Sustainable Local Energy Planning

The Role of Renewable Energy Scenarios

Maya-Drysdale, David William

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THE ROLE OF RENEWABLE ENERGY SCENARIOS

BY
DAVID MAYA-DRYSDALE

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PREFACE

This thesis summarises a PhD project undertaken from 2016 to 2020 at Aalborg University, in the Sustainable Energy Planning Research Group. The research within this PhD has taken me on an academic journey crossing several disciplines where I gained valuable research experience and skills which I am truly grateful. I would like to thank my supervisor Brian Vad Mathiesen (Professor at Aalborg University). Brian continued to provide insightful and constructive advice helping steer my research to the conclusion.

I would like to thank my co-supervisor Karl Sperling, for his honest and constructive feedback and fruitful ideas. Jens Iuel-Stissing for his discussions in the hallway and reflections on research topics I was learning. Also, fellow article co-authors and colleagues who I collaborated with and discussed ideas.

I have worked with numerous professionals during this PhD in the SmartEnCity project, including project partners and interviewees, who I would like to thank. I would like to thank Peter Rathje (ProjectZero) for his encouraging attitude. Simon Sørensen and Per Alex Sørensen (PlanEnergi) for their collaborative work and valuable insights on energy planning in SmartEnCity and Sønderborg municipality.

I would like to thank my family for their support. Lastly, I would like to thank my wife, who kept encouraging me and supported me to the very end.

Copenhagen, May 2020

David Maya-Drysdale

ENGLISH SUMMARY

Mitigation of the worst effects of climate change requires a transition from the fossil fuel energy system to a sustainable energy system. Cities have high energy demand but offer numerous opportunities to implement sustainable energy solutions. The sustainable energy system will be complicated due to energy efficiency, electrification and will require strategic planning. A transition is not only technical or economic but also social and involves numerous stakeholders, multiple levels of governance, and related elements to learn and co-evolve; increasing the complexity and wickedness of the transition.

Learning and co-evolution of stakeholders and actions require clarity around the sustainable energy system to cope with the complexity. Visions and scenarios can help ensure three key learning outcomes: the system is technically feasible and manageable, fully appreciated, and sustainable. This PhD project focuses on how sustainable energy scenarios can facilitate the energy planning paradigm by addressing these three outcomes.

Based on the socio-technical nature of the energy transition, and numerous interpretive stakeholders involved, to understand the facilitation capability of energy scenarios, the PhD uses a mixed-method, quantitative and qualitative approach. The first two studies use a quantitative technical scenario informed by the socio- aspect of the transition. The third study is qualitative focusing on the energy planning practices of city planners. Based on this, facilitation can be better understood.

Study 1 evaluates low-energy regulation for new buildings and the impact this will have on the sustainable energy system. Results show that as the sustainable energy system configuration transitions, extremely low-energy buildings become inessential. Study 2 assesses a city in 2050 to understand which actions and measures should be taken, and provides a methodology as well. Study 3 analyses eight EU cities and their energy vision and scenario practices and evaluates their strategicness - identifying how scenarios could further facilitate these practices.

The scenarios can facilitate the future energy planning paradigm by directing towards new planning approaches. In regards to policy, due to the complexity of the transition, a dynamic approach to policymaking could be implemented. Regarding the selection of actions and measures and strategicness in cities, integration of holistic, long-term scenarios, using simple methods and adaptable models can facilitate this process. Within the socio-technical transition and learning and co-evolution of stakeholders, this facilitation fits suitably. Further research should focus on action research on stakeholder engagements with energy scenarios within the energy planning paradigm to develop facilitation further.

DANSK RESUME

En afbødning af de værste effekter af klimaforandringer kræver en omlægning fra et energisystem baseret på fossile brændsler til et bæredygtigt energisystem. Byer har et stort energibehov men tilbyder adskillige muligheder for at implementere bæredygtige energiløsninger. Det bæredygtige energisystem vil være kompliceret på grund af energieffektivitet, elektrificering og vil kræve strategisk planlægning. En omlægning er ikke blot teknisk eller økonomisk men også social og involverer læring og samudvikling blandt adskillige interessenter, mange ledelsesniveauer samt relaterede elementer. Disse sammenhænge øger omlægningens kompleksitet væsentligt.

Interessenters og handlingers læring og samudvikling kræver klarhed omkring det bæredygtige energisystem for at håndtere kompleksiteten. Visioner og scenarier kan hjælpe til at sikre tre væsentlige erkendelser: systemet er teknisk muligt og håndterbart, fuldt ud forstået samt viser en bæredygtig vej. Dette ph.d.-projekt fokuserer på, hvordan bæredygtige energiscenarier kan facilitere energiplanlægningsparadigmet ved at adressere disse tre erkendelser.

Ph.d.-afhandlingen benytter en både kvantitativ og kvalitativ tilgang for at forstå energiscenariers faciliteringsevne, hvilket baseres på energiomlægningens sociotekniske karakter samt involveringen af adskillige interessenter. De første to studier benytter et kvantitativt, teknisk scenarie præget af det sociotekniske aspekt af omlægningen. Det tredje studie er kvalitativt og fokuserer på byplanlæggeres praksis i forhold til energiplanlægning. Baseret på dette kan facilitering bedre forstås.

Det første studie evaluerer bestemmelser for lavenergi i nye bygninger og disses indvirkning på det bæredygtige energisystem. Resultater viser, at efterhånden som et re-design af det nuværende energisystem mod det bæredygtige energisystem finder sted, så bliver ekstremt lavenergibygninger unødvendige. Det andet studie vurderer en by i 2050 for at forstå, hvilke handlinger og forholdsregler der skal tages, samt fremsætter en metodologi. Det tredje studie analyserer otte byer i EU, deres energivisioner og scenariepraksis samt evaluerer deres strategievner – dette for at identificere hvordan scenarier kunne fremme faciliteringen af disse praksisser.

Scenarierne kan facilitere det fremtidige energiplanlægningsparadigme ved at lede imod nye tilgange til planlægning. Med hensyn til politik kunne en dynamisk tilgang til lægning af retningslinjer implementeres på grund af omlægningens kompleksitet. Integrationen af holistiske, langsigtede scenarier ved brug af simple metoder og justerbare modeller kan facilitere processen med at udvælge handlinger og forholdsregler samt byers strategiske evner. Denne facilitering er passende inden for den sociotekniske omlægning samt interessenters læring og samudvikling. Yderligere forskning bør fokusere på

handlingsundersøgelser inden for interessenters engagement i forhold til energiscenarier inden for energiplanlægningsparadigmet for at videreudvikle facilitering.

SCIENTIFIC ARTICLES

Primary literature

- **(Study 1)** Drysdale, D., & Mathiesen, B. V. & Paardekooper, S. (2019) Transitioning to a 100% renewable energy system in Denmark by 2050: assessing the impact from expanding the building stock at the same time. Energy Efficiency 12:37–55

- **(Study 2)** Drysdale, D., Mathiesen, B. V. & Lund, H. (2019) From Carbon Calculators to Energy System Analysis in Cities. Energies, 12, 2307

- **(Study 3)** Maya-Drysdale, D., Jensen, L. K. & Mathiesen, B. V. (2020) Energy Vision Strategies for the EU Green New Deal: A Case Study of European Cities. Energies, 13, 2194

Secondary projects/literature

- Mathiesen, B. V., Drysdale, D., Lund, H., Paardekooper, S., Ridjan, I., Connolly, D., Thellufsen, J. Z., Jensen, J. S. (2016) Future Green Buildings: A Key to Cost-Effective Sustainable Energy Systems. Department of Development and Planning, Aalborg University

- Roadmap2025 50 steps towards a carbon-neutral Sønderborg (I acted as a process participant) (2018)

- Djørup S., Sperling K, Steffen Nielsen S., Østergaard P.A., Thellufsen J.Z., Sorknæs P., Lund H. and Drysdale, D. (2020) District Heating Tariffs, Economic Optimisation and Local Strategies during Radical Technological Change. Energies, 13, 1172

- J.Z., Lund, H., Østergaard P.A., Drysdale D., Chang M., Sorknæs, P., Nielsen S., Sperling, K. Djørup S.R. (2020) Smart Energy Cities in a 100% Renewable Energy Context. Thellufsen (accepted in Renewable and Sustainable Energy Reviews)

TABLE OF CONTENTS

CHAPTER 1. INTRODUCTION

This PhD project focuses on the local energy planning paradigm towards sustainable energy (decarbonisation) in cities. Specifically, the project focuses on the complex decarbonised energy system as a concept and design demonstrated through scenarios. The research investigates what this means for the local energy planning paradigm asking the research question:

> *"How can sustainable energy scenarios facilitate the local energy planning paradigm?"*

Local energy planning implies city authority coordination and stakeholder collaboration. However, decarbonisation of the energy system is a climate change issue that involves numerous levels of governance and many stakeholders. Thus, planning the sustainable energy system is complex and includes many elements. Planning approaches or improving energy planning practices could be the focus of this PhD; however, I took a technical systems analysis perspective.

The focus of the PhD narrowed down by participating in an EU "Smart City" project, which emphasises technology implementation, stakeholder engagement, and monitoring. Despite the encouraging efforts, it became apparent during the project that the energy system configuration was lacking awareness. Despite some efforts in project meetings to raise this as a concern, facilitation of project and planning activities from system awareness was lacking.

Secondly, during a Smart Cities and Communities meeting held in Brussels, numerous Smart City Lighthouse representatives attended (involving planners and experts). The meeting was a roundtable discussion about solutions; however, I noticed that the focus was very much on implementation without considering scale or fit within the system. During a Q&A, I asked a question about system integration, and the answer was that we had solved the technical integration of wind since we can build wind turbines relatively quickly. Now the challenge is merely integrating smart solutions (although this is a big challenge in itself). I thought this was a strange perspective considering the meeting was focused on decarbonisation, and there is a need to understand the scope and fit within the system. However, this was absent from the discussion.

During the project and EU meetings, it became clear to me that the system aspect of sustainable energy was missing and misunderstood; thus clarifying the focus of my PhD. This thesis begins by going further into the background and problem mentioned above: a specific theoretical construct and conceptual framework direct the research design. Results from the studies help identify key discussion points, conclusions and further research.

1.1. PROBLEM: SUSTAINABLE ENERGY SYSTEM IMPLICATIONS FOR LOCAL ENERGY PLANNING

Human activities are the leading cause of climate change (IPCC 2007). The release of greenhouse emissions from the burning of ancient fossil fuels drives this change (Hansen et al. 2013). Since 1958, carbon dioxide equivalent (CO_2eq.) emission concentration rose from 315 part per million (ppm) to 413 ppm in 2020, and global temperature has increased by 0.98 °C from 1880 to 2020 (NASA 2020). Current trajectories point to increased emissions to >1000 ppm with business as usual and subsequent temperature change between 2.6-4.8 °C by 2100 (high emissions scenario - RCP8.5), which would lead to catastrophic impacts such as a global sea-level rise of between 0.45 to 0.82 m, among other climatic changes (IPCC 2014).

Mitigation efforts to avoid catastrophic climate change need to drastically slow and end the burning of fossil fuels over the next decades. They involve energy infrastructure change, renewable energy and energy efficiency, biological CO_2 sequestration, and CO_2 capture and storage (IPCC 2014). To 2050, the global economy requires a phase-out of fossil fuels almost wholly (Gambhir et al. 2019; Rogelj et al. 2015). To limit global temperature change to below 1.5C, CO_2 emissions from fossil fuels should decrease at a rate of 3.1% per year from 2020-2040 (Gambhir et al. 2019).

Mitigation will involve a rapid transition from the fossil-fuel system to a “sustainable” (decarbonised) energy system in the next decades. By 2050 renewable energies should dominate the energy system (59%-97% renewable electricity min-max), and the system is more efficient (Rogelj et al. 2018). From 2050 to 2100, biogenic CO_2 sequestration removes CO_2 from the atmosphere (Rogelj et al. 2018).

Sustainable energy is any form of energy that does not directly emit ancient greenhouse emissions, such as renewable energy sources like wind, solar, geothermal, biogenic, hydro, and nuclear. Although the manufacturing of these technologies (and fuel for nuclear) releases greenhouse gas emissions in the current fossil fuel system (Amponsah et al. 2014), as the system decarbonises, life cycle emissions from renewable technologies decrease.

International efforts in response to the climate crisis include the Paris Agreement, where countries submit Intended Nationally Determined Contributions (INDCs) after 2020. The aim is to achieve the ambitious climate goal to limit “the increase in the global average temperature to well below 2 °C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5 °C above pre-industrial levels” (UNFCCC 2015). However, current INDCs need further strengthening over time to achieve this goal (Rogelj et al. 2016). The EU green new deal combines a growth strategy with an ambition for no net emissions of greenhouse gases by 2050, decoupling economic growth from resource consumption (European Commission 2019).

Historically economic activity has correlated with energy demand. As GDP grows, the energy demand follows and vice-versa (Oh and Lee 2004). Today global energy intensity and GDP are going down and decoupling (Enerdata 2020). Energy intensity in Europe has been decoupling since 1990 (European Environment Agency 2020). In the sustainable energy system, decoupling is essential and is a core aim of the EU Green New Deal. Although the EU is reducing local energy demand and CO_2 emissions, Europe imports CO_2 emissions from manufacturing countries such as China, and this is also important to consider in the sustainable energy transition (Davis and Caldeira 2010).

The sustainable energy system will require a new form of energy system flexibility and energy storage due to the fluctuating nature of renewable electricity (Connolly et al. 2012). The sustainable energy system will involve technologies for process enhancement, efficiency increase, system integration, and multi-generation (Dincer and Acar 2017). The electricity production, consumption, conversion, and storage requires a mixture of technologies combining to form an integrated and flexible energy system and enabling real-time transfer and integration of electricity flows, creating flexibility and energy storage (Lund et al. 2015). Creating this flexibility leads to a more complex energy system than the existing system today. However, the increased efficiency in the system will aid the increased decoupling of GDP from energy demand.

Although energy intensity is decreasing in Europe, energy demand still correlates with population density (directly and indirectly), and thus cities have a high energy demand (Madlener and Sunak 2011). Cities have the potential to reduce demand per capita due to various solutions, including energy efficiency upgrades in buildings, district energy, public transport, higher density living, and shorter travel distances (Mosannenzadeh et al. 2017). Cities are at the centre stage of the transition since renewable systems enable energy unit decentralisation and distribution (Vezzoli et al. 2018). The increased emphasis on local implementation of sustainable energy systems is already evident in numerous countries, with the well-known example of Germany (Beermann and Tews 2017).

In recent years, city authorities have initiated actions for the sustainable energy transition. These include: setting ambitious targets like carbon neutrality in the Carbon Neutral Alliance (Carbon Neutral Cities Alliance 2018); setting climate goals within policies, for instance in London (Bulkeley, Castán Broto, and Maassen 2014); joining city-networks to share policies and agendas (Gordon and Johnson 2018); collaborating with stakeholders (Krog 2019; Sperling 2017); and evolving their planning processes, developing visions, scenarios and identifying and implementing projects and actions in energy plans, for instance in Sustainable Energy Action Plans (SEAPs) (Kona et al. 2018). These activities are essential for the development and implementation of low carbon measures in the decarbonised energy system (Geels, Kern, et al. 2016). Research interest in municipal energy system analysis also increased in recent years, rising from 88 related articles (per year) at the start of 2016 (when I began my PhD) to 276 articles (per year) at the end of 2019 (Weinand 2020).

City authorities have a role to play in this sustainable energy transition, although they can lack agency and expertise (Bale et al. 2012; Heaphy 2018). The decarbonisation of the energy system in cities is a complex challenge involving numerous energy sectors and stakeholders. Including local companies, NGOs, national and regional governments, and intermediaries that can help develop visions and manage and govern planning processes (Hodson and Marvin 2009). Therefore local energy planning is a paradigm involving city authority responsibility within a network of stakeholders working horizontally and vertically since climate change is a multi-level governance issue (Kern and Bulkeley 2009).

City plan interventions can influence the sustainable energy transition directly or indirectly—for instance, energy-related provisions through transport planning affect driver behaviour and the emission of greenhouse gas emissions (Bale et al. 2012). However, city authorities do not usually practice sustainable energy planning (Cajot et al. 2015), and, likely, cities do not make holistic energy plans (although they submit SEAPs). Energy planning adds to the wicked problem of city planning in numerous ways, such as adding conflicting objectives and conflicting values from diverse stakeholders (Cajot et al. 2017).

The complexity of the energy system transition - technically and involving numerous stakeholders - requires technical sustainable energy system scenarios based on a system engineering approach (Simpson and Simpson 2011) to help understand and describe this complex system, and aid decision-making (Bale, Varga, and Foxon 2015; Basu et al. 2019; McDowall and Geels 2017). They help to engage the numerous stakeholders and communicate consistently between them. Multiple approaches are suggested in research to model, analyse, and understand the sustainable energy system (James Keirstead, Jennings, and Sivakumar 2012; Manfren, Caputo, and Costa 2011; Pfenninger, Hawkes, and Keirstead 2014). The Smart Energy System approach is a potential sustainable energy concept for cities (Lund et al. 2017). This concept takes a holistic system approach and constrains the decarbonised energy system through sustainable development goals (Dincer and Acar 2017).

I summarise this section in three points: 1) the sustainable energy system is complex, 2) local energy planning is a paradigm involving multiple stakeholders in climate change mitigation, and, 3) local energy planning has wicked challenges requiring new approaches and knowledge inputs. Based on these points, it appears useful to research how sustainable energy system scenarios (system engineering) can facilitate the local energy planning paradigm for sustainable energy in cities, which is the focus of this PhD.

1.1.1. STRUCTURE OF THE PHD

The thesis contains eight Chapters (Figure 1), Chapter 2 provides a background to the problem with further details about the research area by providing more information about the decarbonised energy system and concepts and local energy planning. Chapter 3 describes the research objectives, scope and questions. Chapter 4 describes the theoretical construct and conceptual framework, which is split into four subsections presenting the two leading theories and two main concepts underpinning the PhD and methods. Chapter 5 presents the methodology, which consists of quantitative analysis applying system engineering scenarios as well as qualitative analysis. Three separate case studies answer the research question. Chapter 6 presents a summary of the results for each case study. Chapter 7 discusses the results of the three studies in the context of the theories and concepts and evaluates the research process. Chapter 8 presents conclusions from this PhD and further research.

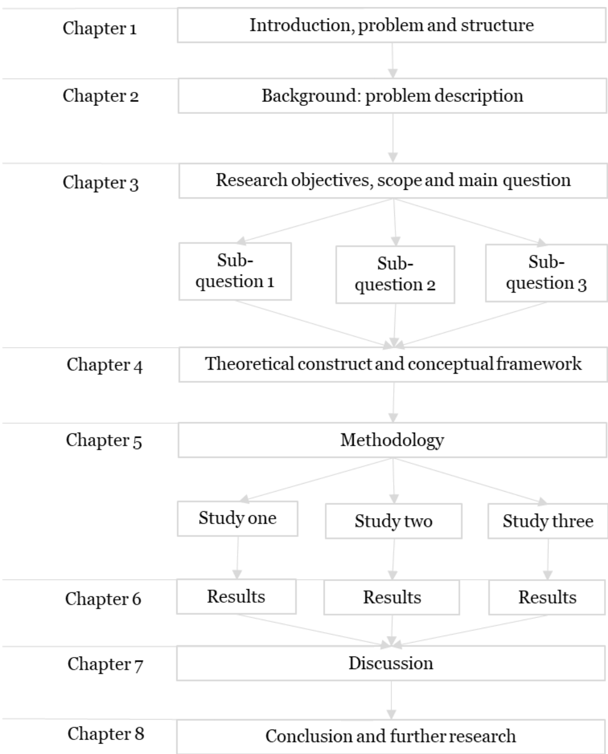


Figure 1: Outline of the PhD research and thesis

CHAPTER 2. BACKGROUND

This section presents the theoretical perspectives on the decarbonised energy system and local energy planning paradigm. The chapter describes focus areas, including sustainable energy concepts in cities, the importance of local energy planning and the role of scenarios in local energy planning. The section finishes by describing the research area for the PhD.

This PhD uses the term “city” to refer to a sub-national region, with a governing authority such as a city, town, village, municipality, and so on. The sub-region can include both urban and rural areas or only urban.

2.1. SUSTAINABLE ENERGY SYSTEM

Decarbonisation involves the transition to an engineered integrated sustainable energy system relying on process enhancement, efficiency increase, system integration, multi-generation (Dincer and Acar 2017), and behavioural change (Gram-Hanssen 2013). Behavioural change is often an exogenous input to system design or modelled separately, for instance, using agent-based models (Scheller, Johanning, and Bruckner 2019). The sustainable energy system will be: highly electrified, based on renewable resources, more energy-efficient, have elements of district energy and hydrogen, high levels of energy distribution, and minimal biogenic fuels due to sustainability concerns and limited resources (Capros et al. 2012; Connolly et al. 2011; Lund 2007; Lund and Mathiesen 2009; Mathiesen, Lund, and Connolly 2012).

The system requires socio-technical system design and transition that balances between production and consumption in short time intervals, i.e. per millisecond to minutes (Lund et al. 2015). The engineered system needs to either consume, convert/integrate or store the generated renewable energy once produced (Lund et al. 2015). With a comparatively low energy storage capacity compared to fossil fuels of today, electrification of the system requires new forms of flexibility and energy storage that differs from the current fossil fuel system (Denholm and Hand 2011). Electric batteries can provide part of the solution, although significantly insufficient and currently expensive (Lund et al. 2016). Although they will serve a dual purpose, for instance, EVs provide a transport solution and an electricity storage solution (Lund and Kempton 2008). Furthermore, the legacy energy system needs upgrading due to the electrification of transport, for example. IRENA predicts total investment in the renewable transition of 130 trillion USD needed to 2050 (IRENA 2020).

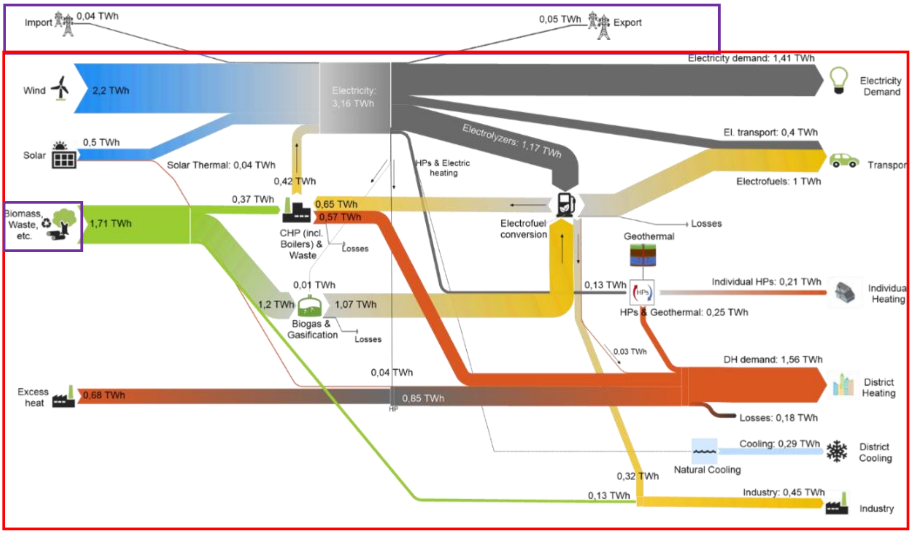
Wind and solar PV (new electricity production capacity) are key technologies with the highest potential for growth and electricity supply. Wind power has been increasing its share of total electricity generation every year for the past two decades in Europe, although more action is needed (European Court of Auditors 2019). Estimates of a 100% renewable Europe state that offshore wind, onshore wind and solar PV may require capacities of 2750GW, 900GWh and 700GW, respectively by 2050 (Connolly, Lund, and Mathiesen 2016). In 2019, installed capacity was 205 GW of wind (onshore and offshore) (Komusanac, Brindley, and Fraile 2020) and 132 GW of solar PV (SolarPower Europe 2019). Mitigation requires both reductions in greenhouse gas emissions from installing renewable energy and continued decline in energy intensity (GDP decoupling from energy consumption) to achieve the sustainable energy transition. Current energy consumption in Europe is already reducing, and the sustainable energy system will help continue this reduction through efficiency gains.

2.1.1. SUSTAINABLE ENERGY SYSTEM CONCEPTS

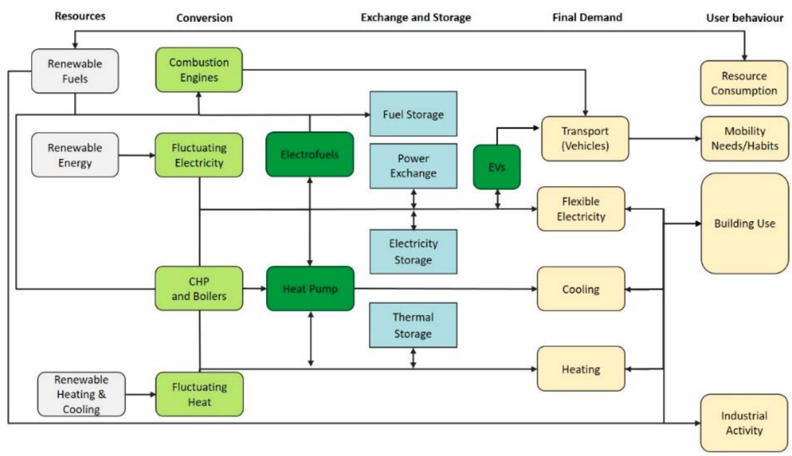
Decarbonisation of the energy system is a complex and highly diverse subject area which relates to the numerous system components (electricity, thermal, gas, transport, buildings, and industry) and their interactions. Research is abundant and growing increasingly in the local energy planning area focusing on topics such as renewable energy, energy storage, district heating, cogeneration (Weinand 2020). Put simply, decarbonisation of an energy system in a city involves the removal of all greenhouse gas emissions from all sectors, which entails reconfiguring the energy infrastructure for the demand-side and the supply side. Cities may not have sufficient land to achieve this reconfiguration which also raises a question about energy system scope. Complexity increases with the flexibility requirements of the sustainable energy system. However, fundamentally the decarbonised energy infrastructure should consist of, "(small- and large- scale) enablers that help, directly or indirectly, with the extraction, production, transportation, and management of energy from producer to consumer" (Edomah, Foulds, and Jones 2017, pg. 766).

Energy demands in the decarbonised energy system need to help enable the management of energy from producer to consumer, directly or indirectly, for instance, by shifting or reducing demand or even increasing demand. Energy supply should focus on enablers for the entire system, including extraction, production, transportation, and also the management of production to consumer (Edomah et al. 2017). Three categories of infrastructure enabling solutions are available: energy conservation, energy efficiency, and renewable energy integration (Lund 2014). Energy conservation directly relates to demand (and indirectly to supply). It involves user behaviour change and the reduction of energy per unit of utility, such as using public transport to travel instead of a car. Energy efficiency directly relates to demand (and indirectly to supply, for instance, district heating). It involves switching to new technologies such as electric vehicles or heat pumps, or Light Emitting Diode (LED) street lighting. Renewable energy adds to the energy supply mix. All are affecting the energy system directly or indirectly. Theoretically, these solutions will gradually diffuse and interlink socio-technically in the current energy system regime until it fully transitions into a new sustainable energy system regime (Geels 2002).

In an integrated sustainable energy system, traditional taxonomies for energy demand and supply (i.e. buildings, transport, power plants, and fuels) will change. They will likely become less important due to the integrated nature of the decarbonised energy system. In the existing energy system, the aim is to reduce energy in each energy sector since this is beneficial to reduce fossil fuel demand and greenhouse gas emissions. In a decarbonised energy system, two key considerations will be essential (apart from the embedded energy and scope three greenhouse gas emissions in imported goods) (Figure 2).



A)



B)

Figure 2. A) Sankey diagram of Aalborg's potential energy system in 2050. (Unpublished paper) Red box and Purple box showing the two primary considerations, internal energy flow and external energy flow, respectively. B) Conceptual interaction between technologies and energy flows in such a future sustainable energy system of a city (Adapted from Henrik Lund, International Journal of Sustainable Energy Planning and Management; Aalborg University Press, 2016 (Lund et al. 2016)."

Firstly, it will be essential to consider the systematised and electrified integration of the local energy system (inside the local boundary) (Weinand, Scheller, and Mckenna 2020). For instance, after producing renewable electricity, it requires consumption, conversion or storage. Thus flexibility is essential and the reduction in the oversupply of electricity. The taxonomy within the systematised and integrated energy system depends on its configuration and integration. For instance, as transport electrifies this can act as energy storage and a supplier of electricity. It is thus making the demand and supply taxonomy more challenging to explain. Buildings could also operate like this if producing renewable energy.

Secondly, it will be essential to consider the external energy exchange with surrounding regions via the two core national grids - electricity and gas - and biogenic resources (Østergaard 2009; J.Z. Thellufsen and Lund 2016; Weinand et al. 2020). Cross-boundary passenger and freight travel is a matter of defining the energy system scope.

Local energy planning for sustainable energy in cities needs to understand the implications of these two key considerations and the required actions. Local planning needs to understand how individual solutions and systematic solutions affect the systematisation and management of energy from production to consumption and exchange of energy across borders and how they integrate. Intertwined with this is how users use energy technologies, which also affects system performance (Gram-Hanssen 2013).

