collaboration
			Sønderborg municipality	recognizing the tool
energyPLAN see e.g. [51]	operation optimisation tool	national energy systems, including transport	City of Copenhagen	recognizing the tool and/or the study conducted using the tool
			Sønderborg municipality	access to results/ influence on results
energyPRO [52]	operation optimisation tool	project-focused, primarily district heating	Helsingør municipality	access to results/ influence on results
			Sønderborg municipality	access to results/ influence on results
LEAP [53]	model generation tool; possibilities for	national energy systems	Helsingør municipality	access to results/ influence on results

	optimization modelling			
Least Cost Tool (LCT) [54]	spreadsheet tool for heat savings calculation	Helsingør municipality, but can be applied elsewhere if data available	Helsingør municipality	access to results/ influence on results
Sifre [55]	operation optimisation tool	Danish energy system	Sønderborg municipality	recognizing the study conducted using the tool
Sønderborg's spreadsheet tool	spreadsheet tool for energy consumption inventory and evaluation of possible measures	Sønderborg	Sønderborg municipality	actively using the tool

The tools that fit the authors' definition of energy system models (see Section 1.1) are: Balmorel, energyPLAN, energyPRO, LEAP and Sifre. The remaining tools are used for energy consumption and CO_2 emission inventorying, project appraisal and simplified evaluation of consequences of possible actions to be taken, e.g. changes in local CO_2 emissions caused by e.g. installing a new wind farm. Out of these, the only tools actively used by the municipalities analysed are: CONNIE in Copenhagen and a spreadsheet tool in Sønderborg.

3.2 Incorporation of energy system models and spreadsheet tools into municipal decision-making

All of the municipalities analysed have a strategic energy plan and/or a climate plan focusing on climate mitigation options. These plans describe visions and projects for future municipal energy systems and in all of the cases energy system models or spreadsheet tools are incorporated into the planning and implementation of these visions and projects, albeit to a varying degree.

Energy system models or spreadsheet tools are primarily used in the beginning and implementation phase of energy planning projects, serving the following purposes:

- to visualise and facilitate

In Copenhagen, the local district heating company involves the municipality in their analyses concerning future heat supply, using Balmorel. In Helsingør, knowledge gained through collaboration with a university using energyPRO and Least-Cost Tool resulted in the municipal planners becoming more aware of the potentials of heat savings and fuel switching in individually supplied areas. In Sønderborg, in connection with the implementation of "Project Zero" and regional strategic energy planning, stakeholder meetings were organized where spreadsheet tools were used to get an overview of the local energy system.

- to calculate basis for strategies and roadmaps

Copenhagen uses results obtained by the local district heating company from Balmorel as input for their tool, CONNIE. According to the interviewees from the City of Copenhagen, energy system models were not used to analyse the data behind the CPH20205 plan. However, Balmorel was applied in a journal article, concerning Greater Copenhagen [49] and projects that may have influenced the CHP2025 plan: "Heat Plan Copenhagen" and "Energy Across". Helsingør has previously collaborated with a consultancy company using the LEAP tool, however the Climate and Sustainability Plan currently being written is based on analyses using Balmorel. Moreover, heat supply and savings options were analysed for Helsingør municipality using energyPRO and Least-Cost Tool. Sønderborg has a heating plan and a strategic energy plan where a consultancy company was hired to conduct analyses using the energyPRO and energyPLAN tools, respectively. Moreover, the municipality is aware of alternative energy supply scenarios that were modelled by one of the authors of this study using the Sifre tool.

- to evaluate the progress and propose new measures through carbon calculators and spreadsheets

In each of the analysed municipality, the CO_2 emissions are accounted for yearly. Copenhagen conducts and reports the data collection on their own. Moreover the evaluation tool CONNIE is used to propose new measures to improve the implementation of the CPH2025 plan. In Helsingør, a consultancy company is usually hired to help the municipality collect and report the data. In Sønderborg, Project Zero collects and reports the emissions data in their yearly monitoring reports, which are quality checked by an external consultant.