2.2. PLANNING FOR SUSTAINABLE ENERGY IN CITIES

Decarbonisation of the local energy system will require a strategic approach to energy planning. Thery and Zarate, (2009), state that energy planning consists of "determining the optimal mix of energy sources to satisfy a given energy demand." Related to this optimality are general challenges such as temporal, geographical, economic, technical, environmental and social (Thery and Zarate 2009, pg. 266). Thus a complicated task. Energy planning for sustainable energy needs to address these challenges, which this definition does not address. This section goes further into detail describing the local energy planning paradigm and the role of sustainable energy scenarios in this paradigm (partly addressing the challenges), which is the focus of the PhD.

2.2.1. LOCAL ENERGY PLANNING PARADIGM

I perceive the city energy transition as managed via a local energy planning paradigm. Not only is the energy system complex but the transition involves numerous local stakeholders associated with the infrastructure including representatives of utilities, local authority, regulators, developers, businesses, citizens, and consumers (Hodson and Marvin 2010). It is also a multi governance challenge involving stakeholders, regionally, nationally and in the EU, although there is an ever-increasing city level agency (Bulkeley and Betsill 2013).

Firstly, the city authority plays an essential role in the local energy decarbonisation - but not necessarily the most influential position (Bale et al. 2012; Hodson and Marvin 2010). Although *energy planning* for sustainable energy can be defined (loosely), *city planning* is more difficult to define because in different countries it has different roles, forms and is perceived differently over time (Cajot et al. 2017). Hopkins (2001), pg. xiii, defines city planning being "…loosely to refer to intentional interventions in the urban development process, usually by local government. The term "planning" thus subsumes a variety of mechanisms that are in fact quite distinct: regulation, collective choice, organizational design, market correction, citizen participation, and public sector action." (Hopkins 2001, pg. xiii). Thus, the city (urban) planning can serve numerous roles and use numerous instruments.

Over time, city planning has shifted from rational planning to collaborative planning, encouraging participation in holistic approaches (Lawrence 2000; Wachs 2001). Dialogue and communication in participatory environments ideally build consensus between stakeholders, favoured over autocracy and rationality (Connelly and Richardson 2004, 2005; Lawrence 2000; Teriman, Yigitcanlar, and Mayere 2010), thus placing city authorities in a suitable position for local energy planning. Rather than just technical experts, they can be informative, persuasive, and provide financial incentives and engage in collaborative action (Rydin 2010). They can serve in so-called meta-governance capacity (Sehested 2009). However, they are not always the central position, due to lack of political will, financial resources, capacity and capability (Bale et al. 2012; Hodson and Marvin 2010).

Many sustainable energy factors are outside the influence of city authorities, such as energy policy, private consumption in buildings and vehicles, and energy utilities (Bale et al. 2012; Bulkeley 2010; Guy and Marvin 1996). Planners traditionally focus on spatial land-use planning, transport changes, urban design, natural resources (green spaces), infrastructure and services. Dependence on other stakeholders such as companies, citizens for implementing measures, and on related skills and finances, and legitimacy constrain city authorities (Hajer et al. 2015).

Intermediaries can support city authorities with collaboration between horizontal planning departments and stakeholders and vertical levels of governance (Hodson and Marvin 2009). They can service the requirements described above, in a mediating role to integrate plural and different values and perspectives (Späth and Scolobig 2017). The existence of intermediaries within a local energy planning paradigm is a sign of advanced energy system regime change in cities and successful trajectory towards transition (Hodson and Marvin 2010).

Although there is a collaboration between stakeholders and or with intermediaries, city authorities continue to write city plans (revised periodically), possibly including developed visions (setting targets and goals), determining objectives, strategies and actions (BBSR 2017). In an integrated and sustainable city plan, relevant stakeholders should participate, in the planning and implementation phases. Ensuring goals for all of the sustainability is included, based on a systematic assessment of the sustainability of final plans and outcomes (Teriman et al. 2010).

Lastly, climate change (in which local energy planning is part) is a multi-governance issue (Bulkeley and Betsill 2005). The EU influences local energy planning via directives and non-legally binding documents and research projects and initiatives (Cajot et al. 2015). Nationally defined laws and rules infiltrate into city energy planning. The EU also set up the Covenant of Mayors in which there are over 10,000 signatories and around 6500 submitted Sustainable Energy Action Plans (SEAPs) (Covenant of Mayors for Climate & Energy 2019).

In this PhD, it is not essential if city planners are the central players in city decarbonisation. Still, I believe they need to play a role as either facilitators or active participants due to their planning expertise and potential agency. For example, planners could influence energy strategies by becoming part of and shaping markets (Adams and Tiesdell 2013).

In this PhD, I argue that in energy planning for sustainable energy, there needs to be learning in city authorities and private stakeholders (including intermediaries) and the networks between them (Rydin 2010). Consequently, the planning approach of city authorities should maintain collaborative and an action-oriented nature with emphasis on vision-related strategic planning (Albrechts and Balducci 2013).

Visions are an essential part of transition management (Kemp and Loorbach 2005; René Kemp and Loorbach 2006; Rotmans, Kemp, and Asselt 2001) since they create and share an understanding of stakeholder interests (Hodson and Marvin 2009). Participatory vision making and negotiation can engage, inspire and mobilise stakeholders (Hodson and Marvin 2010). They lead to a reference point for the development of networks, commitments and actions (Russell and Williams 2002). Visions are essential when the topic is sustainable energy systems; and more potent when coupled with robust scenarios.

2.2.2. THE ROLE OF QUANTITATIVE SCENARIOS IN LOCAL ENERGY PLANNING

Scenarios quantify qualitative visions (Trutnevyte 2014). Scenarios can be *qualitative* and relate to the social complexities in city decarbonisation. However, in this PhD, sustainable energy scenarios conceptualise quantitative technical systems involving interacting technologies, energy demands and supplies, and resource consumption. In these scenarios, the system is decarbonised and sustainable (at least environmentally and economically). The quantitative scenarios help reduce the cognitive complexity of the technical energy flows and identify emergence (discussed further in Chapter 4).

There are energy system models that attempt to include societal factors within quantitative models - Integrated Transition Assessment Models (Moallemi and Malekpour 2018). However, this PhD excludes the role of organisations, society and business models from the quantitative scenarios. I acknowledge that sustainable technical scenarios do involve a simplification of societal transformations, lacking stakeholders and agency (Hofman, Elzen, and Geels 2004). However, this PhD argues that there are implications from technical scenarios that can facilitate the local energy planning paradigm and incorporate with societal and political scenarios (Geels, McMeekin, and Pfluger 2020).

Mirakyan and Guio (2014) use quantitative scenarios as a central component in their Integrated Energy Planning approach in Phase II. The approach suggests scenarios in collaboration with stakeholders facilitating decision-making. Furthermore, Sustainable Urban Mobility Plans (SUMPs) use quantitative scenarios from transport modelling to facilitate this local energy-related planning (Wefering et al. 2014).

Quantitative sustainable energy scenarios are gaining support within transition research, for instance, Socio-Technical Scenarios in the multi-level perspective (Geels et al. 2020). Socio-Technical Scenarios integrate quantitative scenarios as a component to constrain stakeholder-based storylines in different ways (Auvinen et al. 2015; Foxon 2013; McDowall 2014). Geels et al. (2020) as recent as February 2020 describes a detailed eight-step method that represents the transition process and policymakers, including quantitative sustainable system scenarios that aim to ensure social acceptance and political feasibility. Quantitative scenarios offer interpretations and system requirements, but these can be 'black-boxed' since the scenarios cannot articulate socio-political processes and mechanisms (Geels et al. 2020). Socio-technical analysis and practice theory can contribute to opening this box. Most relevant to this PhD, is that quantitative scenarios are also ‘black-boxed’ because of technical system complexities and hidden system dynamics. This PhD aims to contribute further to this latter black-box issue contributing to its opening—and understanding how this could further facilitate the local energy planning paradigm.

2.3. SUMMARY: SCENARIO IMPLICATIONS FOR LOCAL ENERGY PLANNING PARADIGM

City energy planning for sustainable energy is complex. Naturally, it involves a broad range of stakeholders and stakeholder coalitions, including city authorities, citizens, and stakeholders such as businesses, project developers, financiers, and intermediaries. City authorities are not automatically the central authority in local energy planning. Intermediaries can manage the stakeholders and coalitions with or without the city authority (Hodson and Marvin 2009). Coalitions of stakeholders on multiple levels of governance will continue by learning by doing (Bulkeley 2014) implementing mainstream innovations and novel grassroots innovations for local context specificities (Smith, Fressoli, and Thomas 2014). The creation and learning in these coalitions will identify new unforeseen innovations overtime (Brown et al. 2003).

This PhD aims to understand how sustainable energy scenarios can facilitate the evolution of local energy planning. Understanding the role of sustainable energy scenarios in local energy planning is an opportunity for further improvement of energy planning in cities. Local energy planning by the stakeholders should not only focus on local-initiative approaches - indicated by the comments by the city planner from the EU meeting mentioned in the introduction. This narrow focus can lead to the stakeholders only focusing on short-termism, disregarding wider structural contexts. Furthermore, it can be difficult to generalize outcomes from one location to another (Turnheim et al. 2015). This PhD argues that the facilitation of sustainable energy scenarios within the local energy planning paradigm requires more knowledge in terms of understanding the holistic energy system complexities and dynamics, which accompanies local knowledge and socio-technical analysis.

CHAPTER 3. RESEARCH OBJECTIVES, SCOPE AND RESEARCH QUESTIONS

This PhD aims to explore how sustainable energy scenarios can facilitate the local energy planning paradigm. The hypothesis is that sustainable energy scenarios can demonstrate essential implications that are difficult to see without such an approach. Thus it needs to be integrated into energy planning (this is elaborated further in Chapter 4).

3.1. RESEARCH QUESTIONS

The main research question of the PhD asks:

> *"How can sustainable energy scenarios facilitate the local energy planning paradigm?"*

Three sub-questions answered in three case studies help answer the main research question:

- *How can sustainable energy scenarios facilitate national regulations relevant to local energy planning?*
  - National regulation in this context means the Danish building code (Study 1)
- *How can sustainable energy scenarios facilitate the identification of actions and measures in local energy planning?*
  - Actions and measures in this context mean municipal (authority and stakeholder) actions (i.e. changing infrastructure, spatial planning, developing strategy, engaging stakeholders) and measures (i.e. the amount of the action - capacity, size, quantity) (Study 2)
- *How are city authorities across the EU facilitating their energy planning practice with sustainable energy scenarios?*
  - City authorities across the EU can include intermediaries that support the authority, and energy planning practice relates to the development of the authority plans, which is one of their fundamental capacities (Study 3)

3.2. OBJECTIVES OF THE PHD

The overall objective of this PhD is to contribute to the socio-technical transition theory particularly the research on Socio-Technical Scenarios within the multi-level perspective (Geels et al. 2020), by providing knowledge about the facilitation of sustainable energy scenarios in the local energy transition. The research ultimately would contribute to the advancement and evolution of city energy planning over time, leading to better outcomes in terms of climate change decision-making. Three sub-objectives addressed in three different case studies help achieve the main objective.

Sub-objective 1 (Study 1): Evaluate a core national regulation applied in local energy planning using a technical energy system scenario approach.

> ***Article title: Transitioning to a 100% renewable energy system in Denmark by 2050: assessing the impact from expanding the building stock at the same time.***

Sub-objective 2 (Study 2): Analyse the decarbonisation of a city using a technical sustainable energy system scenario to identify actions and measures suitable for decarbonisation within the context of the country

> ***Article title: From carbon calculators to energy system analysis in cities.***

Sub-objective 3 (Study 3): Place the technical energy system scenario approach within a Strategic Energy Planning context, evaluate the performance of energy planning practices of EU cities, and identify suitable recommendations.

> ***Article title: Energy Vision Strategies for the EU Green New Deal: A Case Study of European Cities.***

3.3. SCOPE OF THE RESEARCH: DELIMITATION

Intuitively, the title and objective of the PhD imply in-depth investigation on local energy planning methods and guidelines, prescribed nationally or voluntarily applied in cities. However, the aim is not to analyse the development and merits of these methods via detailed investigation (although Study 3 does this partly). The objective is to take a technical energy system perspective from which to reflect on local energy planning. The methodology of this PhD focuses on city level energy planning. Still, it takes a departure from emphasising the role of technical energy system scenarios to understand how they can facilitate local energy planning. Communication of sustainable energy scenarios to planners and stakeholders is challenging, and a barrier (Iyer and Edmonds 2018) and this PhD does not address this, although it facilitates this in Study 2.

The research assesses and describes sustainable energy scenarios from a technical planning perspective. Although effective local energy planning requires stakeholder collaboration and input and energy planning concepts emphasise the social aspect of the scenarios (Geels et al. 2020; Mirakyan and Guio 2013), technical analyses provide prior insight to engagement, and the PhD focuses on this prior insight. Study 1 assesses regulatory actions towards sustainable energy and indicates how sustainable energy scenarios can facilitate these actions. Although policy creation does not respond solely to the influence of rational quantitative analysis (Wiseman, Edwards, and Luckins 2013), policy decisions should change with new information (Malekpour, de

Haan, and Brown 2016). Study 1 provides new information about how the reduction of energy is not always beneficial to decarbonise the energy system.

Stakeholders with differing objectives and perspectives are involved in local energy planning, and Study 2 develops a method for vision and scenario creation for these stakeholders. Allowing learning and co-evolution, particularly around the selection of actions and measures. The identification of actions and measures is critical for the strategic implementation of sustainable energy systems (Dincer and Acar 2017; Sperling, Hvelplund, and Mathiesen 2011). City authorities and related stakeholders need to ensure local plans are well suited and are not piecemeal and ineffective (Moloney and Horne 2015). This study does not consider the societal implications of the scenario, with implications for final decision-making. Still, the scenario is well suited for integration in a Socio-Technical Scenario since it includes a detailed methodological description and detailed presentation of results.

City authorities present an opportunity to act as a central stakeholder in local energy planning (even if not today), and Study 3 uses a conceptual framework for Strategic Energy Planning to analyse how current energy planning is happening in a selection of EU cities. Based on the results and the analytical framework, Study 3 provides some recommendations. The research does not propose how to make scenario development approaches easier or to explain how to use scenarios. Furthermore, the research does not investigate how to bring the practice of scenario thinking and making into city energy planning (although this is supported by how the scenarios look and what they can deliver which is the main focus of this PhD). This study mentions three levels of strategy, in which level one and two relate to integrating energy planning practice into city planning as an idea (level one) and as a sufficient practice (level two). Level three is about energy vision (and scenario) creation and implementation, which is the focus of Study 3.

CHAPTER 4. THEORETICAL CONSTRUCT & CONCEPTUAL FRAMEWORK

It is indisputable that the sustainable energy system will require a large-scale, long-term and multi-dimensional transition from the fossil fuel system. Most likely technologies will diffuse into markets (and new markets will form) involving numerous incumbent stakeholders and new stakeholders (Geels, Hekkert, and Jacobsson 2008). What is disputable is the way the transition happens and subsequently, how it can be guided (or if this is possible). In this PhD, I take the position that the transition is conflictual, and the energy regime change involves interpretive stakeholders building coalitions through a process of fighting, negotiating, searching and learning (Geels 2010).

The quantitative sustainable energy scenarios that are central to my PhD follow a form of positivist philosophy of science and rational choice ontology. However, an interpretist ontology based on the socio-technical transition theory, the multi-level perspective, guides the PhD research (Geels 2002 2010). This ontology guided the design of my theoretical framework and methodology.

Multiple theories are required to address the various problems and dimensions related to the energy system transition (Grubb, Hourcade, and Neuhoff 2015). The multi-level perspective is a theoretical perspective that allows the use of multiple theories and a combination of methods, as demonstrated by Socio-Technical Scenarios (Geels et al. 2020). In this section, I describe the multi-level perspective further, and I also describe the supplementary theories of system complexity and sustainable development and two concepts for decarbonized energy (used in Study 1 and Study 2) and Strategic Energy Planning (used in Study 3).

4.1. PART 1: SOCIO-TECHNICAL TRANSITION & THE MULTI-LEVEL PERSPECTIVE

The multi-level perspective describes how radical innovations, emerging in niches (Kemp, Schot, and Hoogma 1998), interact in multiple dimensions with existing socio-technical regimes until there is regime change (Geels, Kern, et al. 2016). The energy system transition involves a reconfiguration from the fossil-fuel regime to a renewable energy regime where developments are adopted, link up and reinforce each other in the regime (Geels and Schot 2007).

Incumbent regimes follow predictable trajectories due to path dependence and a lock-in mechanism (Fuenfschilling and Truffer 2014; Unruh 2002); therefore, conflict is common. New choices need to challenge regimes (Lund

2014). A regime shift will occur by aligning successful development processes within niches, reinforced by changes within the regime and the socio-technical landscape (Kemp, Rip, and Schot 2000). Pressure from the landscape and tensions in the regime are essential in creating windows of opportunities for innovations from niches (Geels and Schot 2007). Landscape developments, which cause regime change conflicts, can be demographics, ideology, climate change, economic crisis and so on.

The main premise of the multi-level perspective is that the sustainable transition is a deliberative social learning process. Rather than just technocratic (Smith and Stirling 2010). Interpretive stakeholders develop shared meaning and co-evolve through social interaction, learning, sense-making and debates (Geels 2004). Thus, helping change scientific knowledge, technical artefacts, cultural/symbolic meanings, user practices, consumption patterns, industrial structures and networks, policy, markets, as well as infrastructure (Geels 2004; Hofman et al. 2004). The socio-technical system for electricity provision and use demonstrates an example of these elements (Figure 3).

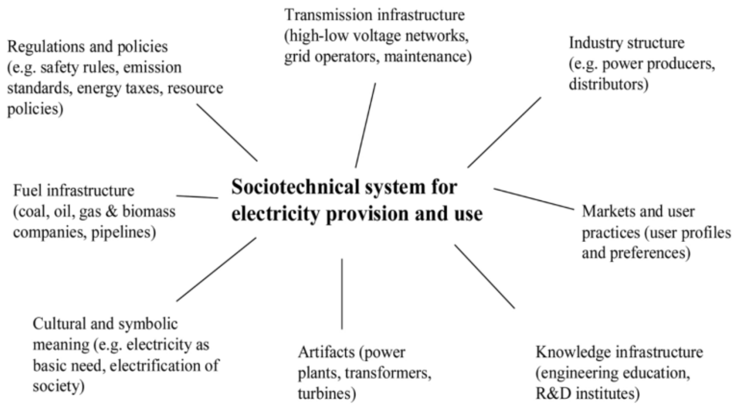


Figure 3: Socio-technical system for electricity provision and use (Hofman et al. 2004)

Technological development and stabilisation are not only led by scientists and engineers but also policymakers, businesses, non-government organisations, citizens, interrelating through regulations, policies, consumption and investments (Geels and Schot 2007). However, different stakeholder types have different social realities and ontologies of transition. Therefore, Geels, Berkhout, and Van Vuuren (2016) argues for a plurality of approaches to be used alongside the multi-level perspective for policy formation and action, addressing different policymaker knowledge needs.

Socio-technical transition research should bridge three theoretical disciplines with structured dialogue and recursive interaction between them, informing governance decisions and practice (Geels, Berkhout, et al. 2016; Turnheim et al. 2015). Each focuses on a different time-scale: 1) Integrated Assessment Models (IAM): future to present, 2) the multi-level perspective: recent past to present to near future, and 3) practice theory: present. These approaches should not integrate due to differing ontologies and epistemologies, making it difficult if not impossible. Still, instead, they all should be bridged and address the weaknesses of each other with the multi-level perspective being the central theory (Geels, Berkhout, et al. 2016). This PhD focuses on creating scenarios with an Integrated Assessment Model, which can inform and bridge with the other two approaches.

4.1.1. MULTI-LEVEL PERSPECTIVE AND THE LOCAL ENERGY PLANNING PARADIGM

It is likely cities will involve a reconfiguration transition which involves solving local problems (improving performance or small problems) with symbiotic innovations (add-on or component replacement) in niches which subsequently trigger adjustment of the basic architecture of the regime (Geels and Schot 2007). In this transition, stakeholders learn and explore new combinations between old and new regime elements leading to technical changes and changes in user search heuristics, perceptions, and practices (Geels and Schot 2007). Demonstrated already with street lighting upgrades, changing heating solutions, and upgrading municipal buildings.

Regime change involves more than these incremental changes. Incumbent regimes explain change linearly, and different interpretive social groups need to challenge this through learning and co-evolution (Sovacool and Hess 2017). Institutions and shared beliefs, interests, capabilities also need to change (Geels 2002). As niche innovations build up in networks that involve deep and broad learning and robust and specific expectations (Sovacool and Hess 2017), this should be within the context of decarbonising the energy system.

'Endogenous enactment' of social groups (i.e. city authorities, intermediaries, stakeholders) is needed to conceptualise towards a socio-technical understanding of the energy transition pathways (Geels, Kern, et al. 2016). It involves experimentation, deliberation, learning, and co-evolution of innovative solutions, user practices and regulations for the system transition (Schot and Geels 2008). Visions, scenarios and actions need to reconfigure understandings and beliefs about the decarbonised energy system (Voß, Smith, and Grin 2009). Enhancing knowledge, social acceptance and political feasibility (Geels, Kern, et al. 2016; Hofman and Elzen 2010).

Sustainable energy scenarios aid learning and co-evolution of stakeholders that surround niche innovations. This is by describing their role in new ways, which relates to the sociology of innovation, where innovation is a socially enacted process (Geels, Berkhout, et al. 2016). Socio-Technical Scenarios are an example of this thinking since they combine and adopt both quantitative (technical) and qualitative (socio-) inputs. Furthermore, the multi-level perspective aligns with policy networks and coalitions of advocates that conceptualise policy-making processes around consultations, negotiations, and power struggles (Geels, Kern, et al. 2016).

Lastly, although landscape pressures are often related to cities, the role of cities within transitions is uncertain, and often cities have different types of relationships with the national transitions (Hodson and Marvin 2010). Transitions pass down to cities (Hodson and Marvin 2009). Therefore understanding the role of cities in transitions should also consider the city within the multi-level governance (Hodson and Marvin 2010).

4.2. PART 2: SYSTEM ENGINEERING APPROACH TO SUSTAINABLE ENERGY SCENARIOS

Decarbonised energy will involve not only a new regime of technologies and stakeholder networks but also a new energy system regime, formed from numerous niche developments – niche-cumulations - of radical innovations within a system reconfiguration (Geels 2002). Due to the complexity of the decarbonised energy system, it will require quantification. This section describes the theory and concepts related to this.

4.2.1. SYSTEM ENGINEERING THEORIES

A technical energy system analysis is a system engineering practice. Quantitative system engineering studies are within the branch of general systems theory (Simpson and Simpson 2011), which aim to analyse and understand the complex non-linear interactions and behaviour of system components (Fraser and Gosavi 2010; Loorbach 2010). Quantification scenarios of the complex decarbonised energy system can address and understand (on different levels and in various iterations depending who the target audience is) three main issues: 1) make the system technically feasible and manageable (due to links between components and uncertainties), 2) fully appreciated (understanding the unpredictable system outcomes and emergence), and 3) sustainability (understanding the nonlinear processes of change and innovation and system evolution) (Dincer and Acar 2017; Fraser and Gosavi 2010; Loorbach 2010). The third aspect relates to the sustainable development theory used to define the decarbonised system concept, and Section 4.3.1 describes this further.

One: Technically feasible and manageable

The decarbonised energy system is complex. Numerous definitions exist for complexity, and Warfield 2002 provides an interesting and useful definition, “Complexity is that sensation experienced in the human mind when, in observing or considering a system, frustration arises from lack of comprehension of what is being explored” (Warfield 2002, pg. 20). Furthermore as described in Figure 2, system complexity arises from the fact that a system (subsystem) exists within a larger system, and thus the larger system should not be sub-optimised by the smaller system (Fraser and Gosavi 2010; J.Z. Thellufsen and Lund 2016). System analysis must consider numerous aspects that create the overall behaviour of the system. These include: the number of objects in a system; the different types of objects in a system (artefacts and people); and the relationships and interactions in a system (Simpson and Simpson 2011). Lastly, an important consideration of the multi-level perspective and systems theory is that systems include humans (Fraser and Gosavi 2010).

Two: Fully appreciated

Combined, the complexity and uncertainty surrounding systems are not merely about the objects and their interactions. The relations and interactions between the objects cannot infer the behaviour of the system as a whole - the whole is more than its parts (Steward 1981). This relates to the dynamic nature of the system and emergence (Goldstein 2004).

Within the learning and co-evolution of the multi-level perspective, emergence is a significant factor since it affects how stakeholders can sense and understand the meaning of the system niches and technologies in the transition to the sustainable energy regime.

4.3. PART 3: CONCEPT FOR A SUSTAINABLE ENERGY SYSTEM

A technological concept of the sustainable energy system in the new regime is useful for informing learning, co-evolution, and narratives. Numerous studies have researched sustainable energy within cities (Weinand et al. 2020). However, due to their disparity (related to the multi-faceted and complex nature of the energy system), a basic conceptual framework is still required for cities to manage their planning, addressing numerous challenges analytically. Therefore, the PhD defines a conceptual framework for a sustainable energy system and uses this in the research. Sustainable development theory frames the concept.

4.3.1. SUSTAINABLE DEVELOPMENT THEORY

Sustainable development theory addresses the third issue of quantification scenarios - sustainability.

Three: sustainability. Normative goals constraint the future decarbonised energy system configuration based on the theory of sustainable development. The theory evaluates the actual contribution socio-technical systems make as they diffuse and the equity between current generations and the future (Sovacool and Hess 2017). The dominating normative goal for a sustainable energy system is to avoid catastrophic climate change (i.e. limit global temperature rise to 1.5C) which would affect future generations. Normative goals exist for other sustainability aspects, including other environmental goals (resource consumption), economy, society (equity), and culture. Sustainable development goals constrain the sustainable energy system within the new energy regime.

4.3.2. SMART ENERGY SYSTEM

This PhD uses the three issues described above (technical feasibility, identification of emergence, and sustainability) to define a decarbonised energy system concept. The Smart Energy System concept meets these three issues. This concept focuses on a sustainable, feasible and holistic energy system. It ensures that the sustainable energy system is analysed holistically, including each energy sector (Dincer and Acar 2017; Lund et al. 2017).

It aims to make the energy system as sustainable as possible, seeking out all opportunities for efficiency and cost-effectiveness. Its sustainability requirements include: exergitically sound; energetically sound; environmentally benign; economically feasible; commercially viable; socially acceptable; integrable; and reliable (Dincer and Acar 2017). Smart Energy System as a concept involves all the basic sustainable energy system engineering elements including process enhancement, efficiency increase, system integration and multi-generation (Dincer and Acar 2017).

Smart Energy System advances beyond the concept of the smart grid (focused only on electricity) by including smart electricity grids, smart thermal grids and smart gas grids (Lund et al. 2017). All being integrated and interacting via energy conversion technologies and energy storages (Paardekooper, Lund, and Lund 2019). Primary sustainability considerations include fuel use, renewable energy shares, CO_2 emissions, and economic costs. More advanced system engineering elements include reserve power capacity requirement, use of import and export of energy, larger system integration (island vs connected), and multigeneration/power plant operation (Østergaard 2009).

Numerous studies have analysed this concept within countries (Connolly et al. 2016; Dominković et al. 2016; Mathiesen, Lund, Connolly, et al. 2015). Also, research has applied the concept in city cases, energy sectors and technology applications (Bačeković and Østergaard 2018; Dominković et al. 2018; Lund et al. 2014; Mathiesen, Lund, Connolly, et al. 2015; Prina et al. 2015).

4.4. PART 4. PLANNING SUSTAINABLE ENERGY STRATEGICALLY

The three critical issues of systems analysis require a rational planning approach. Involving four main steps: (a) analysis of the situation, (b) make goals, (c) identify possible actions, and (d) evaluate and compare consequences of actions (Meyerson and Banfield 1955). Based on this rationality, the PhD methodology researches the facilitation of energy system engineering sustainable energy scenarios within the energy planning paradigm.

Lastly, since collaborative planning is the dominant form of planning in city planning today, a Strategic Energy Planning approach to addressing this rationality is required (Krog and Sperling 2019; Sperling et al. 2011). This PhD uses a Strategic Energy Planning approach as an analysis framework in Study 3.

CHAPTER 5. METHODOLOGY

The methodology of this PhD aims to answer the research question.

> "*How can sustainable energy scenarios facilitate the local energy planning paradigm?*"

I derived the research question by questioning the role of sustainable energy scenarios in the local energy planning paradigm. The question contains three main parts: local energy planning, paradigm, and facilitate.

Local energy planning involves city authorities. However, as mentioned above, they are not the only involved stakeholders in the planning. In the socio-technical energy system regime transition, numerous stakeholders are involved in multiple levels of governance - vertically from EU to city level (Cajot et al. 2015), and horizontally in cities between departments, or with external stakeholders including intermediaries (Hodson and Marvin 2010). Therefore, local energy planning refers to several stakeholder groups, not exclusively the city authority.

Subsequently, the paradigm of practising local energy planning is diverse as well. The paradigm of local energy planning includes micro-scale planning with actual plan preparation by city authorities, to meso-scale with the engagement of stakeholders, and macro-scale with governance engagement with national level or EU level.

Lastly, the definition of "facilitate" is, "to make an action or a process possible or easier (Oxford Advanced Learner's Dictionary 2020)". Thus, within the local energy planning paradigm facilitation can be about making the energy planning practice possible or easier in each of the three planning levels - micro, meso or macro. The research thus can relate to any of the stakeholders involved and any of the practices involved. However, in this PhD, the focus is on facilitation at the sub-national micro-scale level, which involves city authority, local stakeholders (i.e. businesses, financiers, building associations), and intermediaries and citizens.

The PhD research applies a mixed-method methodology directed by the interpretist ontology, combining both quantitative and qualitative methods. Although Study 2 undertook quantitative analysis without the involvement of affected stakeholders, prior involvement with stakeholders (Section 5.3 describes this) informed the research design. The results from the quantitative and qualitative research can inform and evolve the local energy planning paradigm for socio-technical transition within EU cities.

5.1. RESEARCH METHODS

The empirical research period of the PhD was from 2017 to 2019, and the research methods began from a broad perspective without particular engagement with any stakeholder group. As the methods developed, the research narrowed down to focus on city planners and their planning practices in Study 3. Although the local energy planning paradigm is complex, city planners should have a central role in energy planning, strongly related to their meta-governance capacity and city planning capacity (Sehested 2009). Intermediaries can also play an important role as well ideally in partnership with the city authority (this is evident in the Study 3 results). Study 1 and Study 2 were in-depth case studies allowing detailed investigation and analysis. Study 3 was a case study design but across a stratified sample and thus had limited depth (Flyvbjerg 2006).

Regime change involves learning and co-evolution of numerous stakeholders. Learning from quantitative data and visualisation, via prose and structural graphs, is an essential part of understanding complexity (Warfield 1994). Quantitative analysis in Study 1 and Study 2 provided a basis for graphical illustration and prose for this communication. Study 1 analysed a popular sustainable solution (near Zero Energy Buildings) in the context of the decarbonised system (based on my theoretical and conceptual perspective). Sustainable energy in buildings is the focus since they have massive energy consumption in Europe and are relatively easy (technologically) to address via off-the-shelf solutions.

Due to the multiple levels of governance, specific regulations affect cities, which they are not able to control. Study 1 focused on the national level context (Denmark) focusing on such a regulation. Due to the nature of the topic and regulation, it was not possible to research this regulation from the city level perspective. Study 1 focuses on the Danish building code for new buildings (specifically focusing on near Zero Energy Buildings) which is influenced by the EU legal instrument Energy Performance of Building Directive (EPBD) (The European Parliament and the Council of the European Union 2010). This legal instrument affects planning at the national (regulation) and city level since it influences EU member building codes, which infiltrate the city level. This EU directive aims to direct the planning of new buildings to help decarbonise the energy system.

The research method applied the Smart Energy System concept to construct sustainable energy scenarios for 2050 to assess this Danish regulation and its aims. This study developed results from the sustainable energy scenarios that could be used by cities (or various stakeholder groups) to critique and influence national-level building codes (and possibly EU directives)—thus facilitating the local energy planning paradigm. The study also provides a methodology that involves developing sustainable energy scenarios as an analysis instrument for energy planning facilitation.

Study 2 also applied sustainable energy scenarios based on the Smart Energy System concept. However, the analysis was on the decarbonisation of Sønderborg municipality in Denmark by 2050. The study scope is at the city (municipal) boundary and narrows down to city level stakeholders, which could involve city authority, intermediaries or other stakeholders. The method analysed the decarbonisation of the energy system and identified actions and measures required to achieve this. Analysis of the sustainable energy system in the city was in the context of the national sustainable energy system.

The results of Study 2 could help the municipality communicate with national or EU level of government, or city network partners, regarding the decarbonisation of their energy system (Sperling et al. 2011). The study provides results and a methodology to inform and facilitate local energy planning by the city authority, stakeholders or intermediaries. Lastly, the results of the study allow for an understanding of the sustainable energy system at a screening (sailors) and in-depth (divers) level (Braunreiter and Blumer 2018).

Study 3 narrows down on the facilitation of energy planning within city authorities (which could be in partnership with an intermediary). Although Study 1 and Study 2 provide quantitative results, theoretically, the transition to the sustainable energy regime will involve interpretive stakeholders and related societal aspects, and those study results can inform this. However, rather than limiting the PhD studies to quantitative analyses, Study 3 focused on city energy planners (and intermediary representatives) directly to understand their perspectives and planning activities.

Study 3 involved eight EU cities and planners in gathering information about their sustainable energy planning. From this perspective, it was possible to interpret their activities to understand how sustainable energy scenarios could facilitate their energy planning. This study applied the concept of Strategic Energy Planning (informed by the Smart Energy System) in this interpretation (Krog and Sperling 2019). The study was explorative with a limited in-depth examination of the planning activities since this was not the aim. Instead, the study aimed to gather data on the current practice from existing energy planning data (written plans) and new data collected via interviews.

5.2. RESEARCH TECHNIQUES: DATA COLLECTION

The PhD project applied three main research techniques, both quantitative and qualitative, applicable in a case study research (Sovacool, Axsen, and Sorrell 2018). These techniques collected the appropriate data to answer the research question, with the data being: 1) system engineering scenario numerical data, 2) existing numerical and written data, and 3) interview data.

Study 1 and 2 used collected data and system engineering scenario data and Study 3 used interview data and existing written data.

5.2.1. STUDY 1 AND STUDY 2: SYSTEM ENGINEERING SCENARIOS

Study 1 and Study 2 required existing data. Both studies used a Danish sustainable energy scenario for 2050 - IDA Energy Vision 2050 (Mathiesen, Lund, Hansen, et al. 2015), and extracted data for 2015 and 2050 for the appropriate applicability. Government statistical energy data and supplementary sources provided data in the IDA Energy Vision 2050. The study includes user behaviour predictions. The background report describes the data within the scenarios (B.V. Mathiesen, Lund, Hansen, et al. 2015).

Existing numerical data supplemented the Danish 2050 scenario in Study 1 and Study 2. Study 1 analysed the Danish energy system in 2050, focusing on the building stock. Existing data for the Danish building stock came from the Danish Central Register of Buildings and Dwellings (BBR) and Wittchen, Kragh, and Aggerholm (2016). This included building stock and energy demand (heated floor space) data for the buildings assessed in the study (residential and service buildings, representing 85% of heated floor space). This detailed building stock data provided a baseline for 2015 and enabled future predictions.

In Study 2, recent local energy data was required and collected from numerous local sources in Sønderborg municipality and consultancies involved with the Strategic Energy Plan developed in 2018 (ProjectZero 2018).

The creation of new sustainable energy scenarios were central components in Study 1 and Study 2 to generate data to answer the research question. These scenarios were for 2050 for Denmark and Sønderborg municipality, respectively; based on the system engineering approach. This approach addresses the three critical issues related to the complex energy system: technically feasible and manageable, fully appreciated and sustainable (as described above in Chapter 4). The prose and graphics developed from the scenarios make the complex relationships in the system visible and provide overview and meaning (Simpson and Simpson 2011). The scenarios help demonstrate how sustainable energy scenarios can facilitate local energy planning in numerous ways. For instance, using systems engineering one can measure the degree of emergence quantitatively, using statistical tools like the analysis of variance (Thellufsen and Lund 2015).

Practically, energy planning for individual solutions on their own does not cause the emergence nor does the entire system, but rather mid-level solution configurations do. Thus, the facilitation of planning relates to avoiding understanding solutions on an individual level (reductionism (Sondeijker et al. 2006) used in SEAPs (Saheb et al. 2014) and traditional collaborative city planning) or at the highest systemic level (system modelling, i.e. optimisation for economic values). Instead, in the mid-level where solutions interact, and emergence can be understood, for instance, in district heating systems.

EnergyPLAN

System engineering scenarios in Study 1 and Study 2 were all developed and modelled in EnergyPLAN (Lund and Department of Development and Planning Aalborg University 2015) which provided new numerical data. Numerous models exist for local energy analyses (Allegrini et al. 2015; Huang et al. 2015; J. Keirstead, Jennings, and Sivakumar 2012; Ringkjøb, Haugan, and Solbrekke 2018; Weinand et al. 2020). Models can focus on technology design, building design, urban climate, system design, policy assessment and transportation; each with different scopes for spatial (technology to city) and temporal (hourly to annual) aspects and methods of analysis (simulation, optimisation, empirical, econometric). Furthermore, supply and demand data can be endogenous or exogenous to the model (J. Keirstead et al. 2012; Weinand et al. 2020).

EnergyPLAN is an energy system design tool for communities as opposed to a top-down method or bottom-up model for community energy planning (i.e. making master plans, regulatory plans, site plans or architectural design) (Huang et al. 2015). It is an hour-by-hour input/output deterministic simulation tool for the entire energy system, including electricity, heating, transport and gas. Although the model includes all investment costs for system components, it optimises for the operation of the system as opposed to the investment optimisation. It provides all necessary data for analysis and visualisation and for creating prose and graphs (Warfield 1994), thus making the energy system and key energy technologies transparent for learning.

EnergyPlan operates by technical or market-based prioritisation of technology operation. For instance, technical means least fuel technologies dispatched first, and the highest fuel-consuming units dispatched last. Economic means the least marginal cost technology dispatched first, and the highest marginal cost dispatched last.

EnergyPLAN is suitable due to its functionality around energy system design demonstrated by its use in numerous studies (Østergaard 2015; Weinand et al. 2020). By process of elimination (based on Connolly (2010)), I selected EnergyPLAN from other tools that could model 100% renewable energy systems. The main reasons being its focus on shorter time steps (1 hour), allowing the understanding of system dynamics and emergence and not being black-boxed (Geels et al. 2020). It allows users to compute numerous near-optimal scenarios for a sustainable energy system and provide hour-by-hour energy data (Mahbub et al. 2016). The model is applicable at the local level and national level, allowing communication between the two levels. Furthermore, it will enable to use scenarios with people and to identify components and relations that enable seeing where the human is needed, i.e.

not optimising to investment costs, which can lead to inappropriate real-world modelling (Trutnevyte 2016).

Furthermore, in the energy planning paradigm, speed to respond to energy planning processes at the city level is essential since there are numerous stakeholder feedbacks. Therefore, other factors include cost (it is freeware), technologies included (it includes all modern and future technologies), economic assessment (socio-economic analysis), support and ease of use (simulations in milliseconds allowing numerous heuristic iterations).

5.2.2. STUDY 3: INTERVIEWS

Study 3 was an explorative qualitative case study analysis providing insight into energy planning in cities (Yin 2009). The study relied on existing written data (city plans) and new interview data giving insight on the interviewee perspective (Bryman 2003). These data types provided insight into the energy planning practices of the eight cities. Semi-structured interviews used a questionnaire developed in the context of the conceptual framework of Strategic Energy Planning. During the interviews, the order of questions changed as the conversation flowed (Rowley 2012) however, still addressing the main themes. Also, questions and answers around additional themes unused in the study gave further context and informed the areas relevant to the study. The interview data were analysed using content analysis that shifted through several levels of abstraction from meaning units to codes, categories and themes (Erlingsson and Brysiewicz 2017). The themes informed the results and conclusions.

5.3. ETHICS AND CONTEXTUALITY OF KNOWLEDGE

The PhD followed ‘The Danish Code of Conduct for Research Integrity’ (Ministry of Higher Education and Science 2014). Study 1 and Study 2 rely on quantitative data analysis from publically available data. There was no involvement of people other than the authors in the studies. Although, during my PhD, I participated in two research projects and one Strategic Energy Planning endeavour, each involving active engagement with stakeholders. The topic or method of these activities connected to each study in the PhD. These projects could epistemically contextualise the studies. However, my theoretical construct and conceptual framework directed my research design and methods. Study 1 related to the topic in the Future Green Buildings project (Mathiesen et al. 2016). Study 2 related to the topic in SmartEnCity and ProjectZero Strategic Energy Planning for Sønderborg municipality (ProjectZero 2018). Study 3 related to the main project topic in SmartEnCity (TECNALIA Research & Innovation 2020).

To ensure accuracy, validation of collected data was rigorous (within the time constraints). Strict modelling practice ensured that generated data had a low instance of errors in data entry and calculations. The articles clearly described the methodology of all studies. Furthermore, following The Danish Social Science Research Council (2002), Study 3 supports and facilitates the development of the energy planning paradigm in the interviewees' interest, and all cities and interviewees were anonymised. I informed each interviewee about the use of their answers in PhD research.

CHAPTER 6. RESULTS: SUMMARY OF STUDIES

6.1. STUDY 1: TRANSITIONING TO A 100% RENEWABLE ENERGY SYSTEM IN DENMARK BY 2050: ASSESSING THE IMPACT FROM EXPANDING THE BUILDING STOCK AT THE SAME TIME

Energy demand will need to decrease in the sustainable energy system. The building stock has a significant energy demand (40% of European energy consumption), and Study 1 focused on this topic. Near Zero Energy Buildings (nZEBs) are seen as a measure that cities can use to both reduce energy demand and produce renewable energy. The EU defines them as "a building with very high energy performance where the nearly zero or low amount of energy required should be extensively covered by renewable sources produced on-site or nearby" (The European Parliament and the Council of the European Union 2010).

Based on the European Performance of Buildings Directive (EPBD) from 2010 there is a mandatory requirement for building nZEBs for public buildings in 2019 and all other residential and non-residential buildings by 2021 (The European Parliament and the Council of the European Union 2010). The ambition is to contribute to the decarbonisation of the energy system. EU member states can set their own net primary energy demand for the nZEBs. This study focused on the Danish building code, influenced by the EPBD. In 2008, the Danish government arbitrarily decided to reduce net primary energy demand for new buildings by 25% every five years from 2006 to 2025, from which all new buildings have 0 kWh/m^{2}y net primary energy demand (Dyck-Madsen and Jarby 2016; Thomsen 2014).

The study (Drysdale, Mathiesen, and Paardekooper 2019) evaluated these new building requirements within the context of the 2050 decarbonised energy system in Denmark. The aim was to assess whether or not Denmark should mandate these strict nZEB conditions in future years after 2020. The case study examines and evaluates how energy system scenarios can facilitate the local energy planning paradigm by evaluating the regulation in this context.

The study uses a backcasting sustainable energy study considering numerous current trends and realities in the building stock. Such as the existing building stock today and its energy demand, and trends in demolition and new build rates. As opposed to analysing individual buildings and using a reductionist approach, the analysis focuses on the entire building stock within the decarbonised energy system. The results make it is possible to see the large-scale impact of nZEBs on the sustainable energy system. Analysis of the existing and new building stock was in the context of Denmark in 2050 (residential and service buildings). IDA Energy Vision 2050 provided the

2050 decarbonised energy system and is a technically balanced sustainable energy system.

6.1.1. MAIN RESULTS AND CONCLUSIONS

Residential nZEBs exclude electricity consumption for appliances and lighting (non-residential buildings include lighting), which is a large proportion of the total energy demand in these buildings today. With these exclusions, heating becomes the main energy demand. Therefore, the principal results relate to the heat demand of existing and new buildings. The study excludes the exchange of energy (electric) between the buildings and national grids since the focus is on gross heat demand.

Technical results

- Today the existing building stock accounts for around 25% of the total primary energy demand of the energy system
- Within the 2050 decarbonised energy system the total heat demand of the building stock would account for approximately 35% of the total primary energy demand – the proportion changes since total primary energy reduces by 35% from 2016 to 2050
- In 2050 the existing buildings would account for approximately 80% of the total heat demand – new buildings 20%
- In 2016 existing buildings consume on average 132 kWh/m^2 and in the sustainable 2050 decarbonised energy system this would need to decrease to 80kWh/m^2
- In 2016 new buildings are being built with an average heat demand of 56 kWh/m^2
- If existing buildings retain average heat demand of 132kWh/m^2 and new buildings reduce heat demand to 36 kWh/m^2, biomass demand will be unsustainable since heat demand reduces insufficiently
- If existing buildings decrease to 80kWh/m^2 and new buildings remain the same at 56kWh/m^2, this leads to massive heat savings, system cost reductions and sustainable biomass demand
- If both existing buildings and new buildings reduce heat demand: existing to 80kWh/m^2 and new 36 kWh/m^2 there is minimal (2 TWh) reduction in heat demand, and system costs increase, and biomass demand does not reduce significantly

System results

- In the 2050 energy system, waste heat contributes significantly to district heating. As heat demand decreases it diminishes waste heat usage rather than biomass combustion, thus biomass is not affected by continuous heat reductions

- Capacities of non-industrial heat supply units remain the same due to peaking needs and thus heat demand reduction does not reduce cost either, but increases cost from higher building costs
- Net primary energy demand for heating new buildings at 36kWh/m² is 8kWh/m² based on primary energy factors of heat supply. The only outcome from this is that primary energy demand is low, but the system does not benefit.

Study recommendation

- The study concludes that focus should be on renovating the existing building stock to reduce heat demand and the average new build heat demand is sufficient today

6.2. STUDY 2: FROM CARBON CALCULATORS TO ENERGY SYSTEM ANALYSIS IN CITIES

This study (Drysdale, Mathiesen, and Lund 2019) provides a case study of city decarbonisation, of which there are few in the literature (Weinand et al. 2020). With new novelties based on experiences with the Strategic Energy Planning process in Sønderborg municipality in Denmark in 2018 (ProjectZero 2018). The study assesses the energy system of the municipality using system-engineering scenarios for sustainable energy in 2050. The study aims to provide a simple method to initiate energy system analysis and learning about system emergence within the energy planning paradigm-thus facilitating the energy planning paradigm. Avoiding delays from time-consuming technology trend analysis and foresight/forecasting (Battistella and Pillon 2016), and from the lack of data collection or expertise (which can improve with time) (Bačeković and Østergaard 2018; Østergaard et al. 2010).

The central premise of the study is to analyse Sønderborg in 2050 in the context of the Danish energy system transition in 2050. The backcasted scenario enables the selection of actions and measures within energy planning in Sønderborg. The translation of the Sønderborg energy system from the Danish system applies a straightforward approach. Similar to Study 1, IDA Energy Vision 2050 provided the energy system in 2050.

Informed by experience with the city in 2018 - regarding energy planning practices - the study is novel in two ways. Firstly, based on limited expertise in planning departments in energy. The study does not rely on expert knowledge in its scenario construction, which is common in previous sustainable energy studies in the literature (Bačeković and Østergaard 2018; Østergaard et al. 2010). Also, in the Strategic Energy Planning process in 2018 in Sønderborg, experts made iterations. The results and method of Study 2 serve as a bridge between experts and non-experts in energy planning, which can be within city authorities or between stakeholders, and which can help learning and co-evolution in the socio-technical transition.

Secondly, in collaborative planning with stakeholders (dozens of stakeholders were involved in the Sønderborg Strategic Energy Planning in 2018), new iterations are required due to stakeholder feedback. Therefore, the study opened the "black-box" of the system analysis, providing both a methodology, model and results for stakeholder discussion (Geels et al. 2020). This way achieves trial and error (heuristic) optimization as opposed to bottom-up modelled optimization (Mahbub et al. 2016). This approach addresses challenges in communicating model results to stakeholders (Iyer and Edmonds 2018). The method ensures that the sustainability of the energy system constrains the stakeholder iterations. Sustainability considers the utilisation of energy locally and maximising energy own use, maximising technology synergies and reducing biomass consumption.

6.2.1. MAIN RESULTS AND CONCLUSIONS

The study focused on the development of a methodology and applying a case study. The study has six main novelties related to the methodology and the case city.

Methods results

- The methodology develops a technically decarbonized energy system for the municipality in 2050
- The technical system is sustainable based on the definition of a sustainable energy system (described in Chapter 4)
- The analysis presents actions and measures – including emergence outcomes - for Strategic Energy Planning which may include city authority energy planning
- The study and results are developed and presented for communication and applicability in Strategic Energy Planning procedures
  - The methodology and model developed (in EnergyPLAN) delivers results, graphics (structural and charts) and prose for numerous energy considerations. Examples from this study include final energy demands (numerically), energy resource demands (graphically), electricity production, exchange and demand (graphically), hour by hour electricity demand and supply (graphically), district heat and private heating production total supply and hour-by-hour (graphically), transport fuel consumption types (graphically) and investment costs (graphically)
- The case study presents a two-staged methodology (data collection & sustainability assessment), including data requirement types, that can be replicated by Sønderborg in a new iteration, and other EU cities
  - Numerous iterations were required to determine a near-optimum sustainable energy system. Utilizing Microsoft Excel in combination with EnergyPLAN, new data and figures led to a rapid heuristic process.

- The national energy system transition provided the context for the municipality scenario development

Technical system results

- In 2016, the Sonderborg energy data per capita differed quite significantly from the Danish average per capita in some categories, such as industrial energy demand. Stakeholder engagements can discuss this.
- The method uses the Danish per capita data in 2050 to backcast the requirements for Sonderborg in the context of the country in 2050. In some energy categories, Sønderborg is performing better than others. For example, residential electricity demand can stay constant, but commercial industry energy demand may need to reduce significantly. This also provides a discussion point for stakeholders
- Integrating the energy system within the municipality minimizes the exchange of energy and reduces energy resource demands by around 40% from 2016
- Private heat demand is reduced by around half due to the increase in heat pumps

6.3. STUDY 3: ENERGY VISION STRATEGIES FOR THE EU GREEN NEW DEAL: A CASE STUDY OF EUROPEAN CITIES

The first two studies are quantitative with direct application of system engineering scenarios for evaluation. I also gained experience as part of the SmartEnCity EU Horizon 2020 project with numerous EU cities (TECNALIA Research & Innovation 2020). Based on the learnings from Study 1 and Study 2, and informed by the EU project, I did qualitative research in Study 3 (Maya-Drysdale, Jensen, and Mathiesen 2020) to explore how EU cities are doing energy planning for sustainable energy. Based on Study 3, it was possible to understand the local context and activities around energy planning, using my conceptual framework for Strategic Energy Planning for sustainable energy. The study allowed me to know how system engineering scenarios could facilitate the energy planning paradigm based on this contextual analysis. The study suggests recommendations with useful literature for the facilitation and evolution of city energy planning in the future.

The study selected eight EU cities based on their ambition to decarbonise (indicated by their involvement in two energy planning EU projects). The study aimed to analyse their energy planning with a particular focus on their targets, visions, and scenario creation and integration, which are essential parts of Strategic Energy Planning for sustainable energy.

The study makes a case that there are three levels of strategy in energy planning. With the possibility to address each level in a different order, 1) The integration strategy to integrate energy planning into city planning institutions; 2) the practice strategy to develop suitable energy planning practices in city planning institutions, and 3) the vision strategy to create and integrate energy visions and scenarios required for long-term decarbonisation. The study focuses on the vision strategy since energy system scenarios most directly affect this (although the other strategies are indirectly affected).

The study introduces basic and advanced technical considerations, and sustainability factors, cities should consider when making energy system scenarios. These considerations informed the construction of the analytical framework of Strategic Energy Planning. Within Strategic Energy Planning, cities should consider particular energy planning elements when creating and implementing sustainable energy scenarios. Analysis of each city was in the context of the Strategic Energy Planning approach and these elements.

6.3.1. MAIN RESULTS AND CONCLUSIONS

This section presents general results in terms of the energy planning activities in the cities in the context of the Strategic Energy Planning framework. There were minor exceptions to these results described in the article.

Strategy results

- Cities are not following long-term decarbonisation goals, and most are focusing on short-term goals based on EU requirements for 2030. This means they often do not understand complete decarbonisation implications in terms of technologies and emergence
- Cities are not connecting with national goals and analyses. Cities are not considering their contribution to national goals, but this can be because national ambitions are limited
- The cities rely on scenario calculations that are simple and follow silo thinking. Energy solutions are identified individually and not in the context of the system which is related to traditional city planning and actions
- Cities see scenarios as supporting the identification of actions and measures for city plans
- Cities generally extract and abandon the scenarios. Scenarios are not seen as central to planning and as a continuing support tool but a process to get informed on actions and measures
- The cities often use intermediaries, and the city authority is sometimes not the central coordinator. The intermediaries take responsibility for the energy planning process, although local politicians often have a strong influence on final decisions regarding the city plan

Examples of strategy recommendations (the scientific article has the full list)

- Ensure development of scenarios with long-term end targets
- Develop holistic energy system scenarios

- Reflect on the sustainability of the sustainable energy system scenarios
- Retain long-term scenarios and adjust them over time

CHAPTER 7. DISCUSSION: FACILITATING THE LOCAL ENERGY PLANNING PARADIGM

My experience in numerous projects and with multiple stakeholders from 2016 to 2019 informed the three studies, and as the research advanced, the study designs adapted with new learnings. On reflection on my research question and sub-questions in each study, there are some important outcomes to discuss further.

7.1. STUDY 1

In Study 1, I analysed a national regulation, and the analysis demonstrates the facilitation of energy planning. Policy happens within society and in the context of technologies and their practices, and subsequently, scenario studies can often externalise policy (Hughes and Strachan 2010). However, Study 1 attempts to include regulation implications from a communal, societal perspective, analysing it technically from a system perspective using a system engineering scenario. Shifting away from a societal and technological practice level (individual building) to the societal system regime level (system level).

Radical (not incremental) socio-technical transformation evolves within a complex system and has uncertainty (Moallemi and Malekpour 2018). Climate change is a complex and collective challenge, and the integrated energy system requires coordinated solutions. This study focused on these collective outcomes within the energy system. This particular national regulation was selected as an appropriate exemplar to demonstrate how system scenarios could facilitate the local energy planning paradigm regarding regulations.

Furthermore, the EU identifies Smart Cities and climate neutrality as one of their mission areas (European Commission 2020). Near Zero Energy Buildings (nZEBs) are state of the art in the building sector and an essential part of the EPBD (The European Parliament and the Council of the European Union 2010; Lund et al. 2017). These buildings aim to lower net primary energy demand to near zero using a combination of energy efficiency and nearby renewable energy production, done in numerous ways (Mohamed, Hasan, and Sirén 2014). As the Smart City concept develops with the rollout of 5G networks, these buildings are an exemplar Smart City component of the Smart Built Environment (Mosannenzadeh and Vettorato 2014). At an individual building level and private ownership context, nZEBs could be advantageous. These advantages are the core focus of most nZEB research (Becchio et al. 2016). They are a significant energy system component dispersed throughout the country, relying on smart technologies and automation. By selecting these building types and the related building code allowed an evaluation of the individualism emphasised by the Smart City sustainable low carbon mission of the EU. The emphasis of this mission precludes the system-wide impacts, in which this study aimed to highlight.

From this system perspective, the results demonstrate that this regulation would lead to minimal benefits from a technical, environmental and economic perspective. Local planning can apply the results since they demonstrate the prerequisite analysis cities need to carry out to understand the impacts their local actions and measures make to the national sustainable energy system (Lund, Marszal, and Heiselberg 2011; J.Z. Thellufsen and Lund 2016). Furthermore, as cities in Denmark progressively collaborate, they could influence national-level regulatory decisions; for example, the building codes (Gordon and Johnson 2018; Sperling et al. 2011).

Due to the complexity and uncertainty related to the energy system, planning needs to shift from long-term planning approaches (based on prediction and linear optimisation) (demonstrated by the ambition of the Danish building code to 2025) to dynamic adaptive policymaking (Haasnoot et al. 2013; Moallemi and Malekpour 2018). Dynamic policymaking ensures robust favourable policy interventions and strategies which can adapt across numerous possibilities (Moallemi and Malekpour 2018). Based on this dynamic policymaking transition strategies from stakeholders can coordinate actions and commitments within the energy system transition (Hermans et al. 2017; Moallemi and Malekpour 2018).

Good understanding and articulation of the landscape conditions can support a purposive context of cities (in Denmark in this instance) (Hodson and Marvin 2010). Hence, the analysis of the buildings was from the national level since the local level system is integrated into this broader system (J.Z. Thellufsen and Lund 2016). The analysis facilitates the perception and translation of landscape conditions through new learning about nZEBs in the Danish landscape and potential sustainable energy system regime. Denmark has landscape conditions that influence its energy regime, and that can inform different articulations from the landscape. Denmark has a 53% share of district heating which is highly efficient and will likely increase to 63% in 2050. Thus, district heating utilities dominate the heating sector in Denmark, which affect the local regime. As shown in the study, the infrastructure landscape and district-heating regime challenge the regulatory arrangement. Other EU countries should also consider these national landscape conditions.

7.2. STUDY 2

Based on my experience in the Danish and EU projects, it became apparent that the role of cities in the socio-technical transition is implicit, leading to fragmentation and uncertainty (Hodson and Marvin 2009, 2010). The system configuration in different cities influences their reconfiguration dynamics. Furthermore, multiple co-existing and interacting reconfiguration dynamics influence the energy system transition (McMeekin, Geels, and Hodson 2019).