3.3 Limitations of energy system models

The majority of the municipality representatives agree that it is challenging for them to name energy system model limitations and opportunities because they do not use them actively. For example, interviewee S1 admits: "It is difficult to be critical of such things when you do not have such a good insight into how it can be done otherwise." Nonetheless, the municipal collaboration with the active users and the resulting frequent exposure to the model results allows to identify the following limitations:

- too much complexity

All of the municipalities analysed find the models to be too complex and technical to be of use for them. In the words of Interviewee H2: "Modelling is totally outside the world we are dealing with in reality. Such technical calculations take place there [pointing at the nearby CHP plant]." Similarly, Interviewee S2 states: "energy modelling is actually pretty nerdy", and also according to Interviewee C1: "It is a complex tool, it takes a long time to make calculations in Balmorel […], I would not have the ability to run it today".

- perceived narrow focus and lack of synergy

According to Interviewee C1, models do not portray synergy across supply types: "My understanding of Balmorel is that it is a bit narrow-minded […] one misses some of the synergies that occur when thinking more holistically […] flexibility and integration among the supply types are necessary and it is completely missed in these models". However, this limitation is not mentioned by the other interviewees.

- insufficient representation of transport

Interviewee H1 names a limited ability of energy system models to portray their biggest concern - the transport sector: "I could use some models on transport […]: alternatives to electric cars […], if you can refuel with hydrogen in 4 minutes instead of half an hour, that is smart.". Transport planning is mentioned as a problem for Copenhagen as well, as Interviewee C2 points out: "as a Danish municipality we have a big problem, it is not something we have authority over, we cannot regulate traffic neither at the level of the vehicle nor which vehicle can come in or must not enter".

- insufficient representation of measures, including those that depend on behavioral changes

According to Interviewee H1, municipalities need models to represent more measures and effects of different policies and actions, especially at the municipal level: "What I need more are actions, […] rather than some figures [or claims that] everything depends on what the state does, because it is the same as saying: you cannot move anything yourself. We are interested in […] showing what the effect of the action is." This interviewee adds: "If I have to convince the politicians it is a good idea, it would be really good to be able to show that if we put hydrogen up or make more infrastructure for electric cars, make it free to park, free to refuel etc., what effect will it have? If you could figure out such a thing […], the politicians […] would probably say: then we would better do it". However, this limitation is not stated by the other interviewees.

3.4 Limitations of the practice and process of using energy system models

The municipal collaboration with the active users of energy system models allows the study participants to express their views on the limitations of the process and practice of using energy system models. The following limitations were mentioned by them:

- no need for municipalities to be actively using energy system models

The analysed municipalities do not find it relevant for them to actively use energy system models, because they do not feel it would improve their work. As expressed by interviewee C1: "I do not know if we could use it to such a large extent, I do not think it will facilitate my work so much. […] There are also other types of plan tools you can use, but this is not something we really use in our planning." A similar view is shared by interviewee H1 from Helsingør: "Models for us is something that is under surface, a thing behind". The study participant S2 from Sønderborg states: "Our modelling is not for the purpose for modelling, but for the implementing". This interviewee distinguishes between two approaches to modelling: scientific and practical modelling, the latter being an approach that municipalities could take: "Scientific energy modelling and practical energy modelling […] are different from each other. As a scientist you always can formulate your scientific question and say: I would look at 100% biomass energy system or 100% wind and solar energy system and then you can see if the energy system works from a technical perspective, but we still have to look at political or space issues."

- lack of expertise and time to use the models

The analysed municipalities lack expertise and time to be able to actively use energy system models. Interviewee C1 acknowledges: "I don't have the time. […] It's a complex tool, it takes a long time to make calculations in Balmorel. I know there are also some light editions which you can run more simply, but I would not have the ability to run it today". Interviewee H1 pinpoints: "A model is behind calculation, but whether it is one or another it is difficult [to say] for us who are not experts in modelling". The Sønderborg representative S1 says: "I have not at all so many hours to spend on this neither that much demand and it is difficult to be able to use […] it properly, because it is so complex […]. It is just really difficult as a municipality to have the expertise in these things because we simply do not have enough knowledge about it." The same view is shared by interviewee S2 from Sønderborg: "It's very difficult to have some specialists in the municipalities or companies doing energy modelling, because it would be a full time job to follow all the different developments. In order to do good energy modelling you need some knowledge [in that area]".

- simplification of reality

According to the respondent S2, the energy modelling process requires simplifications and other compromises, of which one has to be aware: "The general issue with energy modelling and energy models is, you will never be 100% close to the reality, because you always have to do compromises. When doing energy modelling it is important to have in mind what other issues you might get during the implementation".

3.5 Improvements in energy system models and in the practice and process of modelling

Several limitations of the energy system models and the process and practice of their usage were mentioned in Sections 3.3 and 3.4. The study participants identified the following options for improving energy system models and the practice and process of modelling:

- open data, assumptions and modelling frameworks

All the respondents would welcome more dialogue between model users and municipalities. According to the participant H1 from Helsingør: "You, who make the calculations and use the models must become better at pointing [this] out, […] someone who comes with a model is blind to the others, [they] say: here we have a result and decision makers underline the result, they think it is right because an expert has made it […] Sometimes you make a sensitivity analysis, [...] but you could probably do more. […] If we had a little more control over prerequisites - it could also be the other way round or double up. So this information about assumptions could help make it more useful ".

An increased availability of open energy system models could even encourage Copenhagen to start using models: "We have also talked a little loosely about it in our unit […] if we are to make a fossil-free 2050 scenario and work with simpler energy models to see how such a system can function. […] We could play with simpler models that contain these different technologies and how they work in an energy system." (C1)

Interviewee S2 from Sønderborg also underlines the importance of open energy models: "Energy models should be open […] you need to be able to see what the energy model is doing. A lot of models that are used in Denmark are still closed. I think open source modelling is important and should be driven by the scientists."

- collaboration on data and modelling with local district heating companies

Municipal collaborations with local district heating supply companies are crucial for enhancing municipalities' grasp of energy system models. The collaboration on energy modelling with the local district heating company is considered as very good in Copenhagen. Helsingør and Sønderborg municipalities acknowledge that in some areas they need to improve their collaboration with district heating companies. In the words of the participant S1 from Sønderborg: "It would be smart to have regular contact with [district heating companies], but we simply do not have the capacity for it." The other interviewee from Sønderborg states: "With some of the [district heating companies] the collaboration is better, with some of them is worse, but still we talk to each other and try to discuss" (S2). Interviewee H1 from Helsingør says: "We have […] an agreement on how the relationship should be, that they must deliver the data we need […]. It is not always an uncomplicated and smooth collaboration. I am really happy about the collaboration on the new Climate Plan, but [it is difficult in] the areas of waste and environment ". The other interviewee adds: "It is becoming more open and it is recognized that we must talk more constructively together at an earlier stage." (H2)

The City of Copenhagen identifies a need to improve the collaboration in the area of electricity: "We as a municipality do not have much influence over electricity distribution. […] If we in the future want to electrify a large part of the heat production or supply and the transport sector, then there might be a challenge in terms of energy planning, if the distribution network and the transmission network cannot cope with the increased demand, while at the same time the energy plants in Copenhagen mainly produce heat ". (C1)

- cross-municipal collaboration

In recent years, Danish municipalities have started collaborating on strategic regional planning with each other. Regional projects e.g. "Energy Across" encourage collaboration and inspire planning practice, giving more confidence to the municipalities by providing them with tools and a forum to exchange their experiences.

The study participant from Helsingør describes a collaboration initiative: " We have agreed to enter into this strategic heat plan cooperation because there is someone who can help us to point out some directions we think the municipality should go so that we are not only guided by what supply thinks is good, because we do not have the skills today […]. I also imagine that this collaboration […] will improve possibilities to look beyond our own "local nose", avoiding sub-optimization or getting better at exploiting the potentials that are around instead of focusing only on our own situation" (H2).

Copenhagen also collaborates with other municipalities: "We are beginning to work on strategic energy planning, in a regional perspective. You gather all these actors at the same table to discuss what our supply must be able to achieve […] in 10, 20 years. What energy demand we will have […] what challenges we will be facing […] Waste area and mobility and traffic area […] exceed the municipal boundaries, and are areas where we could work more strategically, where the municipalities have a big role, and must work together to secure the best solutions." (C1)

The Sønderborg representative S1 mentions: "It was in connection with these four southern Jutland municipalities that we have worked together to make strategic energy planning […], we look at how we can help each other to transform the energy system into more renewable energy sources and collaborate […], how can we use each other, [and] increase the level of our expertise to be able to solve the task better".