Thus, whereas, Study 1 does not focus on providing a system engineered scenario for utilisation but rather indicates the outcomes from these scenarios. Study 2 focused on the actual delivery of system engineering scenarios for utilisation in a municipality. Designed to enable the development of prose, graphs and mathematics from the scenario, useful for stakeholders involved in the local energy planning paradigm. This method helps to understand the system configuration as it is today, what it could be in the future (although not the reconfiguration dynamics, which is a separate analysis) and the implications for the transition, thus facilitating the local energy planning paradigm.

Study 2 goes deeper into the conceptual framework for a sustainable energy system. Expanding out a methodology from this theory and the concept of the Smart Energy System and describing its steps. Providing results that can develop an understanding of both system interrelations in an integrated energy system and the combination of technologies with energy savings and energy storages. The method can develop a local energy system that includes, at minimum, key sustainability factors: 1) all energy sectors, and 2) a technically feasible design and analysis. Furthermore, the study describes the necessary data type requirements for making an energy system engineering scenario, further facilitating the energy planning paradigm. The approach in the study provides a method easily applicable to other cities. However, it relies on a premade national analysis.

Furthermore, the socio-technical transition involves both technological development and implementation within cites, which informed Study 2. Technologists and engineers not only shape socio-technical transitions, but it is also about learning and co-evolution of numerous stakeholders including policymakers, businesses, NGOs and citizens. All social stakeholders interrelate and are held together by regulations, policies, consumption, and investments in the regime (Geels 2002). These numerous stakeholders are involved in the socio-technical transition, and a new socio-technical regime requires these interrelations to stabilize a new trajectory (Geels and Schot 2007). It is therefore essential to consider who and which social interests are involved in producing energy scenarios (visions), and what they expect (Hodson and Marvin 2010). Social stakeholders have different interests, motivations and expectations and the ability to engage, which contributes to the wicked problem (Cajot et al. 2015). Lastly, the agency within the city not only relates to a variety of stakeholders and coalitions of stakeholders working at the city scale but stakeholders at national and EU level have intentional and unintentional consequences for the actions at city scale (as demonstrated in Study 1) (Brenner 2004).

Consequently, a vision (and scenario) is an incomplete contribution to socio-technical change. The capacity of stakeholders needs to manifest, and the vision needs to be capable. There needs to be a sense of how to coordinate capacity (Hodson and Marvin 2010), and there need to be detailed steps towards broad social and political support (Geels, Kern, et al. 2016). Study 2 does not address this but provides a methodology and results for pointing towards a direction and a framework for purposive socio-technical transition (Hodson and Marvin 2010). It also helps set long-term targets (Leal and Azevedo 2016).

Socio-Technical Scenarios are one way of translating the actions and measures from the scenario in Study 2 for the involved stakeholders (Geels et al. 2020). Practically and put simply, Socio-Technical Scenarios involve the combination of quantitative techno-rational scenarios (as presented in Study 2) with qualitative theory and methods including numerous heuristic steps and all stakeholders (Geels et al. 2020). These scenarios can ensure ownership and engagement with the stakeholders that participate with knowledge and expertise, and who will translate the vision throughout the transition time-period (Hodson and Marvin 2010).

In this context, techno-rational scenarios (visions) can contribute to a Socio-Technical Scenario within Strategic Energy Planning. By involving the policymakers and other influencing stakeholders embedded in the regime (Geels et al. 2020). They can contribute to developing capacity, questioning the relationships between the multi-level governance scales and demonstrating cities not as places for receiving transition initiatives but as being more purposive in the energy transition (Hodson and Marvin 2010). Socio-technical analyses can inform stakeholder strategies to deal with their struggles with influencing implementation of mitigation options (i.e. blocking from large companies or lack of political will or public opinion). They could support influences on the regime such as re-orienteering large companies, introducing new stakeholders, providing evidence of diffusion of technologies, creating a sense of urgency in public (Geels et al. 2020). These are landscape pressures, articulated into regimes and niches, perceived, and translated by stakeholders. Thus, Socio-Technical Scenarios can help steer the influence of these pressures on niches and regimes rather than them making mechanical impacts (Geels and Schot 2007). Socio-Technical Scenarios can describe stakeholder resources, relationships and their coordination as a response to the landscape pressures (Hodson and Marvin 2010). Although Study 2 is simplified disregarding social and political changes, these can be included later within these Socio-Technical Scenarios (Geels, Berkhout, et al. 2016; Geels et al. 2020).

Planning Support Systems (PSS) could help facilitate the integration of energy system scenarios into Socio-Technical Scenarios using sketch planning (simple communication of a design concept) (Vonk and Ligtenberg 2010). Furthermore, a detailed stepwise approach from vision to project implementation and monitoring could be useful to manage the process (Urrutia-azcona et al. 2020).

Lastly, the decarbonized energy system involves numerous novel innovations and technologies in some countries but not in others. Therefore, the angle of Study 2 is not only the system and what it could be (planning scenario) but to demonstrate an approach to bring technology into a niche and build a network. Novel technology developments need to be kept alive in lasting niches (and eventual regime shift) through innovation, learning processes, networks and expectations and not deemed unsustainable (Geels 2002; Weber et al. 1999). Thus Study 2 is not only an attempt to show the system and its technologies but to allow stakeholders to get new and novel technologies onto the transition agenda through learning about their uses and understanding their contribution to emergence (Hodson and Marvin 2010).

7.3. STUDY 3

The premise of Study 3 is that Strategic Energy Planning helps cities retain focus on the long-term systematic and strategic issues of the energy system transition. This requires a variety of technical, policy and local knowledge with the consideration of social interests including developers, utilities, regulators companies and environmental groups. Over time, these interests are continuously negotiated and integrated (Hodson and Marvin 2010). Thus, by retaining energy system scenarios (visions), it is possible to consistently and strategically plan the energy system transition.

In Study 3, all cities involve energy scenario development and intermediaries, and some cities are ambitious making significant progress forward, thus indicating active engagement. However, often not within a Strategic Energy Planning context as defined in my analytical framework. There is not much deviation between the smaller cities since they are mostly following the same process. Thus far, SEAPs are the most used approach and method. Most cities extract and discard scenarios, and they are used only for identifying actions and measures within a short-term planning approach.

The theoretical basis of this PhD is that the normative direction of the energy system dynamics needs to be characterized and understood. Stakeholders need to understand what the transition is for (Moallemi and Malekpour 2018) (hence the aim of Study 1 and Study 2). Based on the results from Study 3, it is evident there is a need for a standardised approach to assigning the role and scale of actions of cities within the multi-level governance transition. Firstly, the normative direction should be characterized and standardized, making clear the purpose of the transition. This can help determine policy actions (in modelling such as Study 2 and in the real world) (Moallemi and Malekpour 2018).

Regarding the current energy system regime, Study 3 showed that the city authorities, and stakeholders, have limited connection, or are located outside the regime, which was expected (Cajot et al. 2017). The link is via energy-related plans such as mobility plans, climate plans or spatial planning. The cities also develop SEAPs based on project-based planning. To achieve the priorities in cities, the relevant stakeholders need to be influential and take control of the regimes (Hodson and Marvin 2010). Most cities are attempting this by participating in scenario (vision) creation processes, with a couple of cities making numerous attempts to understand a decarbonised energy vision and integrate this into the city plan (although with limited success). All the cities in the study have attempted to identify relevant stakeholders identifying who needs to be engaged and coordinated, which is one signifier for the successful energy transition in cities. Stakeholders need to be continually engaged to avoid failure (Hodson 2010).

The role of a city in the energy transition is often implicit and uncertain (Hodson and Marvin 2009); therefore there is a variety of different relationships that the city can have with the national transition (Hodson and Marvin 2010), demonstrated by numerous cities in Study 3. Most cities carry out their initiatives in the capacity they have, disregarding national goals. Socio-Technical Scenarios described above in Study 2 could help cities integrate national goals and stakeholder interests.

A positive outcome from Study 3 is that numerous cities use intermediaries (sometimes semi-government, sometimes private), especially the smaller cities. Intermediaries can be a space outside city governance regimes and existing socio-technical regimes (Hodson 2008). They can be necessary (as demonstrated by the results in Study 3) to increase political support by lobbying politicians and media, and they can also address numerous wicked problems (Cajot et al. 2015; Hodson and Marvin 2010). Intermediaries are not a predetermined organisational entity. They can be: government or semi-government; energy agencies working at differing scales of governance (demonstrated in Study 3); NGOs; agencies sponsored by utilities; ESCOs; or private organisations (Hodson and Marvin 2010). ProjectZero in Sønderborg municipality is an intermediary funded by local businesses. Although their functions are numerous, involving coordination, demonstrations, advocacy, lobbying, education, network building, among many others, ultimately they have the agency to help develop organisational capacity to reconfigure regimes at the city level (Hodson and Marvin 2010). Scenarios (visions) can be part of this capacity development involving numerous stakeholders within Socio-Technical Scenario analyses and processes.

This study did not investigate further the functionality of the intermediaries and their performance. However applying the Strategic Energy Planning analytical framework showed that most cities do not address strategic elements of holistic energy system analysis, long-term goals or retention of scenarios. Study 3 found that city authorities do not retain scenarios (visions) for directing the transition and often use them for project identification. Since most cities use intermediaries, this demonstrates that the intermediaries in these cities need to adopt a more Strategic Energy Planning perspective and system engineering perspective as well.

Although intermediaries are serving a valuable space outside the municipality offering numerous functionality, intermediaries must also continue to adapt, learn, develop and redevelop their knowledge-base, to ensure the ability to adapt to changing landscape pressures and arising issues. There needs to be an organisational culture of systemic, strategic and long-term thinking rather than project-based thinking (Hodson and Marvin 2010). This will help to develop their productive capacity and capability regarding the energy transition.

The research output from the PhD (both Study 1 and Study 2) is an example of a learning opportunity. Sønderborg municipality (the case study in Study 2 and used here as an example) has a carbon-neutral goal for 2029, and their intermediary ProjectZero leads this. However, it was set in 2007 (proposed by local businesses) and has remained unchanged due to its political calcification. The goal directs project identification and implementation but forces energy system analyses in its direction. The goal is problematic since developed scenarios (visions) should help negotiate and navigate transitions rather than goals (i.e. carbon neutrality) (Delina and Janetos 2018; Dignum et al. 2018). Research indicates that it does not lead to complete decarbonisation (Sveinbjörnsson et al. 2017). In saying this, it appears that ProjectZero and the goal have integrated diverse social interests and achieved political buy-in in Sønderborg municipality reasonably successfully, shown by the continued support for the target since 2007.

7.4. EVALUATION OF RESEARCH PROCESS

The PhD had a broad question and narrowed down theoretically using the multi-level perspective, complex systems theory and the two concepts. Multi-level perspective served a useful theory to structure my research design in a way that allows input from the socio- and technical aspects of the sustainable energy transition. My experiences in Sønderborg municipality and the SmartEnCity EU project demonstrated that socio-technical regime change is happening at a slow pace. The research applied complex systems theory and system engineering to understand how this slow pace could be accelerated.

Systems theory is necessary for the sustainable energy system due to its complexity. In this PhD, I used EnergyPlan to develop systems engineering scenarios. EnergyPLAN enables the identification of the optimal outcomes (in the context of sustainability) near the Pareto point using heuristic analysis (Mahbub et al. 2016). EnergyPLAN results can be analysed further and adjusted in a spreadsheet, meaning it is open for further exploration. Other tools can also soft link with EnergyPlan, to continue further detailed analysis, such as CitySIM (Local energy simulation for groups buildings,/city quarters) and TRYNSIS (simulation for systems and single buildings) (Allegrini et al.

2015). Although, in the context of socio-technical analysis (delivering numerous iterations based on stakeholder feedback), the use of these other tools and their results need to meet particular user needs, such as ease of use.

Furthermore, the system engineering scenarios are applicable in numerous theoretical contexts, including transition management, where participatory exercises identify long term visions and goals (Rotmans et al. 2001). The social construction of technology (SCOT) argues that different social groups attach different meanings to new technologies (Bijker 1995), and the scenarios can help converge shared views and agreement. Lastly, social-technical imaginaries can use scenarios when projecting visions (Jasanoff and Kim 2009).

In Study 2, although the local scale may not be precisely scalable from the national level, the method enables the development of an energy system scenario that is adaptable and transferable. Planners can ask, should electrolysers or wind power be located in Sønderborg, or elsewhere? If certain technologies are outside the local boundaries, new scenario iterations can change the results. The method can demonstrate emergence within the system even if technologies are outside the region (i.e. virtually within the region). Furthermore, the method enables identification of the contribution of city measures and actions to the country (J.Z. Thellufsen and Lund 2016). For instance, Sønderborg municipality may have advanced with some sustainable energy initiatives. Such as household or commercial electricity demand which may be sufficient for the national decarbonised energy system. Thus, the scenario and method indicate whether they need to continue improving in those areas or whether to focus on more critical areas.

Study 3 did interviews with a selection of energy planners and results were mostly consistent, however unexpected. This could be due to selecting the wrong cities, i.e. they are not ambitious. However, all the cities involved energy scenario development and/or intermediaries, and some cities are ambitious, making significant progress forward, thus indicating active engagement with sustainable energy planning. Furthermore, during the research, I realised that the cities did not conceptualise the energy system as I did and therefore further justifying the nature of the PhD.

Although Study 3 suggests three levels of strategy, the study refers to city authorities (not intermediaries which are strongly present). As described in the thesis, city authorities may not be central coordinators. However, their strategies are still relevant within a socio-technical context. When making Socio-Technical Scenarios, there needs to be integration in institutions of some form, practices need to evolve, and there need to be appropriate visions—all related to learning and co-evolution of interpretive stakeholders. City authorities need to take part in this as well, alongside intermediaries and other active stakeholders

CHAPTER 8. CONCLUSIONS AND FURTHER RESEARCH

This PhD project aimed to answer the research question:

> "*How can sustainable energy scenarios facilitate the local energy planning paradigm?*"

To answer this question, the PhD had a broad focus, shifting from national-level energy planning (technically evaluating a national regulation) (Study 1) to local city planning (evaluating planning practices) (Study 3). This is because local energy planning is a paradigm encompassing a multi-level governance arrangement, involving numerous institutions and involving numerous stakeholders (Hodson and Marvin 2010). Coalitions of stakeholders and their shared visions, priorities and interests need to develop within these multiple scales (Bulkeley et al. 2011; Hodson and Marvin 2010).

The central premise of the PhD is that the local energy planning paradigm should incorporate the dynamic nature of the sustainable energy system. Therefore the direction of the energy transition should be considered (Delina and Janetos 2018; Malekpour et al. 2016; Moallemi et al. 2017). However, although addressing climate change is a societal need and normative goal (Moallemi and Malekpour 2018). Society demands the energy system to deliver special functions (i.e. providing electricity to users) and needs (i.e. energy equity), thus requiring the initiation of appropriate policy action. Study 1 was an investigation into this balance.

Study 1 focused on the Danish building code and the contribution of nZEBs in the sustainable energy system. The study used a system engineering scenario approach (based on the concept of the Smart Energy System), to evaluate the building code, which is directed by the European Performance of Buildings Directive (EPBD). The study analysed nZEBs in the context of the long-term sustainable energy system. Based on my theoretical perspective and analysis, nZEBs appear to be silo-thinking solutions standard in the short-term city planning paradigm (Lo 2014). Within a sustainable development framework and energy system engineering concept, nZEBs are shown not to contribute to the decarbonised energy regime based on sustainability (in Denmark). The energy system scenario and results in Study 1 facilitate the local energy planning paradigm by presenting a transition pathway that can help identify and modify policy interventions (Haasnoot et al. 2013; Lempert, Popper, and Bankes 2003; Malekpour et al. 2016; Walker, Rahman, and Cave 2001). Based on the results of the study, it indicates the need for new dynamic policy approaches and interventions (Moallemi and Malekpour 2018, Cooper et al. 1971).

In Study 2, a systems engineering approach assesses the future energy system in Sønderborg, Denmark, to identify actions and measures. Study 2 is a backcasting approach exploring a wide range of possibilities of what can happen (backcasting), as opposed to what will happen (forecasting) (Moallemi and Malekpour 2018). Although this identification is insufficient on its own, stakeholders can use the method and results in Socio-Technical Scenarios (Geels et al. 2020) which capture dynamic transition pathways, the heterogeneity of stakeholders, and contribute to the co-evolution of policy, technology and culture (Moallemi and Malekpour 2018).

The study aims to offer a new approach for stakeholders to discuss and gives them more freedom with ongoing input for adjustment. Study 2 facilitates the learning and co-evolution of numerous social elements, including stakeholders, as well as technical, political, and economic aspects. The approach allows stakeholders to carry out explorative, creative thinking, addressing uncertainties, and leaving their usual frames of reference towards new perspectives, while at the same time deliberating on their challenges (Moallemi and Malekpour 2018). Study 2 also demonstrates how the system scenario can elevate technologies in niches based on their contribution to the energy system through emergence. Furthermore, this analysis supplements and coordinates with national goals for decarbonisation. The implementation of this method and the actions and measures can be strategically managed within the multilevel governance arrangement, particularly at the city level, either by authorities or intermediaries (Sperling et al. 2011).

Study 3 aimed to evaluate the local energy planning practices of eight EU cities. Particularly around the strategies for their energy planning. Analysis of each city was in the context of a Strategic Energy Planning analytical framework, which was informed by the systems engineering Smart Energy System concept. The study found that the strategic level of energy planning in each city is weak in this context - although a couple of cities demonstrate progress. There are potential strategic improvements - in city authorities or intermediaries - by firstly acknowledging the normative goals of the energy transition (making long term goals). Secondly, adopting a methodology to develop sustainable energy system scenarios (holistic, systemic scenarios). Thirdly, retaining the methods and scenarios in ongoing strategic decision-making (to inform stakeholder engagement).

In recent years, city authorities have shifted from rational planning to collaborative planning, and this is evident in the results from Study 3. Collaborative/communicative planning is an essential element in the socio-technical transition as repeatedly stressed in this thesis, and the evolution of the local energy planning paradigm must consider and retain this. However, this PhD has attempted to demonstrate the facilitative functionality of the rational energy planning practice and its usefulness in the continued evolution of the local energy planning paradigm. Based on this PhD research, there are several further research areas to investigate to continue the reintegration of rational energy planning.

8.1. FURTHER RESEARCH

Since the inception of this PhD, research output per year has increased by around 200% in this area (Weinand 2020). Therefore, it is appropriate to reconsider the premise and positioning of the PhD based on this recent research. A recent review analysed all the local energy autonomy studies (Weinand et al. 2020). The study results show that very few studies address the primary considerations in this PhD, regarding the three system engineering aspects 1) making the system technically feasible and manageable, 2) fully appreciated, and 3) sustainable. Most studies focus on parts of the system. For instance, few energy autonomy studies consider heat and transport, which are essential components in the interconnected, sustainable energy system.

Furthermore, in 2017, I undertook a literature review of academic articles that focus on decarbonised energy system scenarios in cities in Europe based on the conceptual framework I presented in this PhD. These studies differ from Weinand et al. (2020) since they are not necessarily about autonomy, but complete decarbonisation (which can involve energy exchange with the rest of the country). This review aimed to learn about sustainable energy scenarios in cities and what they can offer for the energy planning paradigm, thus informing my PhD research. Using a Scopus keyword search for capital cities and countries, I searched for all relevant keywords related to the topic of sustainable decarbonised energy systems. In total, I found six articles that analysed complete decarbonisation within a city (or region) (Bačelić Medić, Ćosić, and Duić 2013; Erik Dahlquist, Eva Thorin 2007; Krajačić, Duić, and Carvalho 2009; Østergaard et al. 2010; Waenn, Connolly, and Gallachóir 2014).

I made two important observations from these studies. Firstly, the number is very small, and the most cited studies are around a decade old. Secondly, none of these studies focused on the implications/facilitation of the sustainable energy results for the local energy planning paradigm. For either the city authority or related stakeholders (this is still evident as mentioned in Weinand et al. (2020)). In general, the studies did not contextualise themselves within the socio-technical transition perspective and thus did not present or discuss a way to facilitate the local energy planning paradigm. Since this review, to my knowledge, there are few additional studies, including my own (Bačeković and Østergaard 2018; Drysdale, Mathiesen, and Lund 2019; Weinand et al. 2020).

Regarding the three studies in this PhD, I have identified eight further areas of research. Some of these areas are likely to have been researched previously, which would simply require doing a new literature review.

Exploring dynamic policy in the context of the sustainable energy system scenario

Firstly, in Study 1, I recommend implementing new policy based on dynamic policy analysis and implementation within a socio-technical transition based on Socio-Technical Scenarios. This topic requires further exploration.

Combining the energy system scenario with socio-technical analysis and practice theory

Secondly, in Study 1 and 2, the research focused on system engineering scenarios fitting within the rational goal-oriented analysis and both allow for further iterations. However, there are two other essential areas considered within Socio-Technical Scenarios, 1) socio-technical analysis and 2) practice theory (Geels, Berkhout, et al. 2016). By including socio-technical analysis and practice theory, planners can make new iterations in a continual circular strategic decision-making process (Figure 4). Both of these have not been analysed in the context of complete decarbonisation energy scenarios since Geels et al. (2020) only looked at the electricity sector in the UK. Furthermore, new iterations should also be aware of the challenges related to the computer model and results within the transition planning (McDowall and Geels 2017)

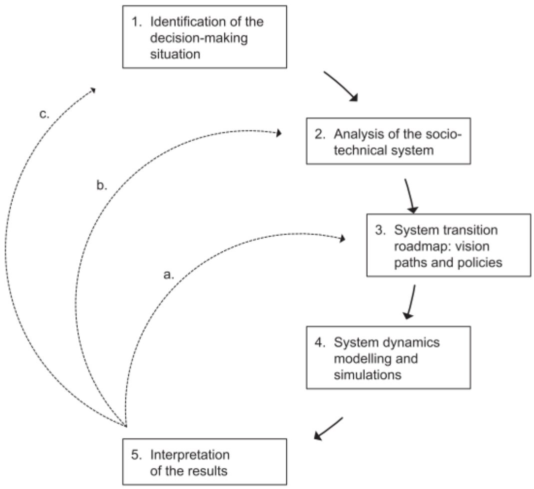


Figure 4: Process supporting strategic decision-making in systemic transitions (Auvinen et al. 2015)

Understanding how to apply the system analysis results with stakeholders

Thirdly, concerning the above, this PhD emphasises the system aspects of the decarbonised energy system. These system aspects are difficult to grasp, and the idea is to promote the concepts of systems. None of the studies in this PhD investigated how to utilise the system analysis results. Further research can focus on understanding how and who best to communicate them in city and national authorities, the EU and intermediaries. In general, additional work building on this PhD should concentrate on implementing Strategic Energy Planning guidance to city authorities or intermediaries supported by the EU. Similar to how the EU implemented the Leipzig Charter for Integrated Urban Planning (BBSR 2017). However, this research and implementation must maintain focus on complete decarbonisation energy scenarios and analysis. Rather than part decarbonisation as that is researched extensively (Weinand 2020).

Using action research to understand how stakeholders use the results and relate to the scenarios

Fourthly, related to the third point, Study 2 developed a method and energy system model; however, without new reiterations with stakeholders. The research did not progress beyond the analyses and research the communication of system awareness and learnings. For instance, the research did not test the results in Sønderborg municipality with stakeholders, analysing both their contributions and their learning and adaptation and capacity building, as suggested in the multi-level perspective. The use of the model and iterations could be analysed using action research. The action research could apply the results in practice and analyse the communication of results. Alternatively, stakeholders could use the model and adjust it, and the research focuses on understanding the impact on energy planning and decision making from the iterations. This learning is an iterative learning process creating different types of predicted, planned and outcome knowledge types (Rydin 2007).

How to communicate emergence within a socio-technical environment

Fifthly, the PhD project emphasises emergence. Since I believe this is insufficiently understood in the local energy planning paradigm (exemplified by the lack of sustainable energy studies in literature). Emergence occurred in Study 1 and Study 2, although it was not explicitly analysed and described in the studies. However, the affected technologies gain higher intrinsic value within the scenario associated with the emergence it forms. Analysing the technologies in a system can assign new expectations otherwise missed. The article provides a method focused on achieving this capability. However, further research can analyse how to quantify (by statistical variance) this emergence and communicate to the interested stakeholders. One approach could be to translate these emergences and develop them into fact-like objects forming new knowledge assemblages (Jensen and Jørgensen 2018).

Make a clear distinction and understanding of real and virtual energy within a local boundary

Sixthly, Study 2 focuses on the simplification of the future local energy system in Sønderborg municipality, but, likely, this simplification of the system in the city will not eventuate like this, due to varying social and political decisions over time. As a researcher with an interpretist ontology, I cannot suggest how the system should look. It is uncertain what would be real or virtual in this system, and this requires further exploration. Three areas of investigation include 1) asking how the virtual and real energy system perspective works, 2) asking how virtual energy affects local energy dynamics such as emergence, and 3) asking how to understand and communicate better the virtual and real energy split and implement it within Strategic Energy Planning around actions and measures.

Understand how intermediaries could operate in the context of the sustainable energy system transition

Seventhly, in Study 3, intermediaries exist in numerous cities, and they present an opportunity to adapt and build capacity with new methods and approaches. The continuous evolution of intermediaries and related energy planning stakeholders (including city authorities) was not a focus in this study, and further research is required. The research could explore the internal reorganisation of practices and cultures—questioning who is in charge. One approach could be to analyse the effect of teaching about the emergence aspects of energy systems. Hodson and Marvin (2010) describe seven main elements that constitute capacity and capability within intermediaries, which could inform the research:

1) Sustained broad-based financial support

2) Security of employee positions

3) Stability of organisational resources and commitment

4) Adaptability and learning

5) Negotiating and integrating different knowledge effectively

6) Careful consideration of how they represent and what they are doing concerning stakeholders

7) Developing a shared organisational view of influence beyond basic funding

Increasing the value of scenarios (visions) in local energy planning so they can facilitate the paradigm

Lastly, although this PhD and discussion have emphasised the role of scenarios (visions) to facilitate the energy planning paradigm, it should be stressed that this is one element of regime reconfiguration. Although it is an important element since it draws together numerous socio-technical aspects, including interested stakeholders and strategy development. Scenarios (visions) may be a small element (as demonstrated in Study 3) in local energy planning, and there may disinterest in improving the strategies of city authorities or intermediaries. However, this PhD did not analyse how to address this further (i.e. simplification of approaches), and further research should focus on this.

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APPENDICES

Appendix A. Interview guide and questions for Study 3

General questions about energy planning

1. What is your city’s long-term low carbon end target? E.g. 2030, 2040 zero carbon etc.
2. A) Why is this your long-term target? B) How did you get this?
3. What technologies and investments will be needed to achieve this target?
4. A) What current energy-related plans/strategies do you have, i.e. mobility, built environment, land-use, others? B) Which of these will you use within your integrated energy plan?
5. A) What is your process to integrate these current plans into your overall integrated energy plan? B) How do you envisage you will adjust your plans to integrate them and to achieve your goal in the long-term?
6. Who will be involved and cooperate inside the local authority and what are their competences? i.e., will you have municipal departments working together to develop and implement the integrated energy plan? How many people will be involved in total? Consultants, other stakeholders?
7. What are the main challenges you face in your region today to achieve your target, in terms of physical environment, stakeholder engagement, regulations, socio-economic and cultural situations, others?
8. A) Are your current actions in the existing plans corresponding to what you view as “possible”? i.e. within the existing regulatory framework B) If so, do these perceived legal barriers limit the possibility to envision a more ambitious transition?

Questions about scenarios

9. A) How do you see the role of scenarios/visions, if any, in integrated energy plan development? B) Is it necessary to make scenarios/visions to help increase your understanding of the energy system (today and in the future), develop your integrated energy plan and achieve your goal, and why?
10. How will scenario/vision creation compare to your current planning practice? (If based on modelling or analysis) i.e., is the scenario vision creation similar to anything you do in your urban planning today or is it new?
11. What past experience do you have with scenario/vision making, (If based on modelling or analysis) i.e. what energy-related scenarios/visions do you currently make to inform energy related policy e.g. mobility scenarios for mobility policy?
12. A) What will you do in your scenario/vision making? B) Whom will you involve, why and how? Does the municipality make the scenarios /visions, how?

13. Complementary to scenarios/visions, what other methods, tools, and processes will you use to identify the “right” technologies /actions/solutions for the integrated energy plan?
14. A) How important is it to quantify the magnitude of impact of the scenario/vision and in which way quantified? B) How would the magnitude of impact influence your decisions for them to be implemented, does it matter whether the measures can be upscaled and interconnected?
15. What do you plan to do after the scenario/vision creation process? i.e., integrating into urban plan, strategic energy plan?
16. How will the scenarios/visions determine the actions needed to achieve the target? i.e. how are scenarios used to make policy decisions in terms of converting results to final policy decision making?
17. Will the long-term actions in the scenarios/visions correspond to what you view as “possible” i.e. within existing regulatory frameworks, or beyond this?
18. A) Where do you see scenario/vision creation and integrated energy planning in your process towards your long-term goal? B) How relevant is continuous learning and knowledge development? Why?
19. How will your goal and vision fit and link within regional, national and European targets and strategies and what is your city’s role in this?
20. When would you consider yourselves as “integrated energy planning experts”? i.e., which competences, experiences, methods and tools would the city have? What are you missing in order to do energy planning, maybe related to scenario or vision implementation?
21. What is your cities progress so far and what are the next steps, technologies/plan development in the energy transition?

Appendix B. Scientific articles

Study 1 – Transitioning to a 100% renewable energy system in Denmark by 2050: assessing the impact from expanding the building stock at the same time

Study 2 - From Carbon Calculators to Energy System Analysis in Cities

Study 3 - Energy Vision Strategies for the EU Green New Deal: A Case Study of European Cities

Study 1: Transitioning to a 100% renewable energy system in Denmark by 2050: assessing the impact from expanding the building stock at the same time

Energy Efficiency 2019 12(1) pg. 37-55

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Abstract

Residential and service (office) buildings consume a large proportion of primary energy in Europe in the form of electricity and all other energy carriers. In response to this, the concept of near Zero Energy Buildings (nZEB) has been developed. These buildings have very low energy demands and integrate renewable energy to supply residual demand. nZEBs aim to increase energy efficiency from a demand-side user perspective. When looking at the entire energy system, there are also energy efficiency gains to be achieved on the supply-side. For example, from a district heating system. If an energy system becomes more efficient on the supply-side, then the question is how much energy needs to be saved on the demand-side, for instance by low energy buildings such as nZEBs. The purpose of this paper is to analyse and understand the implications from building new low energy buildings, i.e. nZEBs, within an energy system that is (a) transitioning to 100% renewable energy and (b) has substantially improved supply-side energy efficiency. A case study from Denmark is used to understand the outcome for the energy system when these new buildings are built in this context. The methodology and results of this study could be replicated for other European countries as well. The analysis looks at the total energy system heat savings, costs and biomass consumption. The paper shows that these new low energy buildings with very low heat demand do not deliver the expected benefits for the 100% renewable energy system transition in Denmark. This is due to the increased efficiency and flexibility of the energy supply system in the future. However, deep renovations of existing buildings are necessary. Furthermore, this paper demonstrates based on the Danish case, that as European countries decarbonise their energy systems over the next decades, they will need to carry out detailed energy system analysis to determine the extent to which heat demand should be reduced in buildings within the context of the transitioning energy system.

energies

MDPI

Article

From Carbon Calculators to Energy System Analysis in Cities

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Abstract: Energy systems in cities need to be decarbonized and are becoming more integrated via energy sector coupling. Today, cities often use simple methods to assess their low carbon targets, e.g., carbon calculators, and these methods use annualized carbon reduction potentials. For example, reductions from heat savings in buildings or fuel demand in transport. This is done because it is simple and fast. This paper describes a methodology that goes beyond carbon calculators and assesses highly renewable energy systems. The methodology is carried out for a case city—Sønderborg, Denmark. Using a national 100% renewable energy study and a suitable energy system analysis tool (EnergyPLAN), the method accounts for inter-sector coupling and energy system dynamics. The energy system is assessed by comparing the results from the analysis tool against numerous key sustainability factors for a Smart Energy System. The paper illustrates how the method delivers a sustainable 100% renewable Smart Energy System for Sønderborg, which can be part of the Danish energy system in 2050 based on local resources. The paper discusses the broader applicability of the method within strategic energy planning.

Keywords: climate change; energy planning; renewable energy; city

1. Introduction

Cities consume vast amounts of energy due to citizen activity in buildings and transport, and commercial activities such as industry. Energy is consumed either in the form of electricity, fuels, or heat, or a combination of these, which releases greenhouse gas emissions (GHGs). To address these emissions, the European Union set goals of 20% GHG reduction by 2020 and 40% by 2030 [1]. In response, 7755 European Cities have signed the Covenant of Mayors, with more than 6000 submitting Sustainable Energy Action Plans (SEAPs) [2]. In these plans, the current energy situation of each city is described in a Baseline Emission Inventory (BEI) which attaches CO_2 equivalent emissions to energy demand, and reduction potentials for these emissions [3]. SEAPs often look at the use of renewable energy, improved energy efficiency in buildings, optimizing public lighting, improving air conditioning, and improving the efficiency of other appliances [4]. Measures are planned with reduction targets attached to each and, when implemented, lead to reductions in GHGs. These reductions are often analyzed independently and on an annualized GHG reduction basis. Consequently, carbon calculators are used when preparing SEAPs for the Covenant of Mayors [5].

1.1. Shifting to 100% Renewable Energy

Shifting from a partial fossil fuel-based energy system to a 100% renewable energy system in a city involves numerous additional factors [6]. For example, the full integration of energy sectors and large number and variety of inter-linked production technologies, as presented for Denmark in Figure 1.

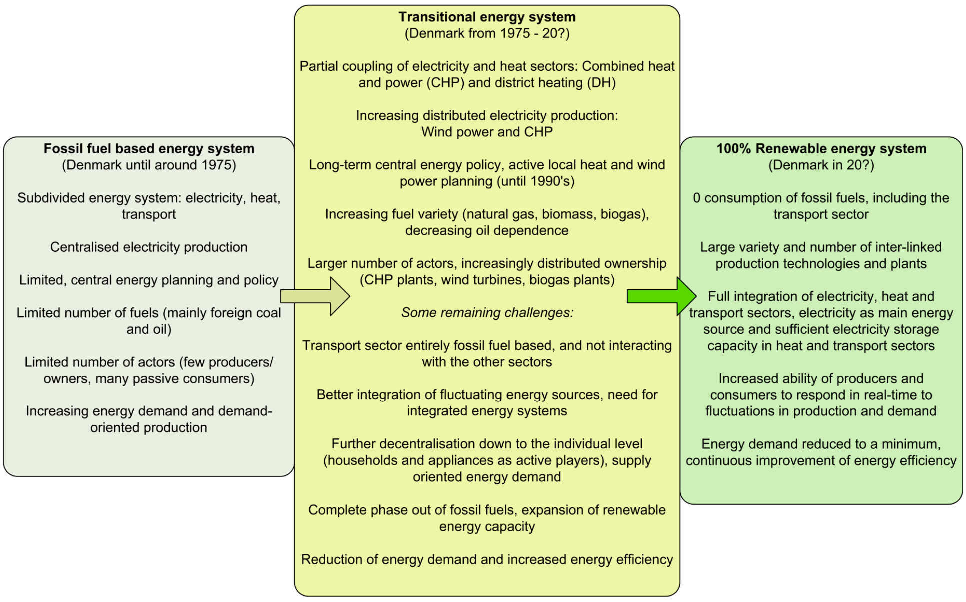

Figure 1. Transition steps from the fossil fuel-based energy system to a 100% renewable energy system in Denmark (Reproduced with permission from Karl Sperling, Frede Hvelplund, Brian Vad Mathiesen, Energy Policy; Elsevier Ltd, 2010. [6]).

The future energy system will be highly electrified and this requires that local energy sectors are integrated, creating numerous synergies via energy storages and flexibility [7]. Energy sectors are already beginning to become more integrated, with decentralized renewable energy, and sector coupling technologies such as electric vehicles [8]. Therefore, in the future when looking at a city as a whole, the energy sectors should be conceptualized as an energy system.

In order for a future 100% renewable energy system to be considered "smart" it needs to meet certain sustainability factors as well, including all energy sectors, improving efficiency and resource use, and improving the environment (Table 1). Addressing these factors ensures that socio-economic costs and biomass consumption are minimized, which are two critical aspects of the future energy system [9].

Table 1. Smart Energy System sustainability factors to be considered in energy system analyses.

Smart Energy System Sustainability Factors [10]	Explanation [11]
Includes all energy sectors	Decarbonize all energy sectors. Synergies are maximized and resource consumption is minimized
Technically feasible design and analysis	Energy imbalances are minimized and unit capacity factors are sufficient
Feasible socio-economic costs	Equal to today, sufficient balance of payments, macro-economic fiscal effects
Feasible energy security	Energy demands are supplied throughout the year
Better efficiency	Resource consumption is minimized
Better resource use	Ecosystem services are maintained
Better environment	Reduction in climate change, health improvements, jobs created

To achieve these sustainability factors, goals need to shift from focusing on the silo effects of individual measures on the energy supply chain, which are too simple, to complex effects in the energy supply chain [12]. In order to set goals, an understanding of the local energy system is required for all the energy system components in an energy system, today and in the future. To develop goals for a Smart Energy System there are three main targets that need to be understood [10]:

1. Resources: fuels, electricity (source);
2. Conversion/exchange and storage technologies (system);
3. Final demand: user behavior end-uses (Service).

All these targets should be analyzed in the dynamic energy system to understand the interlinked and interacting energy flows (Figure 2). Electricity exchange with the rest of the country is also part of this interconnected system (the "energy exchange" box in Figure 2).

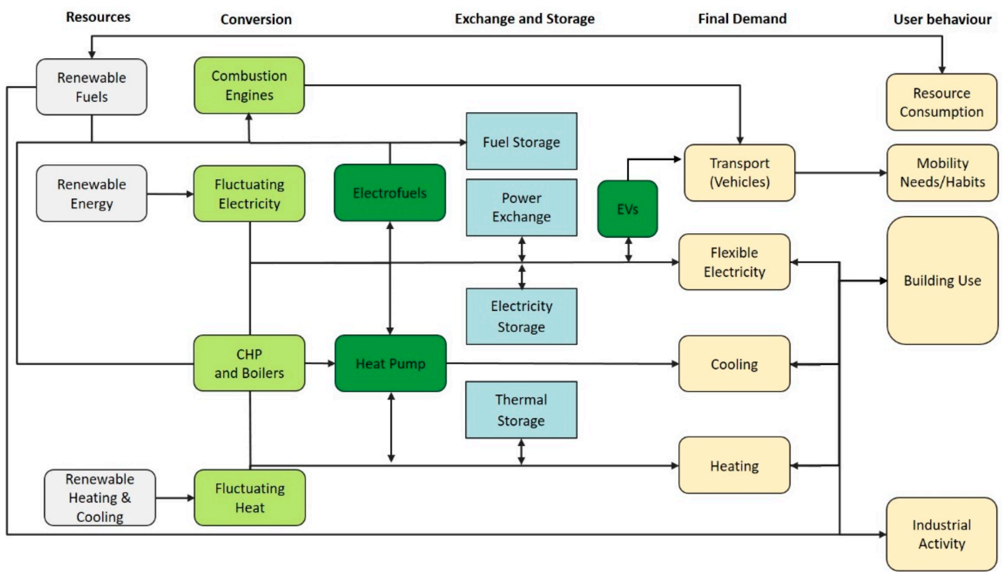

Figure 2. Example of technologies and energy flows in a future smart energy system of a city (Adapted with permission from Henrik Lund, International Journal of Sustainable Energy Planning and Management; Aalborg University Press, 2016. [9]).

The method in this article is focused on developing a local energy system that includes, at minimum, the sustainability factors of: 1) all energy sectors, and 2) a technically feasible design and analysis. In the future energy system, it is assumed that numerous technologies will be local and distributed in many sectors, and the results from the method will develop an understanding of both their interrelations in an integrated energy system and the combination of these technologies with energy savings and energy storages. This requires the use of urban energy system models. Keirstead [13] reviewed the state of the current practice of urban energy system models. The conclusion was that there are four main challenges, which include understanding model complexity, data quality and uncertainty, model integration, and policy relevance. They suggest improvements to the current practice in urban energy systems modeling by focusing on sensitivity analysis and cloud computing, data collection, and integration techniques, and using activity-based modeling as an integrating framework. This article advances from this research by focusing on the sustainability factors of the energy system as well as data quality and verification, as described in [13]. Allegrini [14] investigated numerous district level models and tools for district energy systems and renewable energy. The present article focuses on the broader scope of the city rather than districts, and smaller scale systems in buildings, which apply different methods and tools.

Urban energy system modeling should not be an isolated activity. It should be relevant and done within a planning process. Mirakyan [15] describe integrated energy planning (IEP), which involves city energy system modeling and analysis coupled with the engagement of stakeholders. IEP partly addresses the challenge of policy relevance mentioned in [13]. Mirakyan [15] present numerous options for methods and models for energy system analysis but no clear methodological procedure around assessing the sustainability factors is presented, which is described in this article.

Numerous studies have focused on future energy systems in cities. Aalborg Municipality, Denmark was investigated for how it could rely on renewable energy sources in all the energy sector—electricity, heating, and transportation [16]—specifically using low-temperature geothermal heat, wind power, and biomass. The study was designed to have a self-sustained internal power balance to the highest extent possible, called the "inter-connected island mode", which helps lower transmission losses and avoid transmission grid expansion [17]. This study looked at local resources and applied local expert judgment to build a technically feasible model. The study followed the sustainability factors, however the method is uniquely related to the Aalborg case and is based on local expert judgment. A similar study was performed in the Frederikshavn municipality, which utilized low-temperature geothermal energy for district heating, and modeling was done with expert judgment [18]. Bačeković and Østergaard [19] analyzed Zagreb, Croatia as a traditional renewable energy system and an integrated smart energy system. The analysis modeled numerous technologies in the city as an isolated energy system. For determining the energy supply, the approach followed five criteria:

1. 100% renewable heat and electricity and fossil free transport and industry;
2. Sustainable biomass;
3. Isolated energy system;
4. System balances itself;
5. Technically feasible technologies.

The study followed the sustainability factors, however, to gather data, and to determine the technically feasible technologies, local expert judgment was used. Prina [20] developed a specific method for Bressanone-Brixen, Italy, and analyzed the city as a single node, minimizing the exchange of electricity with surrounding areas. Electricity exchange was limited by using electric and thermal storages, large heat pumps, seasonal thermal storage, and batteries. De Luca et al. [21] developed a method for Altavilla Silentina, Italy to become zero GHG by 2030. They considered all the energy sectors, and the exchange of electricity with surrounding areas was limited. The study also considered the neighboring regions in a scenario analysis. The study demonstrated the potential to share excess electricity between neighbouring regions, which is possible if coordinated. However, some studies have shown that there are potential imbalances in the exchange and balance of electricity between a city and the rest of the country, which poses new challenges [22,23].

1.2. Aim of this Article

The aim of this article is to present a simple approach to determine the configuration of a sustainable energy system of a case city that has been derived from a national 100% renewable energy system (Figure 3). The article provides a systematic methodology and efficient data collection approach, which minimizes the need for detailed local expert knowledge. Such an approach can provide information on which technologies to use in the city within the national context and how a 100% renewable city energy system can be designed in order to contribute to long-term national energy goals.

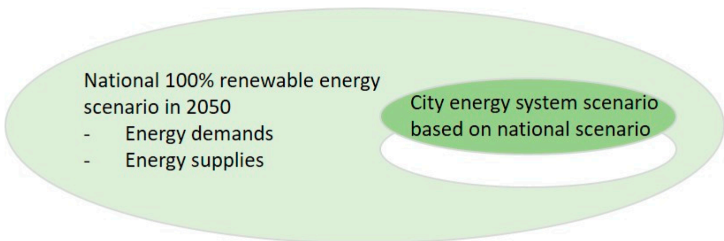

Figure 3. Illustration of the concept of this study, where the city energy system is derived from the national 100% renewable scenario for 2050.

In this study, the term "city" is used, which refers to either a city—i.e., urban area—or municipalities, villages, or towns. Sønderborg municipality in Denmark is used as the case study in this article—herein called Sønderborg. The area includes a medium sized city, a few villages, and rural areas. The energy system for Sønderborg is determined based on the Danish 100% renewable energy system for 2050. In the case study, the method determines:

- The 100% renewable city energy system configuration and role of the technologies within the national 100% renewable energy system;
- The implications for Sønderborg for bioenergy, wind, and solar resources within the context of the national energy system and key sustainability factors.

The methodology is a two-staged approach of: 1) energy data collection and 2) sustainability assessment. In relation to the sustainability factors shown in Table 1, the energy system is refined around local technical feasibility, socio-economic costs, better resource use. This is done by analyzing the results from an energy system analysis tool against the sustainability factors.

The study is presented in five sections. In Section 2, the methodology for the study is described. In Section 3, the case study of Sønderborg is presented. In Section 4, the results for the 100% renewable energy system in Sønderborg are presented and described. In Section 5, the methodology is discussed in terms of its broader applicability within strategic energy planning, including some limitations, and some conclusions are presented.

2. Methodology

The methodology in this article took inspiration from Sperling [6], who suggested that the energy visions and concrete focus areas of municipalities should be provided based on a 100% renewable national strategy. Based on analyzing Danish cases, they suggested that long term national objectives (i.e., 100% renewable energy) should be linked with relevant, sector-specific goals (i.e., for heating, electricity, transport, urban planning, energy savings, and efficiency), where municipalities are given relevant responsibilities and tasks. In other words, a national energy system analysis for 100% renewable energy in 2050 needs to align with city level energy system analyses and actions. National highly renewable energy system scenarios are often detailed and analyzed in their entirety, including all interconnecting sectors and often hour-by-hour [24]. National renewable energy visions can provide useful insights for city energy systems. This approach can ensure that renewable resources are shared between cities and one city does not hinder another city in also converting to 100% renewable energy.

Based on Sperling [6], the methodology derived the 100% renewable energy system of Sønderborg from the Danish 100% renewable energy system in 2050. In this section, the steps for deriving and analyzing the city energy system of today and in the future are described. The method involved four main steps and each step will be described in detail. Steps 1–3 determined the nationally-derived local energy system, and Step 4 was about analyzing the local energy system regarding the sustainability factors. The results from applying the methodology in Sønderborg are presented in Section 3 (steps 1–3) and Section 4 (step 4). The steps included:

1. **City energy system diagnosis today:** Define boundary conditions for the city and gather energy dataset for the city for a recent year;
2. **National long-term energy study and per capita data:** Locate a national study that has both an energy system scenario for a recent year and that looks at 100% renewable energy in the long-term, i.e., 2050. The scenarios should meet specific characteristics, which are described in more detail below;
3. **Per capita energy data for the city in the future:** Quantify per capita energy data for city energy system based on the national long term 100% renewable system (2050);
4. **Analyze and balance the city energy system:** Using the per capita data for the city in 2050 and an energy system analysis tool, assess the city energy system in 2050 with regards to the sustainability factors.

In summary, the approach required three sets of data: (1) recent city energy data, (2) recent national energy data, and (3) long-term (2050) national energy data.

2.1. Step One: City Energy System Diagnosis Today

The first step of the method was gathering the city energy data from a recent year. The data collected in this step was only used for comparing the current (recent year) city per capita data with the country per capita data in Step 2. The city dataset was based on numerous data points for the energy system, which were derived from Figure 2. (Table 2).

Table 2. Data types for a city energy system analysis.

Resource Inputs (1)	Conversion Technologies, Capacities and Efficiencies (2)	Exchange and Storage, Capacities and Efficiencies (3)	End-User Demands (4)	Final Energy Demands (5)	Total Energy Sector Demands (6)	Temporal Demands and Energy Inputs (7)
Fossil fuels; Renewable fuels; Imported electricity; Renewable energy.	Boilers; Combined heat and power plant (CHP); Power plant; Wind; Solar; Motors; Engines; Luminaires.	Thermal storage; Fuel storage; Energy storage; Electricity exchange and distribution (+ losses); District heating distribution (+ losses).	Lighting; Heating; Cooking; Cooling; Driving.	Residential; Industry; Commercial; Light duty vehicles; Heavy duty vehicles.	Electrical energy demand; Thermal energy demand; Cooling energy demand; Transport energy demand.	Hour by hour

The city energy system was not separate from the national energy system, for instance, vehicles cross the boundaries, i.e., cars, air travel, and electricity flows through the national grid. Therefore, there were two main considerations when collecting this data: (1) the geographical boundaries of the energy system being analyzed, and (2) the exchange of energy across these boundaries. Assumptions could be made for transport for what was accounted for and what was not.

Table 2 is a tool for data collection and presents all the basic data collection components required for the energy system analysis. When reporting the data for Sønderborg, the data type number was used, e.g., resource inputs is 1. Data in one category are connected to all the other categories, for instance, resource inputs are quantified with data from conversion technologies, end-user demands and distribution, and storage losses (if any). See [25] for a template example for data connections. Energy conversion technology data (data type 3) are the capacities and efficiencies of the technologies doing the energy conversion of fuels or electricity into end-use energy. Distribution of electricity and district heat were assigned an energy loss. The final energy demands (data type 5) were an aggregate of end-user demands and provided sufficient data for an energy system scenario. The final energy demands contributed to the total energy sector demands (data type 6). The final energy demands included only the end-use energy requirement and excluded the energy losses from conversion and distribution. Resource inputs were entered into the system to supply the total energy sector demands, and during conversion and distribution, resource inputs increased due to losses.

To effectively analyze the sustainability of the Smart Energy System of the city, the total energy sector demands were provided at a temporal resolution higher than annualized data. For instance, hour by hour. This enabled the analyst to understand and analyze the dynamics of the energy system with energy storages and to identify imbalances in the energy system.

Data sources for the city could include local and national databases (energy statistics), e.g., industry fuel consumption, which provides an up to date account of the energy demand and supplies, or private heating fuel demands. For data type 7, average local data could be used or national hour by hour demand and supply data.

2.2. Step Two: National Long-Term Energy Study and Per Capita Data

The second step of the method was identifying a national 100% renewable study (or similar) which provided data for the current energy system and for the future energy system in the city. The study was used for two purposes. The first purpose was to determine per capita national data that fitted the data types in Table 2. This per capita data could be compared with the per capita data in the city in a recent year to understand the differences between the two datasets. The second purpose was to provide future 2050 per capita data that could be used for determining the future city energy system data in Step 3. The national study needed to have the same types of data as the city, including final energy demands (data type 5), and it needed to provide a rough estimate of technologies to use in the city. It needed to have at least conversion technology data (data type 2) and a list of storage technologies and efficiencies (data type 3) that could be used in the analysis.

Per capita energy data from the city and country was calculated and compared for the closest year the data was collected for each energy system (i.e., 2016). This comparison was informative and helped the energy system balancing in Step 4. Both demand and supply data were determined using a per capita approach. However, a few electricity demands changed due to the energy system analysis, for example, the tool determined the electricity demand for large-scale heat pumps and electric boilers, since they are used for system balancing. Most energy demand data remained the same from Step 3 to Step 4. Some energy supply data were influenced by the energy system analysis and balancing in Step 4. The formula for calculating the per capita energy data for the city and country is:

$$\text{Per capita energy data value} = \frac{\text{data in recent year}_{\text{data type 2,3,5}}}{\text{population}_{\text{city/country}}}. \tag{1}$$

Per capita energy data were calculated for: (1) recent city energy data, (2) recent national energy data, and (3) long term (2050) national energy data. These data were entered into a spreadsheet.

2.3. Step Three: Per Capita Data for the City in the Future

The third step of the method was quantifying the energy system data for the city in 2050 based on the national study. In this step, the rough 100% renewable energy system in the city was determined (before analysing it in Step 4). The future city energy system data were determined based on the 2050 per capita data of the country, except for some values dependent on Step 4, such as electricity demand for large-scale heat pumps and electric boilers. The main aim of this step was to get per capita final energy demand, conversion, and storage data (data types 2, 3, and 5), which were used in the analysis in Step 4. The future city per capita data were calculated by following a simple formula:

$$\text{Country2050}_{\text{demand/supply}} = \text{Country2050}_{\text{demand/supply}} \times \%\ \text{of city population of national population}. \tag{2}$$

Cost data (i.e., investment costs, lifetime, and operation and maintenance could be assigned to the energy technologies and other system costs—such as district heating grids and related technologies—that will be implemented until 2050.

2.4. Step Four: Analyze and Balance the City Energy System

The fourth step was analysing and balancing the future city energy system to meet the Smart Energy System sustainability factors. Some final energy demands and energy supply data were adjusted as a consequence of this analysis. To analyze the energy system, a tool was required, which included the entire energy system and could model a 100% renewable energy system in a high-resolution temporality (i.e., hour-by-hour). The appropriate data collected from Steps 1–3 were entered into the energy system analysis tool. When the tool was run, a set of results were delivered that were entered into a spreadsheet for visualization, analysis, and decision making. A small selection of tools could achieve the requirements—Mesap PlaNet, H2RES, SimREN, EnergyPLAN [26]. Other factors were also considered, including the speed to respond to energy planning processes at city level with numerous stakeholder feedbacks, price of the tool, ease of use, tutorials, and accessibility. Based on these factors, EnergyPLAN was used in this study.

The analysis in Step 4 was based on the three previous steps and was an iterative process going back and forth, considering:

- The local energy system that exists today, e.g., district heating network (Step 1);
- The energy system of the country in 2050 and the technologies that can be used locally (Step 2 and 3);
- The sustainability factors are met, for example all energy sectors are included and energy demands are met, resource consumption is low and energy is efficiently used, i.e., district heat is not being overproduced (Step 4)

2.4.1. EnergyPLAN

EnergyPLAN (Version 14.2, Aalborg University, Aalborg, Denmark) is freeware and it provides results fast (within a second) and transparently. EnergyPLAN is a deterministic simulation model that does partial optimization of the energy system using the energy system inputs and outputs entered by the user (Figure 4). When the user enters all the energy system data, i.e., energy demands and capacities and efficiencies of the conversion and storage technologies, the tool determines which energy supply technologies and which energy storages should be utilized in different energy grids in each hour during the year in order to achieve the lowest fuel consumption, or socio-economic cost, in the system. This helps to model, and identify, opportunities for flexibility in the different energy grids. This inter-grid connection and integration with energy storages is a key element of the Smart Energy System [7].

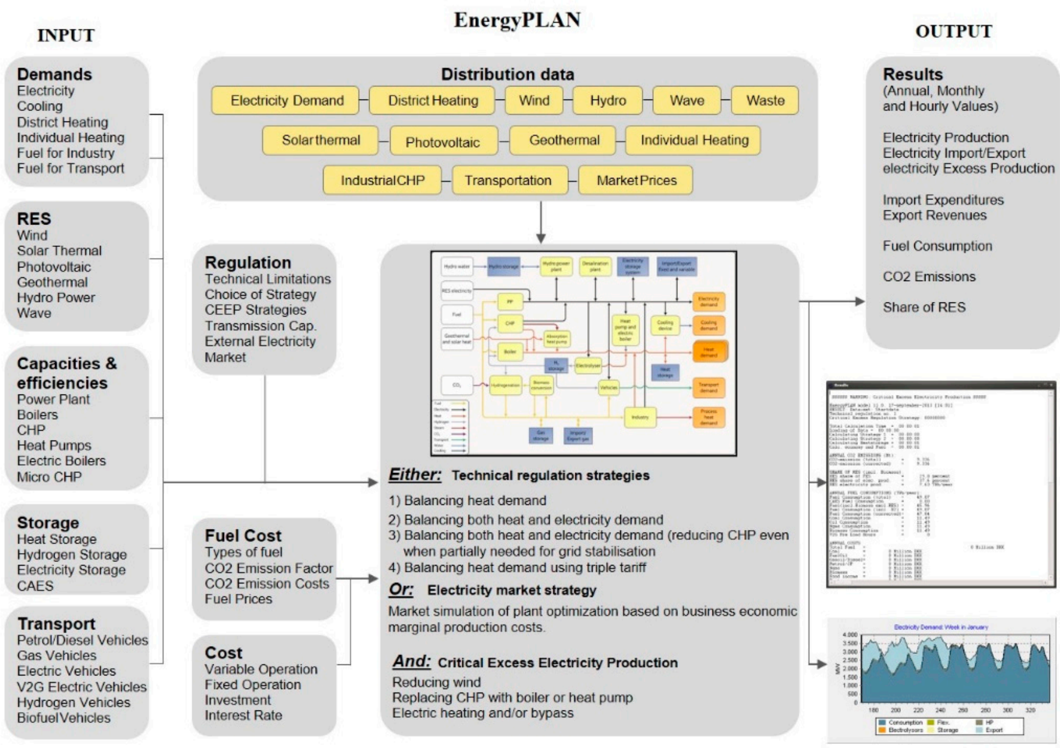

Figure 4. Illustration of the EnergyPLAN inputs and outputs and regulation strategies (Reproduced with permission from Henrik Lund, Renewable energy systems - A smart energy systems approach to the choice and modeling of 100% renewable solutions; Elsevier Inc., 2010, 2014. [27].

EnergyPLAN has been used in numerous energy system studies, including city energy system analyses [28]. Further details about EnergyPLAN are found here: [29].

2.4.2. Balancing the National Energy System with Power Plants

To balance the future renewable energy system, it is expected that power plants will be utilized in times of limited renewable electricity to balance the electricity system, producing around 5–10% of the total production during the year. Smaller regions do not usually have a local power plant and they import most of their electricity. Thus, it can be argued that these cities have virtual power plants. It is assumed that this will also be the case in 2050, and the city analysis for 2050 should include a virtual power plant in EnergyPLAN. The upstream resource input to produce the electricity in these power plants should be considered in the total resource input into the city. In 2050, the resources would be gasified biomass and biogas.

2.4.3. Using the Simulation Tool

The appropriate data from Steps 1–3 should be entered into EnergyPLAN. When running EnergyPLAN, the energy system is arranged to meet all electricity and heat demands locally to the extent possible, and imports electricity when necessary. It quantifies the additional energy demands for large-scale heat pumps and electric boilers. EnergyPLAN is a fast tool and via heuristic analysis with numerous iterations the sustainability factors for the Smart Energy System can be addressed, for example, resource consumption is limited, all energy demands are met, and the district heating system is balanced.