The same study participant explains why this collaboration came to life: "some of our municipal directors have probably seen an opportunity to go together and say: the whole of southern Jutland should continue to be an attractive place so let's try to […] ensure there is enough green energy and that it will still be cheap and attractive etc. for the companies to stay in our area. It can be a leverage to collaborate on energy planning, if you expand the scale, […] we can make it more optimal, so it probably was because we are next to each other, we have the same challenge of attracting labour, etc. because we are located where we are." (S1)

- technical modelling with models, implementation by municipalities

Both Copenhagen's and Sønderborg's climate strategies are accompanied by separate documents called Roadmaps, containing measures and initiatives to implement their respective CO_2 neutrality goals. Helsingør is also primarily interested in measures that could be used to implement goals. However, some measures such as e.g. information campaigns are difficult to represent with models. This is where the coordinating role of the municipalities and the local knowledge is important. In the words of a Sønderborg representative: "We act on so many parameters that not every one of them can be measured specifically, but we are moving in this direction, […] every other year we go around different departments and ask: - Last time you wanted to do this information campaign - how did it go, so in this way we can then follow up." (S1).

According to Interviewee S2, models should not represent social and political issues: "It's not a good idea to build a huge holistic model, […] when I do energy modelling the answers I'm searching for is will the energy system work in the way I put it together, will there be enough storage, enough biomass, enough wind energy and solar. Energy models are pretty good at doing that. I think it's not a good approach to [analyse] political issues or social issues [with models] […]. Energy system modelling is already very difficult to do […]. You have [to have] in mind what other issues you might get during the implementation and that is why I think scientific energy modelling and this practical energy modelling that I described are different from each other."

4 Discussion

This article analyses only three out of 98 Danish municipalities, so it is challenging to generalize the findings across the entire country or worldwide. Nevertheless, important themes emerged from the three case studies. The results are similar for all the municipalities regarding the type of tools they use and how energy system models are incorporated in their planning processes. The differences among them occur in limitations of the models and the modelling process. One common limitation is model complexity - as Lopion et al. [44] discuss, energy system models are indeed becoming more complex to better represent the growing complexity of energy systems: increased intermittent renewables, flexible demand, electrification of transport and heating etc. Although energy system models have a lot to offer for their users, their lack of user-friendliness for municipal practitioners may be discouraging. In the related realm of planning support systems, where low adoption by practitioners has been an issue for a long time [56], tool developers and researchers try to address both user-friendliness and usefulness (additional value for planning) [57].

Danish municipalities are experienced in heat planning and are taking a role as creators of energy strategies, but according to Petersen [10], these strategies are of varying quality and need to be updated. Even if in Denmark, most of the final municipal decision-making is political, the contextual knowledge that lies within municipalities may be insufficient for managing the implementation of urban energy strategies, because smart energy systems require a thorough technical system knowledge. Thus, the use of energy system models may be one of the competencies required for enabling successful urban energy strategy implementation. Our study, similarly to Petersen [10], identifies that Danish municipalities lack the technical expertise and staff and time resources to conduct such tasks. Moreover, our results show that the analysed municipalities do not find it relevant to actively use energy system models, because they do not feel it would improve their work. In this context, it is understandable that municipalities have to rely on a collaboration with supply companies or hire consultancy firms to conduct energy modelling. Krog [58] argues that, as long as local actors are involved, such an approach can also enrich energy planning by bringing additional knowledge. We suggest that mutual expectations are clarified before and during the process, so that municipalities are not left alone with project implementation responsibilities and their consequences. On the national level, a systematic approach to collaboration between Danish ministries and universities is still lacking [59] - local governments could also possibly benefit from a more formalized approach. Another idea for municipalities could be to participate in research projects and collaborate with universities to host students, PhD fellows and postdocs.

While local energy strategies focus on local problems, this study identifies the importance of cross-municipal collaboration, which can better equip municipalities and increase their understanding of and involvement in energy modelling. More technical support from the Danish Energy Agency despite the decreasing focus on strategic energy planning in recent years, could also be part of solution.