3. Applying the Methodology in Sønderborg

In this section, the results for Sønderborg from the first three steps are presented. The results from Step 4 are presented in Section 4.

3.1. Step One: City Energy System Diagnosis Today

The Sønderborg municipality as defined by the Danish Government defines the boundary of the energy system analysis, and this includes the main city of Sønderborg, a few villages, and some rural settlements (Figure 5). These are governed by a single municipal authority. Sønderborg has a population of around 75,000 inhabitants, with around one third living in Sønderborg city.

(a) (b)

Figure 5. The location of Sønderborg in Denmark and the residential locations of inhabitants in Sønderborg, including the three main district heating areas: (a) Sønderborg Municipality location in Denmark (in red), and (b) location of residential locations in Sønderborg based on heat demands (indicated by orange areas) and three main district heating areas (circled).

The first step of the method was gathering regional energy data from a recent year. In Sønderborg, data were collected for the year 2016. Data sources included numerous local and national databases. Data were collected for data types 1, 2, 3, 4, and 7 (from Table 2). End-use data were collected for end uses such as lighting in households. Heat and electricity production data were collected from industry. The region has three main district heating systems and data were collected for each system. The distribution losses for electricity and district heating were estimated. Data types 1 and 6 were aggregated based on all other data inputs (Figure 6). All the data collected for Sønderborg were presented in an energy balance in a Microsoft Excel file, similar to [25]. The structure of the data in this file is similar to Table 2.

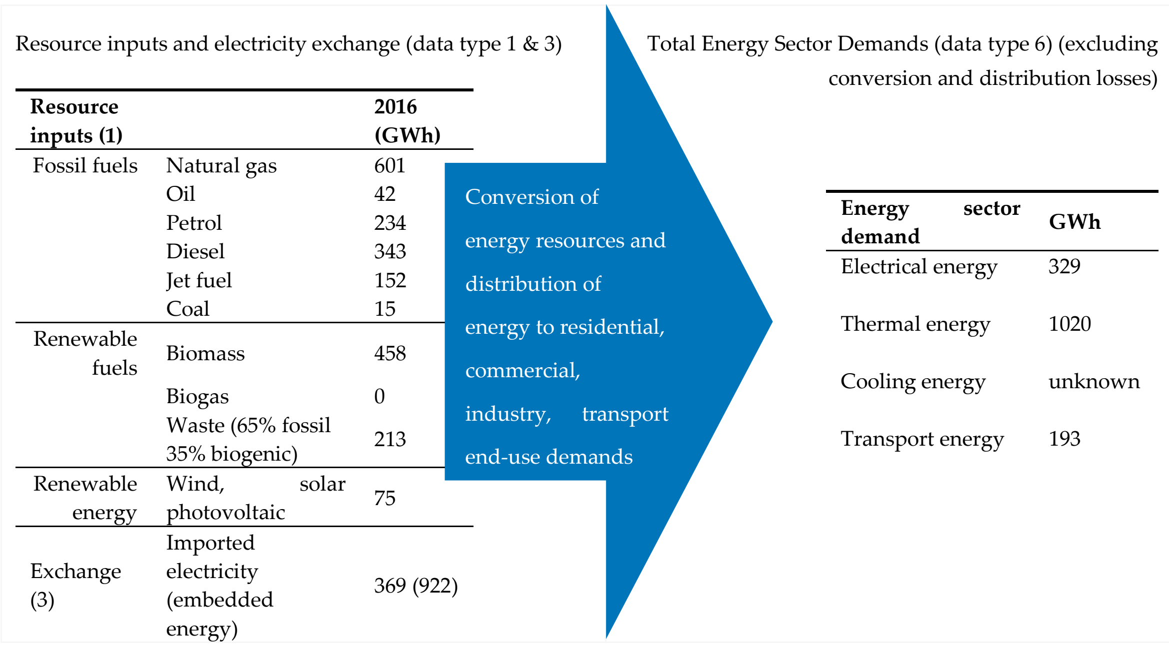

Figure 6. Resource inputs, electricity exchange, and total energy sector demands in Sønderborg in 2016.

The total energy sector demands are the energy required to achieve the end-use, excluding the conversion and distribution losses. The efficiency of the energy system was determined based on resource inputs and total energy sector demands. The embedded energy of imported electricity was 922 GWh (assuming a power plant efficiency of 40%). The efficiency of the energy system was 50%, based on a total resource input of 3079 GWh and total energy sector demand of 1542 GWh.

Local energy conversion technologies in 2016 included electricity production units, private and district heating units, industrial boilers, and vehicles. For each conversion technology, the production of energy, and their efficiency, are presented in Table 3.

3.2. Step Two: National Long-Term Energy Study and Per Capita Data

The second step of the method was identifying a national 100% renewable study (or similar) which has data for the current national energy system and for the future energy system. This study provided data to make a per capita comparison, as described in Section 3.2.2. The latest study carried out for Denmark becoming 100% renewable was used in this study: IDA Energy Vision 2050 [30]. IDA Energy Vision 2050 was completed in 2015. This study provided sufficient data required for Table 3, providing data for final energy demands and conversion and storage technologies for 2015 and 2050 (Table 4).

Table 3. Energy production and conversion efficiencies (in brackets) of conversion technologies in 2016.

Conversion Technologies (2)	Electricity Production (GWh)	Thermal Production (GWh)	Final Energy Demands (5)
Wind (onshore)	33 (100%)	-	Electrical & thermal energy
Wind (offshore)	0	-	
Solar PV	16 (100%)	-	
CHP (decentralized)	5 (37%)	6 (49%)	
CHP (waste)	28 (13%)	159 (75%)	
CHP (industry)	16 (38%)	19 (46%)	
Imported electricity	369	-	
DH boilers	-	271 (~102%)	Thermal energy demand
DH boiler (electric)	-	8 (96%)	
DH solar thermal	-	20 (96%)	
DH geothermal	-	5 (100%)	
Industry boilers	-	253 (90%)	
Private boilers	-	324 (~75%)	
Solar thermal (private)	-	2 (100%)	
Heat pumps (private)	-	7 (300%)	
Electric heating (private)	-	15 (~100%)	
Private cooling	No data	No data	Cooling energy demand
Motors/engines	1.9 (85%)	211 (~25%)	Transport energy demand

Table 4. Key Danish energy system data in 2015 and 2050 (data sourced from [30]).

TWh/Year	Energy Component	2015	2050
Resource inputs (1)	Biomass + waste	40	65
	Wind	11	80
	Solar + geothermal	1	16
	Fossil fuels	155	0
Conversion technologies (2)	Data available but not presented		
Storages and exchange (3)	Electricity import	0	0.8
	Electricity export	−2.2	−14.6
	Electrofuel storage	0	31
Final energy demands (5)	Data available but not presented		
Total energy sector demand (6) (excluding conversion and distribution losses)	Electricity	31	67
	Heating	42	42
	Cooling	5	5
	Transport (Total energy sector demands excluding conversion and distribution losses were not provided for transport so they were estimated based on efficiencies of vehicles today. Efficiencies were 25% light vehicles, 33% for heavy vehicles, 33% for aviation and shipping, and 85% for electric vehicles.)	16	13

3.2.1. Danish Changes to 2050

IDA Energy Vision 2050 integrates numerous energy supply technologies and storages, such as wind power, heat pumps, thermal storage, and electrolyzers. The report provided the capacities and efficiencies of these technologies. Regarding the change in energy demands from 2015 to 2050, the main assumptions of the study included:

- Heat demand in buildings was reduced by 40%, which was based on the cost of renovations against the cost of supplying heat.
- Household electricity savings were reduced by 25%, which was based on three factors:
    - The future increase of equipment of 10%;
    - Technical savings of 15%;
    - Behavioral savings of 20%.

- Industry and service sectors, including agriculture and construction, assumed business as the usual growth of 40%. This energy demand was reduced via savings for fuel and electricity and a coordinated implementation of district heating and cooling, electric heat pumps, and replacement of fossil fuels with electricity, biomass, and upgraded hydrogen (methanated biogas).

All these changes in energy demands were assumed for Sønderborg.

3.2.2. Comparing the Per Capita Energy Data of Denmark and Sønderborg

In this step, the Danish per capita energy data was compared to the Sønderborg per capita energy data. Note that in the study these comparative results were only informative. To make the comparison easier, the per capita data were scaled up to represent the population of Sønderborg instead of being per capita. Firstly, the per capita data for Denmark and Sønderborg were calculated using Formula 1. Secondly, the per capita data in Denmark in 2015 were multiplied by the population of Sønderborg, and these results were compared to actual data collected in Sønderborg in 2016 (Table 5). In 2015, the population of Denmark was 5,669,081 and the population of Sønderborg was 75,000—around 1.3% of the Danish population.

Table 5. Final energy demands in Sønderborg in 2016 and calculated final energy demands based on Danish per capita values from 2015.

Final Energy Demands (5)		**Sønderborg 2016 (GWh)**	**Sønderborg Based on IDA2015 (GWh)**	**Sønderborg Difference**
Electrical energy	Residential	79	115	−46%
	Industry	146	129	+12%
	Commercial	104	112	−7%
Thermal energy	Residential	578	556	4%
	Commercial	148	316	+40%
	Industry	294		
Cooling energy	Residential	unknown	59	n/a
	Industry	unknown	26	n/a
	Commercial	unknown		n/a
Transport energy	Light vehicles	109	112	−7%
	Heavy vehicles (including rail)	26	35	−19%
	Aviation	50	45	+11%
	Shipping	8	8	0%

3.3. *Step Three: Per Capita Energy Data for the City in the Future*

The third step of the method was quantifying the city energy system data for 2050 based on the national study. By using formula 2—multiplying the future population of Sønderborg by the Danish per capita energy system data in 2050—the final energy demands for Sønderborg in 2050 were calculated (Figure 7). The final energy demand data provided numerous key values for EnergyPLAN. All capacities and efficiencies for conversion technologies and storages were also provided by the IDA Energy Vision 2050 and these data were entered into the energy system analysis tool in Step 4. Step 4 was carried out to ensure the technologies were at the appropriate level, considering the sustainability factors. In 2050, the population of Denmark is expected to be 6,229,193 [31] and it is assumed Sønderborg would still account for 1.3% of this, therefore having a population of 80,979.

Conversion technologies (capacities and efficiencies) (2)	Exchange and storage (3)
Boilers CHP Power plant Wind Solar Motors Engines Luminaires	Thermal storage Electricity exchange (+ losses) Fuel storage Energy storage

Conversion and storage for final energy demands

Final energy demands (5)		Sønderborg 2016 (GWh)	Sønderborg 2050 (GWh)
Electrical energy	Residential	79	86
	Industry	146	265
	Commercial	104	
Thermal energy	Residential	578	555
	Commercial	148	163
	Industry	294	
Cooling energy	Residential	unknown	99
	Industry	unknown	26
	Commercial	unknown	
Transport energy	Light vehicles	109	95
	Heavy vehicles (including rail)	26	69
	Aviation	50	34
	Shipping	8	13

Figure 7. Final energy demands in Sønderborg in 2016 and 2050 and conversion and storage technologies.

4. Results: Step Four—Analyze and Balance the City Energy System

The fourth step was analyzing and balancing the energy system in EnergyPLAN and ensuring the sustainability factors were met. In this section, the final results from this step are presented for a selection of the data types.

4.1. Data Type 1—Resource Inputs

The final resource inputs for Sønderborg in 2016 and 2050 are presented in Figure 8. Resource inputs include local and imported resources. Figure 8 shows the connection of the Sønderborg energy system with the national electricity grid via the import and export of electricity. Electricity import is minimized in 2050 due to the energy sector coupling and an increase in the efficient use of energy, a key sustainability factor, and in this study the imported electricity was 89 GWh (5% of the total energy supply). Electricity export is limited to minimize the risk of not being able to integrate electricity into neighbouring regions and due to limited synergy effects between the regions [23,32].

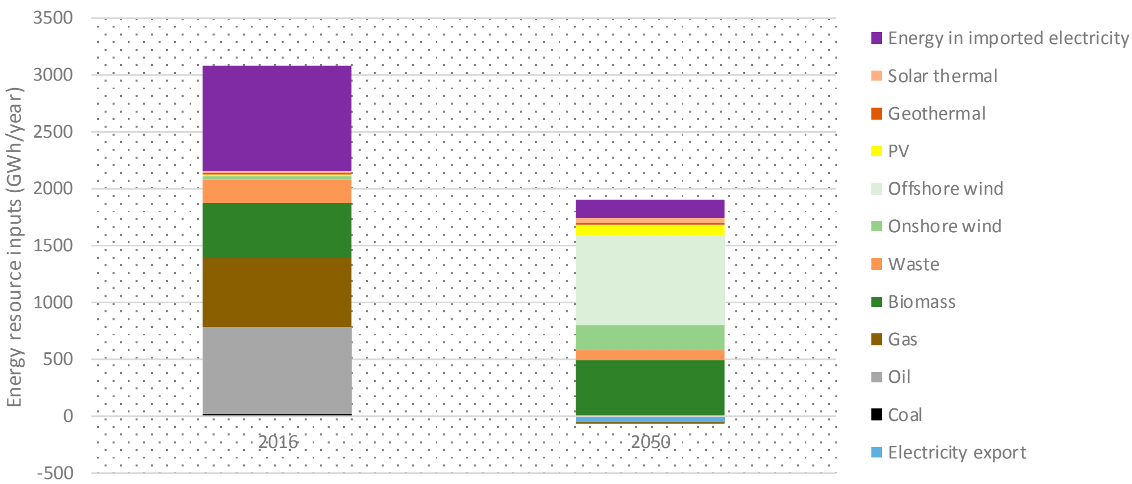

Figure 8. Energy resource demands and electricity export, in Sønderborg in 2016 and 2050.

In Sønderborg in 2016, the total energy supply was 3079 GWh, and was mostly from imported fossil fuels and electricity supplemented with biomass and waste. Electricity import was also high, which added 922 GWh of embedded energy (based on assumed 40% power plant efficiency), mostly sourced from coal and biomass. In 2050, the total energy supply could be decreased to 1907 GWh and largely be composed of wind electricity, biomass, and waste, sourced locally. Imported electricity from power plants would be fueled by biomass and biogas. The total energy sector demand would equal 1405 GWh. The results show a loss in the energy system in 2050 of 26% compared to 50% in 2016.

Sustainable biomass in Sønderborg, based on a proportion of the Danish potential for livestock manure, biofuel, and energy crops, straw, firewood, and wood chips, should be approximately 600 GWh. In 2050, although locally sourced biomass demand is 489 GWh and local biogenic waste is 94 GWh, which is within the sustainable range, the embedded biomass in imported electricity from power plants is 162 GWh. These values indicate that to have a sustainable biomass consumption nationwide there would need to be coordination between the regions around biomass production, distribution, and consumption.

4.2. Data Types 2 and 3—Conversion Technologies (Production) and Storages and Exchange

Conversion technology capacities and efficiencies were determined for all energy system components, including electricity, district heating, private heating, electric vehicles, electrofuel production, and energy storages. Data can be presented for all these units. However, for brevity, in this section only electricity, heating, and transport production results are presented—the associated energy storage capacities and efficiencies are not presented.

4.2.1. Electricity Production

Electricity is produced locally, and a large production is from offshore and onshore wind (Figure 9). There is less imported electricity than in 2016 and a minimal amount is exported.

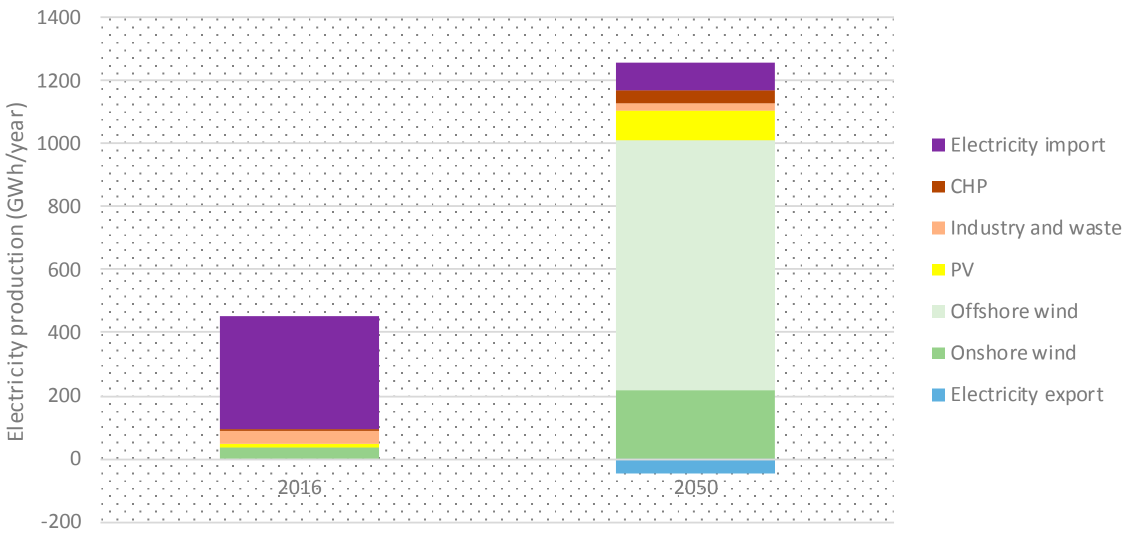

Figure 9. Electricity production, import, and export, in Sønderborg in 2016 and 2050.

To understand the technical feasibility of the energy system, hour by hour electricity production data was analyzed. A small sample of the quantified results for the 8760 hours during the year is presented (Figures 10 and 11). Electricity demand was met mostly by internally produced electricity and supplemented by the imported electricity. In the first two days of January, offshore wind and imported electricity accounted for the majority of electricity supply, whereas in the first two days of July, offshore wind and solar photovoltaic provided most of the electricity.

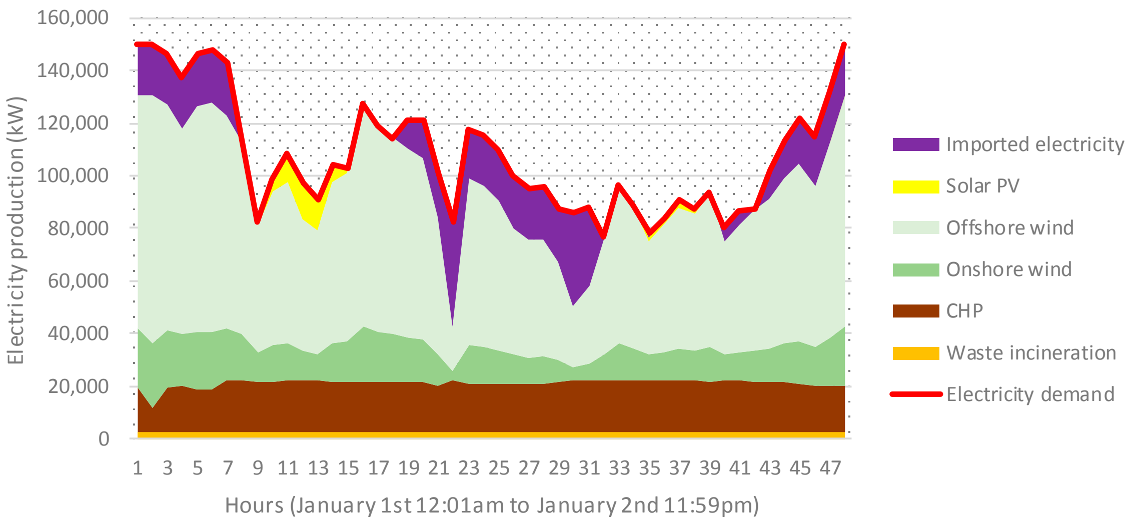

Figure 10. Electricity demand and supply in Sønderborg in 2050: first two days of January.

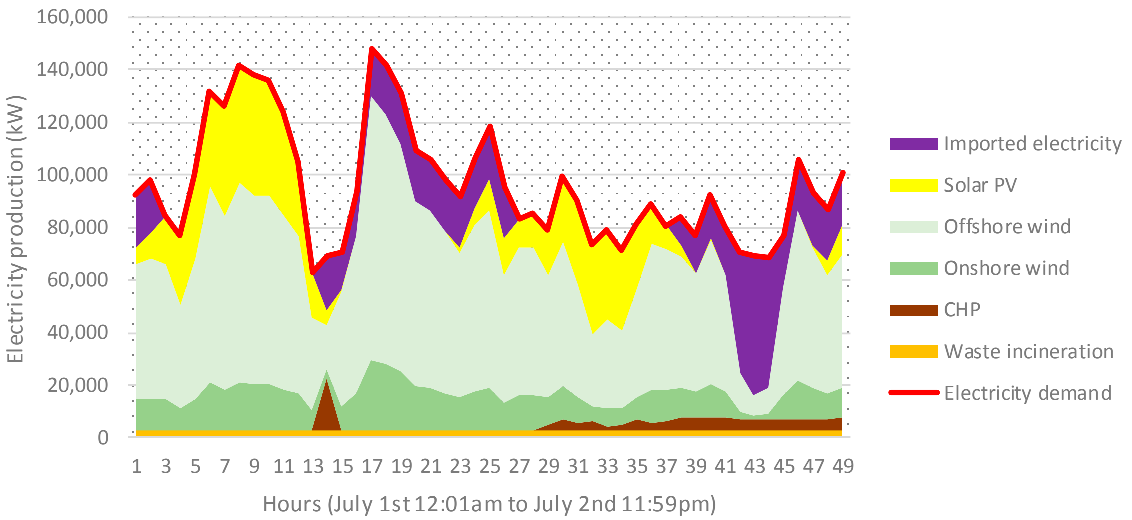

Figure 11. Electricity demand and supply in Sønderborg in 2050: first two days of July.

4.2.2. District Heating and Private Heating

District heating in Sønderborg consists of the three district heating grids, but since Sønderborg city accounts for most of the consumption (85%), all the grids have been aggregated in these results (Figure 12). From 2016 to 2050 district heating is expanded to cover 66% of the heat demand, but total heat demand is reduced. Total heat demand in 2016 is 743 GWh and in 2050 is 559 GWh. This is due to private heating, which reduces from 384 GWh to 190 GWh. In 2050, private heating is produced mostly with heat pumps. All heating demands are met sufficiently and all three district heating grids are in balance throughout the year, with minimal heat surplus or deficit, and this is a key indication of better resource use. A large share of district heating is supplied by large-scale heat pumps.

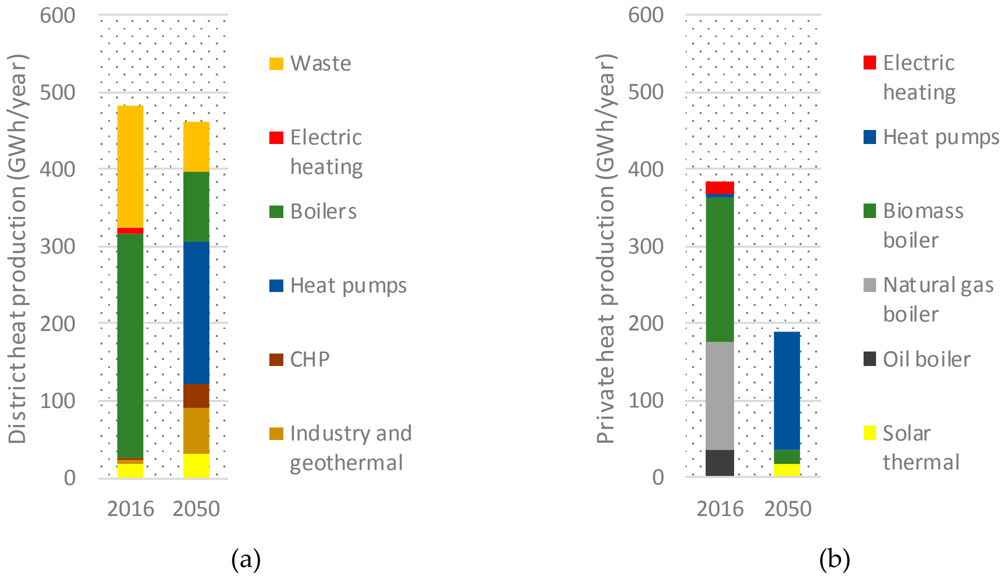

Figure 12. Heat production from: (a) district heating units and (b) private heating units in Sønderborg in 2016 and 2050.

Hour by hour district heating data is presented for a sample of the 8760 hours (Figure 13). In the first week in of January, in Sønderborg city, large scale heat pumps provided the most district heat, with a few hours of oversupply being stored. This stored heat was utilized later in the year. The remaining district heat was produced by boilers, geothermal, industry, and waste incineration.

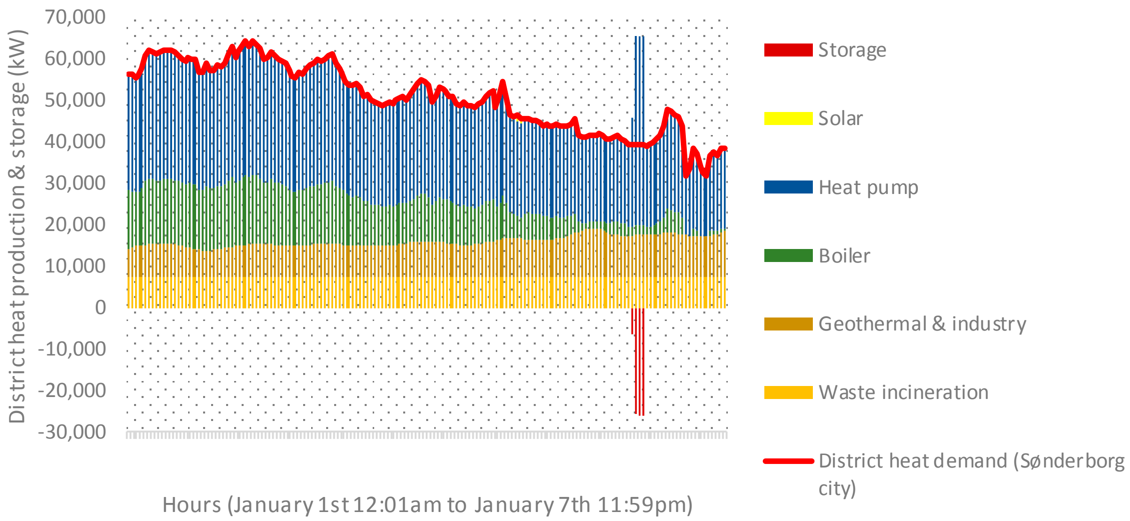

Figure 13. District heating demand and supply (and storage) in Sønderborg city in 2050: first two days of January.

4.3. Data types 4, 5, and 6—Final Energy Demands, End-Use Demands and Total Energy Sector Demands

A mixture of final electricity demands (conventional demand) and end-use electricity demands (household heat pumps) are presented in Figures 14 and 15. Total electricity demand is the sum of all individual demands. Conventional electricity demand is an aggregation of lighting and appliances for residential and office buildings, and industry. From 2016 to 2050, conventional electricity demand remains largely the same. However, new end-use demands add to the total electricity demand, for instance electrified transport and electrolyzers.

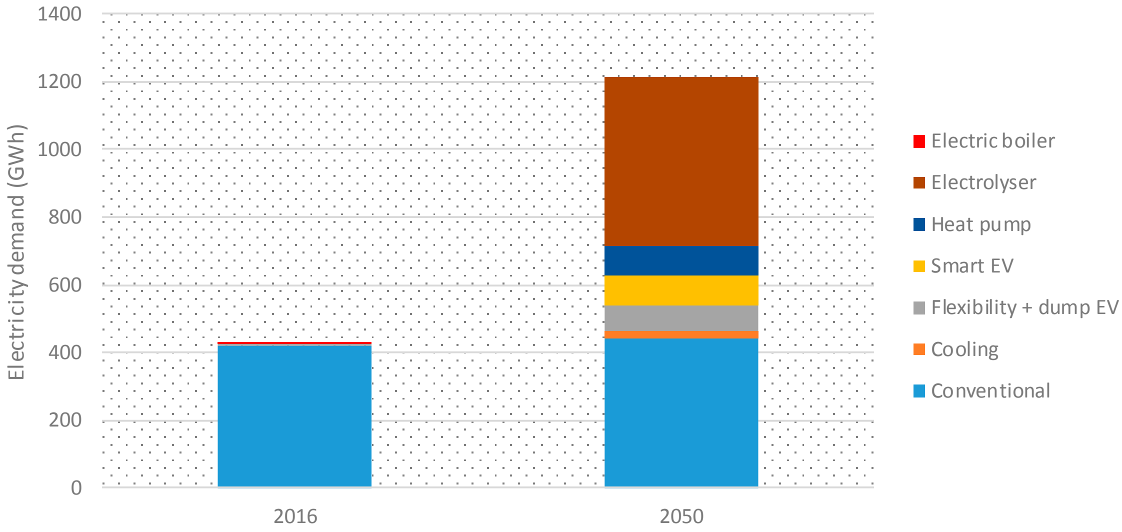

Figure 14. Electricity demand by different end-uses in Sønderborg in 2050.

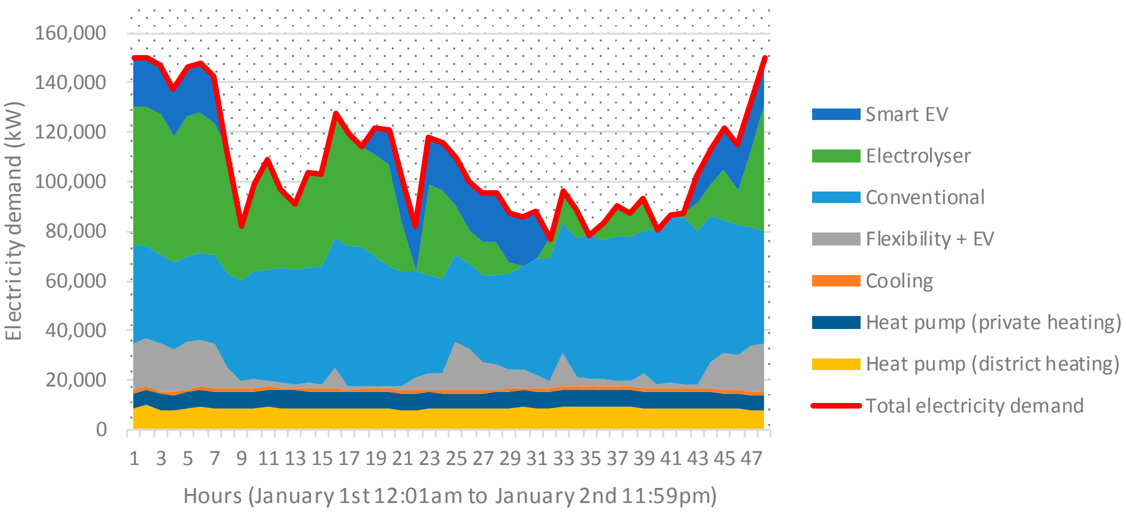

Figure 15. Electricity demand by different end-uses in Sønderborg in 2050: first two days of January.

The consumption of electricity by different types of electricity demands is shown for a selection of hours in the first two days of January (Figure 15). The electricity demand of heat pumps in the district heating system is constant, which provides the heat shown in Figure 13. Smart charging vehicles charge during the night, as seen in hours 1–7. Electrolyzers operate when there is cheaper electricity, for instance when wind power is high (see Figures 7 and 15). Conventional electricity demand fluctuates between day and night.

The total transport energy demand is reduced from 720 GWh to 510 GWh. Transport fuels shift from being sourced from fossil fuels to being sourced from electrofuels and electricity (Figure 16).

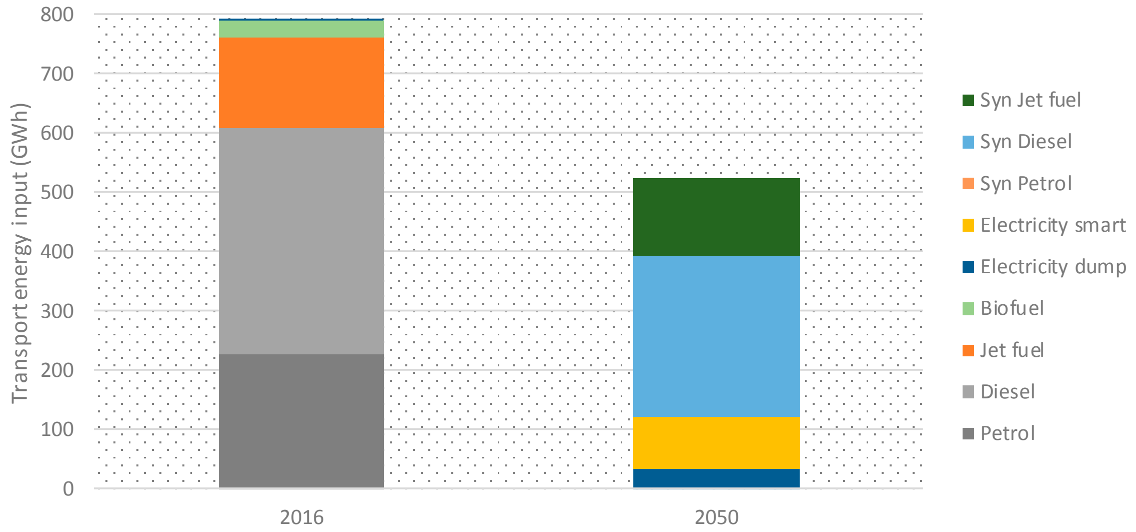

Figure 16. Transport fuel consumption in Sønderborg in 2016 and 2050.

4.4. Potential Investments Towards 2050

Investment cost data for technologies and energy efficiency initiatives could be entered into EnergyPLAN, and based on this the tool calculated the total potential investments. Potential investment costs for the technologies, or efficiency improvements, such as building retrofitting or district heating expansion, in the Sønderborg energy system were an important factor in determining their sustainability and for project implementation (Figure 17). The total investment costs were based on predicted unit costs in the future and the present value of money, and not total cost of ownership. Annualized costs based on lifetimes can be calculated but it is uncertain when these energy system changes will be implemented, which influences the annualized cost calculations. With more local knowledge, a roadmap can be combined with these investment costs to create annual expenditures.

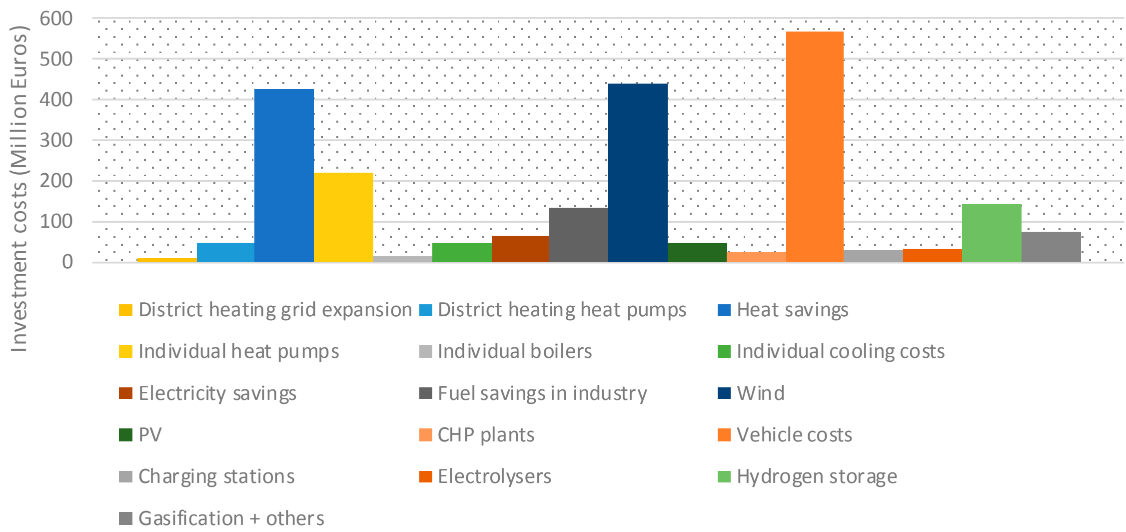

Figure 17. Potential total investment costs between 2016 and 2050 for a selection of technologies and energy efficiency initiatives in Sønderborg. These costs are indicative based on the Danish 2050 energy scenario and further analysis at the local level should be undertaken.

5. Discussion and Conclusions

The aim of this article was to present a methodology to determine the renewable energy system of a city derived from the national 100% renewable energy system. This was tested with the case study of Sønderborg. It was a two-staged approach of: (1) data collection and (2) sustainability assessment. The four-step methodology was able to analyze the complex renewable energy system locally. The method included all potential components of the future energy system and analyzed this on an hour-by-hour basis to understand the energy system dynamics from a Smart Energy System perspective. This showed how the technologies operate and interact.

This study advances the research field by focusing on the sustainability of the Smart Energy System rather than on improving energy data collection, which is often the focus [13,33]. Furthermore, the approach advances from focusing on silo measures in individual energy sectors, for instance, electricity measures in the electricity sector, which use particular models. Furthermore, to understand the dynamic energy system and the real need for energy storages, the method depends on higher resolution hourly data during the year rather than annualized data, as used in other methods and models, such as SEAPs.

The method was not simply focused on the modeling tool. EnergyPLAN was used as the tool in this study, but other tools can be utilized. However, other tools should be able to measure the sustainability factors. The method was focused on how the tool is used to understand how the city can go to 100% renewable energy in a sustainable way, i.e., in the scenario design. The article applies key sustainability factors for Smart Energy Systems to ensure the energy system is sustainable—utilizing energy locally and maximizing energy own-use (feasible energy security), maximizing technology synergies (better efficiency), and reducing biomass consumption (better resource use).

The methodology is not unique to Sønderborg and can be replicated in other countries and cities. By leveraging the national study, the method allows one to do rapid analysis, providing insights into the synergies and resource use in the energy system and potential technologies in the future. This can lead to long term goals and to understanding the potential of the energy system. The methodology avoids time consuming local energy system data collection, i.e., trend analysis and forecasting. In cities today, as part of SEAPs, the first step in the method of this article is usually undertaken, but to determine long term visions and goals within strategic energy planning, steps 2–4 can be undertaken (Figure 18). The methodology can be applied by one or two energy planners, and results can be visualized, communicated, discussed, and updated later by stakeholders, as is done in strategic energy planning [34]. The methodology, analysis, and results should be seen as an initial framework for future iterations—to analyze different actions, the detailed analyses can be continually adjusted in ongoing revisions. New iterations should consider if the planned energy system is "smart" by analyzing it in terms of the sustainability factors, as described in this article.

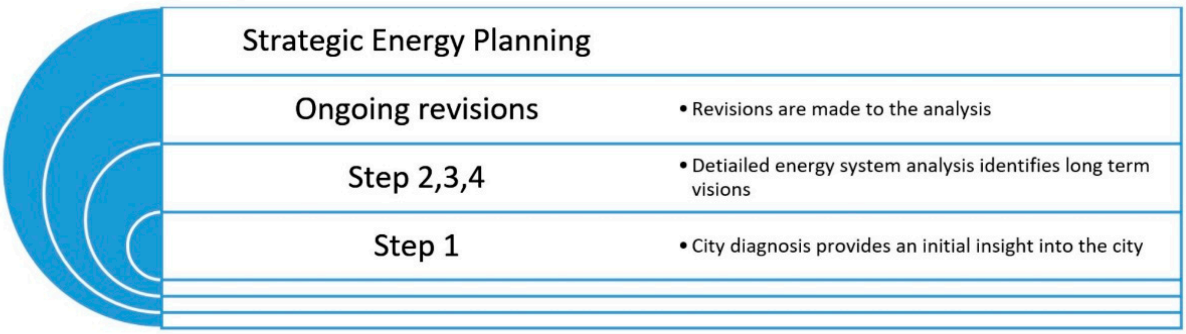

Figure 18. Energy System Analysis within strategic energy planning.

This study does not consider the implementation of specific projects in the city, which will require a more detailed understanding of certain aspects of the energy system, and further analysis using other methodologies or tools. Furthermore, the study does not include analyses on the need to change concrete policies and taxes, or the changes that will occur for the re-distribution of costs and power between stakeholders. The overall economic consequences were assessed and prove to be level with the current costs, but the transactions between individuals, the government, and other stakeholders need to change in order to implement such changes. Furthermore, it is unknown what the energy system will look like in the future, some technologies may not be located in Sønderborg, however the purpose of this approach is to present an initial analysis and results for one sustainable scenario from which to make new iterations.

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Energy Vision Strategies for the EU Green New Deal: A Case Study of European Cities

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Abstract: There are three strategic levels for successful energy planning in cities: 1) Integration strategy for integrating energy planning into urban planning institutions; 2) Practice strategy for developing suitable energy planning practices in urban planning institutions, and 3) Vision strategy for the creation and integration of energy visions and scenarios required for long-term decarbonisation. The vision strategy is critical but not well researched and is the focus of this article. Using Strategic Energy Planning (SEP) as an analytical framework, the vision strategy of eight forerunner European cities are analysed. Some critical elements of SEP include the use of long-term targets, holistic energy system thinking, and retention of scenarios. The results indicate that the level of understanding and practice of the vision strategy is still deficient in the cities. Cities often use the practice of urban planning, which does not fit very well with energy planning, particularly with the vision strategy. The energy planning in the cities mostly focuses on shorter-term goals and actions, and they often abandon energy scenarios once extracted. However, through trial and error, some cities are finding ways forward. The article concludes with several recommendations, particularly that cities need to see scenarios as retainable long-term servants providing information desired by the planner, rather than serving as a guide to the planner.

Keywords: climate change; strategic energy planning; city; decarbonisation

1. Introduction

The EU aims to be climate neutral by 2050, which is at the heart of the Green New Deal and written into the Climate Law [1]. The role of cities needs to be enhanced to achieve this goal so that they can contribute effectively [2]. Local initiatives in cities are important in achieving overall national and international goals since most energy technologies have a regional planning element in distributed energy systems [3].

Climate change has been a focus for cities for many years [4], particularly addressing challenges to institutionalise it in planning practice [5–7]. The focus on climate change within urban planning involves Energy Planning, defined by [8] as "determining the optimal mix of energy sources to satisfy a given energy demand." Optimality considers multiple criteria for decision making, including the traditional multiple scales (temporal and geographical) and quantitative technical and economic criteria [8]. Energy planning in the climate change context relates to the measures and actions of a city and their qualitative environmental impact and social criteria that lead to a decarbonised energy system.

Energy planning has been practiced by urban planners in Europe for a shorter period than climate change since energy is not traditionally under their authority [9,10], with some exceptions, such as the Danish heat planning law and Swedish energy planning law. Recently, cities are setting ambitious energy decarbonisation goals (for example, Copenhagen, Hamburg, Frankfurt aiming for 100% renewable energy by 2050) [11]. Cities are also joining city energy networks to share knowledge and develop methods [12], joining EU energy projects [13], and engaging local stakeholders in their local energy measures [14]. Furthermore, countries have set low carbon goals [15] (for example, Denmark and Sweden aiming for 100% renewable energy by 2050 and 2045, respectively), which will help cities achieve their goals by decarbonising the electricity grid that electrifies them [16].

This article argues that there are three primary strategic levels to achieve successful energy planning in cities. Although, there is no predefined order since cities can operationalise them independently, and they all constantly interact. The first level is about integrating the practice of energy planning as an institutionalised strategic practice in planning departments, with a particular focus on building legitimacy [6]. The second level is about developing sufficient energy planning practices in urban planning, for example, through Integrated Energy Planning [17], involving implementation and collaboration with stakeholders. Efforts have focused on teaching energy planning to urban planners [18]. The third strategic level of energy planning is about developing strategic visions and scenarios for a decarbonised energy system and making appropriate plans towards this [17,19]. This level is herein called the vision strategy and is the focus of this article.

For energy planning for decarbonisation to emerge, we regard the Vision strategy highly essential. The Covenant of Mayors Sustainable Energy Action Plan (SEAP) is a successful, although limited, approach cities have used to address the vision strategy [2,7,20,21]. In Europe, the SEAP approach helps cities in their ambitions towards the EU 2020 and 2030 targets, and involves city diagnosis (baseline emissions) and identifying measures to address emissions to meet specific CO_2 goals. The approach clarifies the local energy problems, using energy visions and scenarios to help identify potential solutions [22]. However, we argue that the vision strategy needs to be more advanced and based on some key Strategic Energy Planning (SEP) elements, including long-term decarbonisation targets, holistic energy system thinking, and retention of energy scenarios.

1.1. Aim of This Article

This article aims to analyse which strategic practices forerunner European cities currently employ to promote decarbonisation in energy planning. The article analyses how eight European forerunner cities are addressing the vision strategy in terms of the creation and integration of decarbonisation visions and scenarios. The energy planning practices of each city are analysed via an analytical framework based on SEP, as described in [23].

The cities are chosen based on their ambition for achieving decarbonisation in the future. Each of the eight European cities is analysed and evaluated regarding the manner that each city addresses the strategic level to:

- Understand the basic energy planning practices
- Understand how the cities plan, create and integrate decarbonisation visions and scenarios
- Overall evaluate the Vision strategy in each city

This article uses the term city broadly to include subnational areas, which may include municipalities, small regions, villages, towns, or cities.

1.2. Structure of the Article

Section 2 describes the method, which involves interviews and desktop research, and the analytical framework to analyse the cities. This section also describes the strategic levels of energy planning, emphasising the role of creating and integrating decarbonisation visions and scenarios.

Section 3 presents the results for the cities concerning some critical themes related to the vision strategy of energy planning in the cities.

Section 4 discusses the results in the context of the vision strategy.

Section 5 presents some conclusions for future energy planning in cities.

2. Methodology

The study selected eight diverse forerunner cities from Europe that have demonstrated ambition and progress regarding energy planning and decarbonisation. For each city, the energy planning vision strategy is evaluated based on a framework described in this section. The interviews contained questions based on the analytical framework.

2.1. Strategic Levels of Energy Planning in Urban Planning

Decarbonisation of the energy system involves developing a highly interconnected energy system that is more efficient, cost-effective, and with minimal (imported) biogenic resource demands [24–26]. Such integrated systems have been researched in recent years, for example, in Denmark for 100% renewable energy (Figure 1).

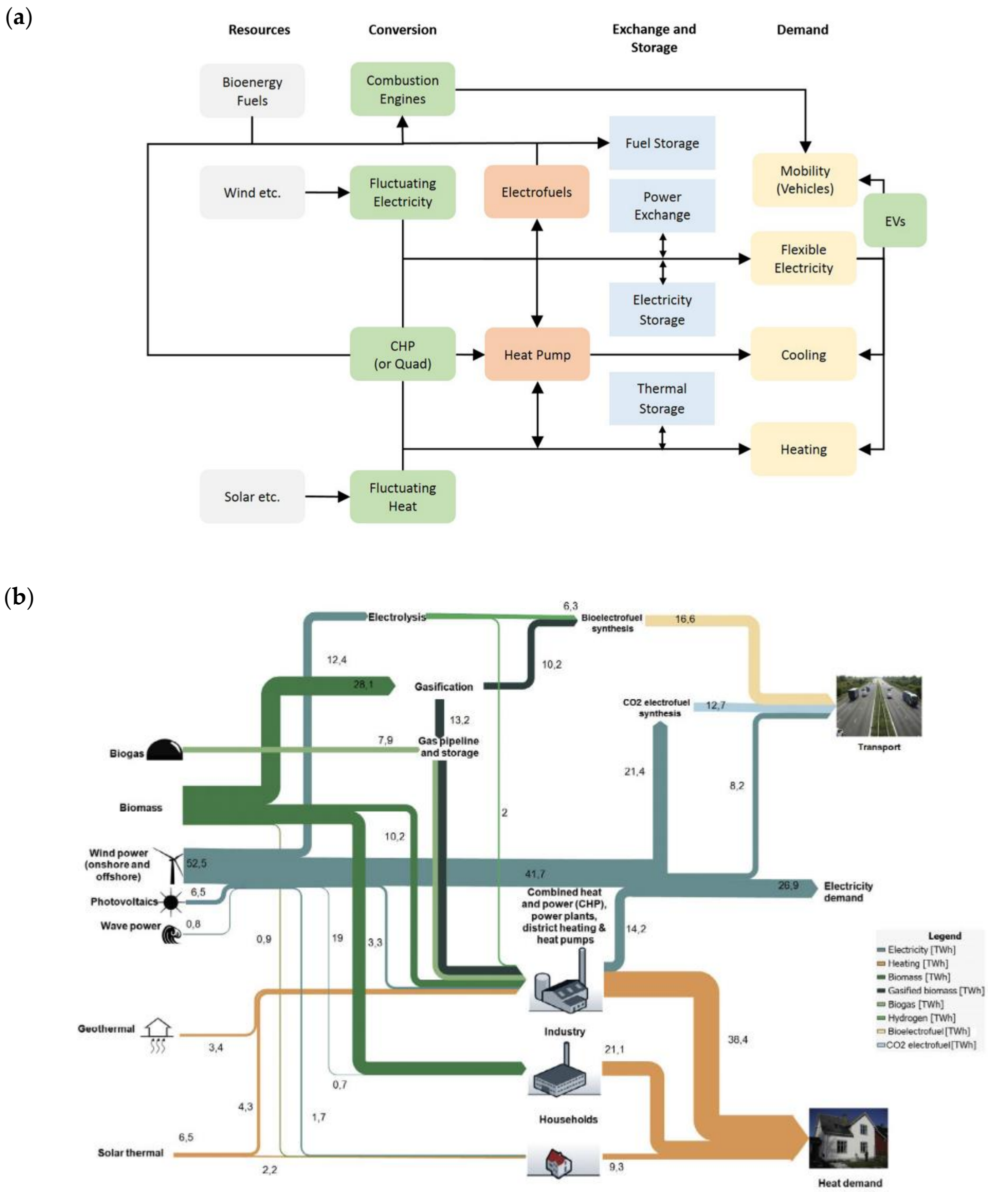

Figure 1. (**a**) Interconnected renewable energy system components [27] and (**b**) efficient energy flows [26].

At a planning level, the transition to a sustainable energy system involves a complex mix of agents (stakeholders), objects (technologies and infrastructures), and the environment [28]. The environment provides resources but also sets the conditions for the energy system socially, politically, and culturally. The new energy infrastructure regime will likely emerge as Bulkeley ([5], p.1477) states as a "configuration alongside and in-between the existing socio-technical systems" [5]. The energy system adapts in a self-organised emergent behavior of the agents and objects of the system [28]. Strategies could include and empower numerous actors and stakeholders in strategic thinking and strategic architecture rather than rational strategic plans [29], forming meta-governance arrangements that have emerged in recent years [30]. A meta-governance arrangement develops where the institutions influence the interaction of agents through networks [28,30]. These complex elements bring a new set of wicked problem conditions into the urban and energy planning practice. Including a "lack of a single problem statement", "conflicting values", and "conflicting objectives", to name a few [10]. Furthermore, the complex adaptive energy system lends itself to scenario models that are good at prediction and forecasting [28].

Stabilising a new decarbonisation regime could emerge through the (re)alignment of discourses, actors, institutions, techniques, and artefacts [5], with the three critical strategic elements being institutions, techniques, and artefacts [31]. Discourses and actors are essential to the regime change and play a role in vision and scenario creation, thus strongly linking to the artefacts.

This article proposes that these three elements require three levels and practices of strategy. Cities develop strategies independently for each level, although they are all interrelated, and there is no predefined order. Over the last decades, the concept of sustainable development has slowly struggled and emerged within urban planning via strategic actions at levels one and two [32–35].

Strategic level 1. Institutions (integration strategy). Strategic level one relates to addressing political buy-in and aligning internal departments and resources to ensure sufficient energy planning. Often, city administrations divide into silos with limited cross-sectoral coordination, and practices lack standardisation [36,37]. Furthermore, crucial sectors related to greenhouse gas emissions are not within the influence or responsibility of cities since they often focus on other issues such as land-use planning [4].

Strategic level 2. Techniques (practice strategy). Strategic level two is about developing and improving energy planning know-how (i.e., practices, skills, competences, and expertise) to ensure sufficient energy planning. Researchers have proposed methods, such as Integrated Energy Planning [38] involving stakeholders and creating discourses through visions and scenarios, as well as implementing energy plans.

Strategic level 3. Artefacts (vision strategy). Strategic level three is related to developing appropriate visions, scenarios, and reports and plans to ensure sufficient energy planning. This strategy comes from the fact that cities often focus on individual initiatives that are small-scale, creating disproportionate system effects [39]. Energy planning needs to have clear long-term goals, clear vision, scenario creation within a strategic order, and involve the right stakeholders in the municipality, which is a rather new and unknown territory in most cities.

Strategic visions and scenarios can provide insight into the decarbonisation of energy systems, especially system integration in cities. This article focuses on the decarbonised energy system and its requirements and what planners need to do in response to this, often referred to as backcasting [34,40], as opposed to what planners are doing to integrate energy planning into their practices. The Vision strategy requires a mix of rational strategic planning (to understand the interconnected energy system) and stakeholder engagement (to provide local knowledge and partnerships for implementing the interconnected energy system). This article does not interpret the results for the first and second strategic levels, although these have been researched previously [5,6,41].

2.2. Making a Case for a Vision Strategy in Energy Planning

Cities are centres of high energy demand and have great potential to reduce this demand. A recent study extrapolated Covenant of Mayors individual trajectories to 2050 and indicated that they are on track to meet the central aim of the Paris Agreement-the pursuit to limit global temperature rise of 1.5 °C above pre-industrial levels this century [20]. However, the challenge is that when emission reductions increase, as renewable energy increases on a large-scale, the energy system has new integration challenges [42]. Technologies in the renewable system will be interconnected and interactive [24,42], involving process enhancements, efficiency increase, system integration, and multigeneration [43]. The behavioral change will also be a significant contributor [44]. Combined, this has implications for local energy planning for planning new infrastructures and integrating them. Studies that extrapolate to 2050 preclude identifying and understanding these integration challenges and opportunities.

2.2.1. From Silo to Energy Systems

As the energy system becomes more integrated and decarbonised, the extent of the vision strategy increases (Figure 2). Planning shifts from not only basic non-concrete statements or silo-thinking about site or plant level efforts, such as the need for renewable energy measures, but to advanced system-level thinking considering the need for system integration, or sector coupling. The basic level is still there and essential: cities will always need to implement projects one-by-one. But on top of this, the bigger picture has changed and is getting more complicated-requiring systems-level thinking. For example, understanding the import and export of energy between sectors.

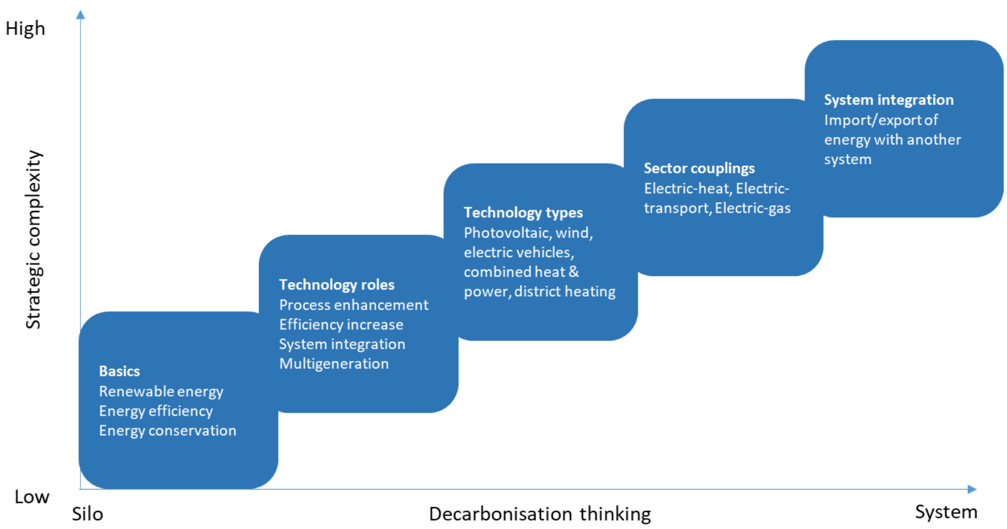

Figure 2. Relationship between increased decarbonisation thinking and strategic complexity.

As the strategic planning intensifies, the strategic complexity increases, and the decarbonisation thinking needs to shift towards system thinking. Often computer tools are required to help this [19,45]. The strategic thinking about system integration increases the likelihood of sustainable decarbonisation because the certainty around the system interconnection is better known and better planned.

Although some energy sectors can transition via technology replacement-e.g., light transport and EVs and efficient technologies in the electricity sector-several energy sectors pose a challenge to the transition. Including the heating sector [46–48], heavy transport [49,50], gas sector [26,51], and industry [51]. All require a mix of energy conservation, efficiency gains, renewable energy, and energy sector integration [52]. There is a risk of unsustainable outcomes if the energy system is not understood and planned with a detailed understanding of how to get to the long-term target. Including missed opportunities to integrate energy sectors, missed efficiency gains, overinvestments in infrastructure, unacceptable electricity demand costs, unsustainable biogenic resource consumption, and costly path dependency and lock-ins.

For long-term deep decarbonisation, cities need to strategically plan their technical energy transition from an energy system perspective as opposed to individual measures [23,53,54]. Three key analytical groups need to be considered and understood about the interconnected decarbonised system (Table 1): (1) essential elements [53,55]; (2) sustainability elements (economically, environmentally, socially) [43]; and (3) advanced energy system elements for an optimal energy system in the city and with surrounding regions [55,56].

Table 1. Elements to consider for the energy system in the Vison strategy.

Essential Elements	Sustainability Elements	Advanced System Elements
• Energy demands • The balance of all energy demands and supplies • Variety of resources and production technologies • Fuel/energy mix • Flexibility • Energy conservation needs • Grid affects • All sector-sector couplings • All grid interactions • Land use requirements • Resource demands • Economic costs • Region-to-region interaction	• Exergetically sound • Energitically secure • Environmentally benign • Economically feasible • Commercially viable • Socially acceptable • Integrable • Reliable	• Reserve capacity requirement • Use of import and export energy, i.e., system imbalances & integratability • Island mode/connected mode/or connected island mode • Condensing mode operation • Primary energy consumption/fuel use • Renewable energy shares • Carbon dioxide emissions • Societal costs • Cost of energy/utility costs and rate impact • Total resources spent • Short & long-term marginal costs

Numerous studies have investigated decarbonised energy systems within cities in this integrated way [53,57–59], although only from the technical energy system and not in terms of the strategic energy planning practices of the cities. Studies have paid little attention to the status of strategic vision and scenario creation and the integration process in cities. Numerous studies propose methods for analysing renewable regions based on rational strategic methods [53,60–62]. However, this article moves beyond these quantitative studies to understand and develop strategic thinking inside the city departments.