Focusing on the infrastructural context helps understand the differences in collaboration patterns in the municipalities analysed. With the local supply company providing district heating (over 98% of the municipal heat demand), it is practically a monopoly in Copenhagen, while more competition occurs in municipalities such as Helsingør and Sønderborg. Thus, it is natural for Copenhagen to have a very close collaboration with the district heating supply company and focus on changes in that sector. In cities such as Helsingør and Sønderborg, due to lower district heating penetration, it is more important to reach out to the local citizens and thus also model changes in the individual sector.

One respondent expressed that a specific energy system model "can't model flexibility", while in fact is has been used before for modelling various flexible system configurations, see e.g. ref. [60]. This misunderstanding of the model feature can be caused by the acknowledged lack of modelling expertise or unclear model presentation and explanation of model choice. These aspects touch upon knowledge transfer issues, where further work would be necessary.

The interviewees identified the need to question results more. Similar findings occur in the literature. Focusing on Swiss researchers, Braunreiter and Blumer [30] analysed the use and misinterpretation of energy scenarios. Iyer and Edmonds [31] claim the importance of tool developers and researchers showing modelling results to the public, with all the proneness to errors and assumptions behind. As a remedy to the misuse of energy modelling results, adhering to modelling "best practice" schemes is suggested by DeCarolis et al. [33] and "transparency checklist" by Cao et al. [61]. Moreover, participatory modelling [62] and open energy system modelling emerge as possibilities for more involvement in the modelling process and critical review, see also refs. [63–66]. The dialogue between technical modelling and practical implementation could also be facilitated by appointing mediators, or knowledge transfer intermediaries, in the modelling process, who would allow incorporating multiple perspectives [20,67].

One study participant claims that models should not portray other aspects than technical, because that's not their role, and to avoid becoming too complex and computationally heavy. Some transition scholars advocate a similar plurality of approaches [68]. A solution to the computational aspects could also be model coupling or linking, where results from one model are fed into another model in an iterative manner. Furthermore, as our interviewees highlight, a model’s capability of balancing demand and supply, is just the first step in the “practical modelling" world of planners: practitioners want to know the potential effects of actions and “softer” (behavioural) measures – especially in the transport sector (e.g. free EV charging). Such a “likely rate of adoption” is difficult to make assumptions about for most of the existing energy system models, if "exact" results are expected. Nonetheless, the current trend in model development is to try to address the institutional, political and social challenges connected to implementing sustainable energy systems with socio-technical energy transition (STET) models, see e.g. Turnheim et al. [27].

5 Conclusion

This study examines the use of energy system models within municipalities and their role in contributing to the municipal energy transition. Six semi-structured interviews with key stakeholders from three Danish municipalities: Helsingør, Sønderborg and Copenhagen were conducted and evaluated using qualitative content analysis.

The analysed municipalities actively use CO_2 calculation or evaluation tools rather than energy system models, which in turn are used by the heat supply companies, consultancies or universities. Nonetheless, the municipalities use model results when collaborating with these active model users. Energy system models or spreadsheet tools are incorporated into the planning and implementation of municipal energy visions and projects, albeit to a varying degree. They are primarily used in the beginning of energy planning projects and when a project is running, helping to visualise and facilitate, to calculate the basis for strategies and roadmaps and to evaluate the progress and propose new measures.

This study finds that, according to municipalities, energy system models are: too complex, have narrow focus and lack synergy, as well as represent transport and measures in an insufficient way. This paper also finds that the municipalities lack expertise and resources to use the models and they do not find it useful to actively use energy system models.

The paper identifies that energy system models and the practice and process of modelling can be improved by: being open about the data and assumptions - and possibly using open energy models, collaborating on data and modelling with local district heating companies and across municipalities and finding a balance between technical modelling and practical implementation.

This paper contributes with an exploratory analysis of the subject of energy system models use and model limitation from the practitioners' perspective. These insights can be used to improve the incorporation of energy system modelling in municipal planning practice and to address the model weaknesses. Since cities conducting strategic energy planning are often on the outlook for methods to design their strategies, such as energy system modelling, the subject of this paper is also relevant e.g. for cities belonging to the Covenant of Mayors [69].

Further work will focus on analysing this subject in the broader geographical context of the EU and the broader thematic context of knowledge transfer and evidence-based policy-making, similarly to refs. [21,70].

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