2.2.2. The Role of Energy Visions and Scenarios

Strategic visions and scenarios are needed to understand the interconnected energy system and the three groups of considerations. Therefore, the creation and integration of decarbonisation visions and scenarios in energy planning is a critical process and is a core part of energy planning practice and the vision strategy [23,63]. Both are usually interlinked. Qualitative descriptions communicate energy visions [63]. Examples of visions include "fossil-free by 2050" or "energy secure by 2050". Visions are usually not formed by using tools but created by the city authority, sometimes via stakeholder engagement in workshops.

Scenarios are a quantitative translation of the vision [63] and are important to define concrete actions and measures for implementation. Scenarios enable a city to make better planning decisions towards decarbonising their energy system, either by being able to understand what they need to do, communicate their plans better to other planners and stakeholders, and collaborate with other planners and stakeholders better. In general, scenarios are usually quantitative, and several tools can be selected to quantify and translate the values that meet the vision, including simulation, optimisation, and system dynamics tools [17]. There are also methods explicitly designed to mathematically translate from vision to scenario [63–65].

2.3. Selection of Cities

Ambitious cities were required for the study since they would be suitable beacons to determine where the current energy planning practice is at present. The collection is a stratified sample of the population of cities in Europe [66]. There are over 10,000 signatories in Covenant of Mayors, and over 6000 cities have developed a SEAP, meaning that many cities demonstrate this ambition. In this study, the aspiration was determined based on participation within the EU Horizon 2020 smart city lighthouse projects. The focus was on the projects within the "Smart Cities Information System" since this demonstrates ambition and progress [13]. Numerous projects focus on smart technologies, and only two projects have a specific focus on improving the integration of energy and urban planning. The cities were selected from these two projects and have been anonymised (Table 2 and Figure 3). Involvement in these projects indicates that the cities are either experienced with energy planning, have developed their methods, or are willing to advance their knowledge and planning approaches and have an expectation on how to proceed.

Table 2. City code, population, and representative interviewed.

	Population	Person Interviewed	Internal/External
City A	<300,000	Engineer (planning department)	Internal
City B	500,000–1,000,000	Group manager	Internal
City C	500,000–1,000,000	Environmental investigator	Internal
City D	<100,000	Project manager	External
City E	<100,000	Consultant	External
City F	<100,000	City planner	Internal
City G	<100,000	Expert (in energy & planning)	Internal/External
City H	<300,000	Environmental technician	Internal

Figure 3. General location of the eight case cities in Europe.

Based on these two projects, eight cities were selected since they demonstrate ambition to become decarbonised and to practice energy planning. These cities began with SEAPs but graduated with individual methods. Urban planning in different countries will differ due to differing local conditions such as institutional and political arrangements, horizontally and vertically [30]. However, this analysis investigates the regime change at the strategic level, with the expectation that each country is the same strategically, although planning practices and geographical conditions may differ under the strategy.

2.4. Structure of Interviews

Since energy planning is in its infancy and has not been insitutionalised yet, in most cities, it was not possible to find "energy planners" nor sometimes "planners" who worked on energy systems. However, the authors identified the most senior energy-related "planner" associated with the city. Sometimes located outside the city authority in an energy agency. They were identified based on their involvement, or coming involvement in plans related to energy such as a climate plan, energy plan, SEAP or similar. They were contacted and asked if they would do a semi-open phone interview to provide insight into their energy planning and scenario creation and integration process.

The authors carried out eight one-hour interviews (one from each of the eight cities). The authors collected and analysed relevant supplementary energy/climate plans to learn more about their energy planning. The authors carried out interviews from November 2018 to January 2019, and according to the themes of the analytical framework, were transcribed, coded, and categorised, allowing for analysis [67].

The authors believe that taking the view of a senior energy-related planner is sufficient for the article in this infancy phase. Furthermore, the small sample of interviews provides adequate insight for the research question since the cities offer broad coverage of Europe, including cities from the north, south, east, west, and central Europe. Also, the authors interviewed senior staff with detailed knowledge of the energy planning process as it is practiced today and will be in the future.

Although the main focus is on the Vision strategy, the interviews asked questions about all the elements for regime change, as described by [5] (Table 3). Since they are all relevant and interrelated in the (re)alignment of the regime, making the analysis more comprehensive.

Table 3. Themes informing the interview questions and analytical framework.

Theme	Regime Element	Insights
Energy planning arrangement	Institutions	How the city does planning and energy planning and who is involved
Targets	Techniques	Types of targets they have, the longevity of the targets
Stakeholder engagement	Actors	Stakeholder engagement in the creation of scenarios
Energy scenarios & technologies	Discourses & Artefacts	Creation and integration of scenarios in energy planning and how stakeholders involved, i.e., business, industry, experts, citizens
Plans	Discourses & Artefacts	Main urban plan and energy-related plans

The authors also asked questions about: (1) the energy technologies for decarbonisation and their role in achieving the targets, and (2) the local conditions that affect energy planning, since these are essential elements in the complex energy system and provide further insights [28].

2.5. Analytical Framework

The results of the interviews were analysed using an analytical framework developed from the concept of "Strategic Energy Planning" (SEP) as described by [23]. Strategic Energy Planning is being used in Denmark by Danish municipalities to develop local strategic energy plans [14,23,36], and has been evolving for the last decade and is still developing [36]. As renewable energy has increased in Denmark, it has required more "strategic" energy planning at the local level [54], since ongoing development of the energy system requires understanding the system in the future to plan for it.

The "strategic" aspects of SEP in Denmark is centred around the long-term target of 100% renewable energy system by 2050. Based on this target, it is necessary to create strategic energy visions and scenarios to understand the energy system in the future [23,54]. The visions and scenarios created towards this goal allow for energy system awareness over time, shifting away from silo- to systematic longitudinal- thinking. The strategy focuses on the final energy system; however, environmental conditions will change over time, meaning continuous development of scenario iterations towards the final energy system design (i.e., every couple of years). Meaning, a strategic element of SEP is the use and retention of scenarios because it allows for ongoing reflection and adjustments on the vision, energy system transition, and planning.

State authorities and researchers have developed long-term national goals and plans. However, there also needs to be a coordinated effort locally since the national level cannot do this alone [54,68,69]. Stakeholder engagement and collaboration are seen as necessary to achieve this complicated transition since stakeholders will need to develop some of the initiatives. Local and national governments need constant collaboration influenced by local needs, and scenarios can help achieve this [54]. Therefore, SEP also focuses on strategically aligning national and regional goals to coordinate national and local planning activities. If needed, cities can make micro-level strategies for neighbourhoods or districts based on the understanding of the holistic system of the whole city.

This advanced stage of renewable energy integration and energy planning practice in Denmark allows for using SEP as an analytical framework for the eight cities. The analytical framework applies several critical strategic elements in the analysis (Table 4). The authors analyse each city in terms of their strategic visions and scenario creation and integration process using these SEP elements.

Table 4. Core strategic elements for effective decarbonisation energy planning utilized in the analysis procedure.

Strategic Elements Used in the Analysis	Description
Decarbonisation target	Full decarbonisation of the entire energy system as opposed to part
Long term target	Informed target for the energy system and resource use
Medium-term target	Informed by long term target
Short term target	Informed by long term and medium-term target
Consistent target	Long term target does not change
National to local coordination	Reflecting local changes against national goals
Holistic systemic approach	Whole energy system to allow for strategic technology integration over time
System awareness	Role of technologies well understood within the system
Retention of scenarios	Retaining scenarios which can be adjusted. Meaning all these elements can be (re)understood if something changes.

3. Results

The results from the analysis are presented according to the core strategic elements in Table 4 and grouped into descriptive topics. The five topics dealing with the "targets" in Table 4 are dealt with together, as are the two topics "holistic system approach" and "system awareness".

3.1. Consistent Long Term Decarbonisation Target: General Absence of Long-term Full Decarbonisation Targets

Except for City A, who tentatively focuses on a long-term target-climate-neutral 2050-the other cities do not have a long-term target in mind (Table 5). Neutral means net zero emissions over one year. In City A, this target is an intention, and every plan reflects on this target; the city vision and climate plan integrates the target. The interviewee mention that Covenant of Mayors does not go far enough and has set a climate-neutral goal by 2050 to account for all emissions.

Table 5. Final target year and decarbonisation target of each of the eight cities, and ideal strategic end target.

	Description	Ideal Strategic End Target
City A	Intention of climate-neutral 2050	End year (i.e., 2050) complete decarbonisation
City B	Politically stated 2037 carbon neutral. Likely follow national government net-zero 2045	
City C	2050 sustainable and equitable CO_2 level	
City D	Will set a target for 2030 undecided for 2050	
City E	40% of 2007 for 2030, undecided for 2050	
City F	2029 carbon neutral	
City G	40% reduction over 2010 by 2030	
City H	Undecided. Region target is 80% by 2050	

City F has a goal of carbon neutrality by 2029, determined by a group of stakeholders in 2007, which they see as an end-goal target. City F has no target beyond the carbon-neutral target of 2029, even though carbon neutrality involves exporting energy to offset local emissions, and the reality is that emissions remain after 2029.

Most cities have a medium-term target to 2030 for municipal, residential, industrial, and transport sectors based on the SEAP ambitions, or their planning cycle. Some cities have not set the target yet. For instance, City E makes a new plan every ten years, and the target often follows this. In their new plan, City E will determine the target based on a recalculation of the baseline in 2017 to understand the progress so far and understand the real reduction to 2030. City D is also undecided for 2030.

Most cities do not aim for complete decarbonisation and have explicit opinions about this. They see medium-term targets (2030) as incremental goals from which to make a new target when the time comes and do not mention in connection to longer-term scenario creation. City D sees long-term targets with high decarbonisation is not realistic since the aim should be incremental targets. If they cannot achieve them, then they cannot set a more ambitious target. They see targets as stepping-stones from which to set new targets when the time comes, rather than a way to plan towards the long term. City D specifically stated them as not necessary, and there is no reason to make them.

Some cities simply align with the region or country. For instance, City H will likely align with the regional government target of 80% reduction by 2050. Furthermore, City B has set a carbon-neutral goal for 2037; however, the interviewee sees carbon-neutral as a political target and unrealistic and achieved with creative accounting. City B is in the process of making new targets and stated they are likely to follow the national government net-zero target by 2045. Although the interviewee of City B says that the EU 80% reduction by 2050 is very ambitious and before making these types of ambitious targets, they need to ensure it is achievable. They continue by saying they need to be careful when making strategy documents.

3.2. National to Local Coordination: Soft Links from Local to National Goals

All the cities have a connection to targets of other authorities but not always the national level (either national, regional, or other municipalities). For instance, in some cities, the national or regional level is not ambitious enough. For example, City A has Europe as a reference, not national or regional, since they are too slow and not ambitious enough. Also, City G is pushing the national level by having more ambitious targets along with the capital city.

A few cities follow national goals. City B tries to achieve national government goals in their local goals by aligning with the national government by focusing on sustainability, carbon reductions, and fuel poverty. City C link their climate program to regional and national goals. City F follows the national legislation about making commune plans, which contains a link with the national target. But not so much the EU.

City D collaborates with other municipalities and exchanges information and is in line with the goals and principles of surrounding municipalities. They are also part of the broader national framework and follow the national priorities and see how they fit with them. In general, they fit because they harmonize with the EU goals.

3.3. Holistic, Systemic Approach and Systemic Awareness: Scenario Outcomes Informing Traditional Urban Planning Actions and Problems

Cities D–H are moving beyond their SEAP 2020. They are following the Foresight method and are forecasting technology trends in their scenarios. The expected outcome from these scenarios is often similar in regards to understanding the effects of actions based on technology types, characteristics, and costs. For instance, City E sees the scenario foresight activity useful to give the possibility to identify and understand priorities and main action line strategies for the highly important but uncertain drivers of change, with the scenarios showing the drivers for future years. They will use scenarios to quantify the effects of actions. City F sees scenarios as a tool in the process of finding specific projects. City F quantitative scenarios partly inspired the commune plan with actions and have already taken scenario results and translated and integrated some actions into the commune plan.

City G also stated that scenario results and objectives go hand in hand with action plans. They mention that action plans are separate but need to suggest actions that will support the objectives when working with stakeholders. City G expresses that these people usually use a very practical approach to planning and do not function from pure theoretical concepts of energy and climate policy. They want to see what exactly will happen; therefore, they say they always discuss feasible actions together with ambitious targets. City G will try to include more social translation and visualisations of scenario results.

City D sees scenarios as rooted in economic reasoning and a way to quantify and determine economic feasibility and CO_2 reductions from energy measures to determine the measures. They use scenarios to optimize for economics, finding the optimal scenario in terms of achieving targets with optimum resources. City D does not see it as possible to ignore economics within the scenarios since private entities need to know the economics of projects. Furthermore, the scenarios show which measures and costs to include in the urban plan and from where the money comes. Although City D mentions that they see scenarios useful for setting up future targets, they base it on finding the most sensitive variables and most influential end results from which the largest impacts can come.

City B has shifted from a technology focus to a problem-based approach focusing on scenarios for particular problems they face or related to the EU projects in which they participate. City B has done numerous scenarios for numerous components of the energy system. For example, one project focused on EVs and the effect on the grid. City B is now developing a local heating and efficiency strategy in response to its energy poverty challenges.

City A stressed they are now at a point where they are always trying to make the step from vision to action as short as possible. City A did an energy scenario for the city using a consultancy. They are now focusing on districts and replicating one plan from one district to another; therefore, they used the scenario results to "zoom" into certain districts going into detail about thresholds and possibilities. They state that zooming into districts gives better insights to tackle challenges and make tailor-made actions for investors.

3.3.1. Simple Scenario Calculations and External Support

Based on the action-oriented scenarios, cities often focus on simple approaches, continue from previous activities, or simply leave quantification to external consultants.

City G will utilize an Excel spreadsheet and use and modify calculations looking at several reductions and total CO_2, based on assumptions for different scenarios. E.g., electricity reduction, recalculation of emissions from electricity. They also want an energy balance and flow chart of the city, with the primary sources of energy coming in and used inside the municipality.

City E is starting from SWOT analysis of the city and questionnaires (similar to the SEAP process and standard in the Foresight method), saying then they will have a useful input for scenario planning and the definition of main strategic actions.

In City D, new scenarios will build on the old ones and introduce the Foresight method, considering technical, economic, financial, administrative, legal, and administrative aspects. City D scenarios will investigate the achievements, what is the current status, and what are the different potential areas. They then look at what is economically feasible after choosing the potential actions in different areas and different technologies based on the previous plan.

City H will leave quantification up to a consulting company prescribing that they want impacts on CO_2 quantified in the tender. City H will also hire a consultancy for developing the energy transition strategy. The consultancy develops the energy transition strategy from scenarios with budget and activities prioritized with estimated impacts. The strategy is used as the backbone of the system giving the timeline and roadmap over the next years for the city as a whole, integrating mobility, retrofitting, and renewable energies. The "energy centre" of the authority will assist and advise on the process and how to identify sector stakeholder activities and prepare the timeline and budget estimations with the consultancy help too.

City F also used external support for societal vision scenarios about the future to 2050, and detailed quantitative energy system scenarios for carbon neutral in 2029. Their detailed quantitative scenarios determined how the energy system would look when carbon neutral in 2029, and their qualitative scenarios looked into the future to start to think about how to act on that.

City B focus on specific problems leading them to focus on particular energy components. They work with external support for addressing different issues; for instance, they work with a University using modeling to understand impacts of energy efficiency on buildings, optimum charge and discharge efficiency of batteries concerning solar with the output being CO_2 reductions.

Although some cities have made detailed decarbonisation studies, this has led to limited influence. For instance, City A has done detailed scenario work for the city, but the work emphasized biomass and therefore was not useful. However, they say it was helpful to have expert input, and they have utilised its detailed energy scenario to focus on districts.

City C has a fossil-free 2050 investigation, kept active in planning circles; however, its climate program does not integrate it well. The investigation suggested dozens of measures in different areas, e.g., car traffic, buildings, cycling, walking, mass transit, energy efficiency, air traffic, renewable energy, renewable fuels, and so on. Broad measurements for each measure were quantified rather than specific, with measures evaluated on either having a minor, medium, or significant impact on climate emissions. The cost of each measure was also estimated, with an additional aim to quantify the time horizon for when the measure reaches full potential. However, this investigation has a limited influence on actual planning and decision making.

3.3.2. Systemic Thinking versus Silo Thinking

Cities are not speaking about systemic integration and interconnection of technologies in an energy system. Rather than placing the measure or action in an energy system context, typical answers from the cities focus on off-the-shelf silo thinking where they see solutions as being available, and the only issue is purchasing and implementation. Which is likely related to the focus on actions and simple approaches. For instance, some cities stated that all or some of the necessary technologies are already there, such as district heating or ICT (City H, City G). City G says that it is not a question of technology since new efficient technologies are on the market for all sectors. They see technology implementation as a critical challenge and only about replacing energy-efficient technologies.

Some cities emphasise only one energy sector. For instance, City H emphasise reducing and electrifying demands by focusing on high capacity electric transport and electric public transport (e.g., 100% electric busses and electric trams), and EVs. They state that batteries are necessary for renewable energy, and costs are decreasing, and this has a significant impact on the city.

Cities appear to focus on the elements they have influence over; for instance, cities often focus on municipally-owned assets, particularly buildings (standard in SEAPs). City E mentioned the installation of micro-wind systems in public buildings (e.g., schools), installation of PV panels in public buildings (e.g., schools), retrofitting in public buildings for energy efficiency purposes. Generally, the cities focus on energy efficiency (i.e., converting boilers to biomass (City D)), improving insulation and windows, integrating renewable energy (e.g., PV on rooftops during retrofitting (City H)).

Some cities don't know if it is essential to upscale or interconnect actions. City E is such a city; however, they mention that if going for 100% renewable in 2050, then they probably would shift from being a consumer to a producer of energy, so the focus should be on renewables and from waste, biogas, thus indicating some systemic thinking. Some systemic thinking is evident by City G saying that it is not just about technology; it is also about rearranging their processes to be more efficient and waste less. City G is looking at energy communities, collective production, collective ownership of energy production, and they say that if the aim is to develop PV or similar, then they need co-ops.

City D has a different concept of the energy system; they explain about systemic energy in terms of the building level, considering energy efficiency from insulation and windows, renewables on rooftops, and heat pumps.

City F took a systemic energy approach in their scenarios where they are focusing on integrating district heating, wind, solar thermal, solar PV, and biogas. They agreed to dozens of project proposals, and they developed an energy strategy to 2025 for 75% emission reductions. Despite the systemic scenario approach, the city authority of City F translated only some elements into the commune plan. The municipality abandoned the scenario since it served its purpose for the commune plan, however the external partner and stakeholders govern the holistic overview of the measures and technologies.

Some cities are implementing system integration technologies. For instance, City B is looking at ways to bring technologies together in a holistic approach using a smart grid and energy storage to maximize the local benefit from local innovation. A lot of work that City B does is about energy efficiency and heat decarbonisation, and they have implemented numerous technologies. Including ground source heat pumps, district heating islands in housing networks linked to gas CHP, renewable solar and wind, and solar thermal. They are also starting to deploy heat pumps from the river and water source as an alternative to gas CHP.

3.4. Retention of Scenarios: Extracting and Abandoning the Scenarios

Often cities would mention abandoning the scenarios once obtaining the information. As mentioned above, City F has a systemic understanding of the energy system; however, the scenario is abandoned by the city authority since it has served its planning purpose. Although their external energy partner maintains the vision and scenario themselves. City D says once they know the economic feasibility, they abandon the scenario.

The detailed technical scenario of City A, carried out by a consultancy, was too biomass dependent. Although they want views and innovative ideas of consultants, the outcomes are always not entirely as they wanted, they do not get all the answers with surveys, and they do not take into account some aspects. They want to have more freedom and do not want prescriptive descriptions so detailed and so rigid, so they calculated their own. Once they extracted the technical scenario, they abandoned it, and now the focus is on districts from which they "copy and paste" onto other districts.

4. Discussion

The vision strategy includes long-term decarbonisation targets, holistic energy system thinking, and retention of scenarios. All the cities have carried out scenarios or are about to begin. However, the results demonstrated that cities do not make scenarios in light of the critical aspects of the vision strategy. Cities are doing scenarios for short-term targets and actions. Generally, the cities continue to focus on technology problem-solution, which leads to silo solutions and a focus on off-the-shelf thinking. This outcome is not surprising due to the low political appeal of long-term actions, and the appeal of immediate results [2]. Even in cities that analysed all aspects of the energy system, they often focus on actions, or they do not know how to use the results. Iyer and Edmonds [70] explain how this can be because there is missing information on how to interpret the results. For instance, in City C, although the study was sent to relevant departments and public companies and committees numerous times and revised, it has not been clear how to utilise the results, with measures poorly integrated into action plans. Furthermore, the involved stakeholders lack organisation. The planners have been asked to point to measures that should be taken but the investigation attempts to do this. In City F the detailed scenario was partly integrated into the commune plan but the planner says they only have about ten percent of their time to work on this and this is not their core task. Therefore only some aspects are integrated.

Typical targets are often short-term as opposed to long-term, so not strategic, and this reflects SEAP ambitions on a medium-term basis, usually to 2030. Lack of long-term targets is common in most European cities in their SEAPs [20]. Alternatively, urban planning processes dictate targets, e.g., every ten years in City E and City G. This means energy scenarios are not long-term. Short-term targets may influence the will to retain long-term systemic energy system scenarios, and means scenarios are often not retained by the city and discarded.

In most cities, it was not possible to find “energy planners” or planners who worked with energy systems. There was a mix of external and internal coordination, showing a lack of competences and indicating why the transition is happening at such a slow pace. Furthermore, an ongoing challenge is the power and influence of politicians who can influence how scenarios are being made and integrated into planning. The typical process is (1) visions, (2) scenarios, (3) actions, (4) plan, and then (5) approval of budgets by politicians. Often the scenarios are stunted to get adoption in the plan and approval. Scharpf ([71], p. 41) describes this outcome as “governance in the shadow of hierarchy”. This outcome was evident, for instance, in City H, where an external consultancy develops an energy transition strategy along with the “energy centre” and then propose this to the politicians. The politicians decide on the budget and choose projects and activities.

Furthermore, artefacts such as energy-related plans are often only supplementary, and this diminishes the role of scenarios since they will serve a part purpose within the final plan or energy-related plan. For instance, City A integrates its heat plan into its climate plan. City F integrates the energy plan into the commune plan. Once the integration is complete, they abandon their scenarios.

Some cities are just beginning their process and have limited awareness of the strategic level required. For instance, in City G, doing scenarios and making an integrated energy plan is a new territory and unique. They are challenging themselves to create something more open and more inclusive than the past. City G already sees the SEAP as an innovative approach; therefore, they will base their scenarios on their previous SEAP in 2015 and make something more radical for outcomes.

All the cities demonstrated a meta-governance type arrangement of horizontal and vertical urban and energy planning governance, involving citizens, interested organisations, and private interests in the scenarios finding solutions to local problems. The scenario process reveals the mutual impact of the actors, and consensus can be achieved [30]. This meta-governance enabling is usually the second governance technique [69]. It is evident in City E, for example. City E explains that scenarios create a possibility to put in place different stakeholders and also citizens and make clear to them the future development of energy and mobility. Stakeholders define the actions or a list of possible actions and validate the scenarios. City H uses scenarios as part of the preliminary strategy and to get feedback from stakeholders, where the data from feedback is useful for the strategic plan or energy transition strategy. They explain how citizens need to change certain things since they are primary energy consumers, and they see scenarios as important as a way to empower them to engage citizens in workshops and for people to feel the problem.

There are indications of cities learning new strategic ways within their energy planning practices. In City A, of the numerous approaches they attempted (i.e., entire city analysis, transition management with arenas, district-level focus, backcasting), backcasting is seen as promising and enables them to see where they should be in 2040, 2030, 2020, and today. Backcasting is an essential method in the Vision strategy since it begins discourse about where the energy system should end [34,40]. Furthermore, backcasting creates awareness of choices [52]. For example, in City A, they look at options in the district zones based on backcasting, and this helps to stress urgency. City A mentions that the other approach with targets to five years or ten years is less ambitious, so they go the other way around discussing where they want to be in 2050 with numerous stakeholders. Back-casting was also used for the climate program of City C and in City F.

Furthermore, more advanced cities are seeing scenarios as becoming more beneficial over time and see the benefits of scenarios as they gain more experience. City B sees scenarios becoming more valuable as they get more data, thus increasing their ability to visualise and analyse data. Data can support the scenarios, and the cities can do them quickly to provide insights, and this gets better as the use of data gets better.

Based on this research, we present some recommendations for cities to help improve the Vision strategy in energy planning, along with selected useful references (Table 6).

Table 6. Summary of key lessons learned from the cities, aligned with suggested recommendations for the further development of energy planning practices in cities, including selected useful references.

Key Lessons Learned	Suggested Recommendations and Useful References
Cities have a general absence of long-term full decarbonisation targets	• Ensure to develop scenarios based on long-term end targets [57,72–75] • Ensure to develop long-term scenarios [57,72,74,75]
Cities have soft links from local to national goals	• Create scenarios in relation to long-term regional and national goals and strategies [53–55] • Communicate and understand the needs and interests of local actors (i.e., strengthen the dialog with local actors) [17,76,77]
Cities rely on simple scenario calculations and external support using silo thinking as opposed to system thinking	• Ensure to develop holistic energy system scenarios [24,26] • Avoid action-based silo thinking scenarios unless based on holistic scenarios [27,58,78] • Reflect on the sustainability of the decarbonised energy system and the advanced energy system considerations going into the future [43,56]
Cities use the scenario outcomes to inform traditional urban planning actions and problems	• Utilise systematic scenarios for visualization, enriching visions, roadmap creation, learning resource about the energy system and technologies [46,79] • Use scenarios to understand the scalability of technologies and integration/interaction of technologies including a development timeline [46,80] • Ensure scenarios are developed suitably useable for the energy planning authorities [76,77]
Cities generally extract and abandon the scenarios	• See scenarios as servants providing information desired by the planner, rather than serving as a guide to the planner (in which the planner can shape as well) [76,77] • Retain long-term scenarios in the city authority and alter them over time [23,54] • Strengthen the link between energy scenarios and energy plans [10,79,81,82] • Reflect on high-level visions and make new scenario-informed visions [63,77]

5. Conclusions

This article aimed to evaluate the vision strategy in the energy planning of eight ambitious European cities. The main focus of the study was on how the cities create and integrate strategic visions and scenarios which are vital in the vision strategy of energy planning. The article evaluated the cities by applying an analytical framework of critical elements of SEP for 100% renewable systems.

Strategic energy planning requires a long-term end decarbonisation target, holistic energy system thinking, and retention of scenarios. All cities demonstrate an ambition to achieve carbon reductions, and all include the ephemeral scenario development process in the energy planning arrangement, involving stakeholders and citizens in workshops. However, the cities are not approaching the vision strategy very effectively. The practice of energy planning is still often tied to the urban planning paradigm and traditions, and this limits the strategic energy planning requirements. Urban planning does not fit very well with energy planning and particularly not the vision strategy. The energy planning mostly focuses on shorter-term goals and actions, which are often in silos. Cities are not speaking about the systemic interconnection of technologies, and no city describes the integration of technologies in an energy system. Cities appear to focus on shorter-term targets and urban planning areas; for instance, often cities focus on municipally-owned assets or isolated off-the-shelf solutions. This self-governing is usually the first governance technique [69].

The cities do not yet show the needed competencies and ownership of energy system scenarios, which has consequences for making priorities and the overview of the different components and energy sectors in the energy system over time. Also, there is a mix of external and internal coordination, and there are some uncertainty and a methodological variety regarding making scenarios, which could lead to misaligned scenarios due to misinformed external partners.

There are promising signs and signs of a desire to break out, and through trial and error, some cities are making progress. But the results indicate that a level of understanding of the Vision strategy is still insufficient. For full, smart decarbonization, the energy scenarios of the cities need to change, and associated governance actors need to retain scenarios for ongoing revisions [19]. Even if not part of the urban plan, there needs to be a parallel way to ensure scenarios remain alive.

This article did not investigate the first and second strategic levels; however, further research should analyse how the vision strategy influences and integrates with these. Furthermore, research should focus on better exploitation of the vision strategy through understanding energy systems thinking in scenarios and the use and usefulness of scenarios. Research should ask why cities abandon scenarios and how they can be relevant (addressing simplicity, comprehension, useability, feasibility, ownership/control, value). The research could focus on collaborative approaches with cities to boost the vision strategy. On a policy level, the authors recommended strengthening the vision strategy by making SEP mandatory with a long term perspective (2050).

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