Flexibility in the interface between district energy and the electricity system

Sneum, Daniel Møller

Publication date:
2020

Document Version
Publisher's PDF, also known as Version of record

Flexibility in the interface between district energy and the electricity system

PhD thesis

Daniel Møller Sneum

April 2020

Flexibility in the interface between district energy and the electricity system
PhD thesis

By
Daniel Møller Sneum

Supervisors: Senior Researcher Lena Kitzing (DTU MAN), CEO Klaus Skytte (Nordic Energy Research) and Chief Analyst Nina Detlefsen (Green Energy)

Funding: Institute scholarship, supplemented by Otto Mønsteds Fond, P.A. Fiskers Fond and Marie & M.B. Richters Fond

Published by: DTU, Department of Management, Sustainability Division – Energy Economics and Regulation Group. Produktionstorvet, Building 424, 2800 Kgs. Lyngby Denmark
www.man.dtu.dk

Summary

In the transition to increasingly environmentally and economically sustainable energy systems, the flexibility and coupling of energy sectors are well-documented measures. The thermal energy sector, with its heating and cooling, is of considerable size (for instance, it makes up half of the final energy consumption in the European Union). The potentials and benefits of integrating the district energy (local heating and cooling systems) and electricity sectors are equally well documented, especially in Europe. The question for policy makers is understanding the framework conditions for implementing such flexible integration in the interface between district energy and the electricity system. This thesis contributes to answering this question by presenting analyses of the framework conditions for district energy and what these mean for flexibility in the district energy-electricity system interface.

The primary research question, *Which framework conditions hinder flexible operation in the district energy-electricity system interface, and what are their consequences?*, is answered by identifying barriers found in the literature and testing these findings against real-world conditions. In six research papers (five peer-reviewed, one working paper), we identify 40 barriers, verify these among real-world stakeholders and analyse their impact through model-based analysis.

Answering the research question takes the thesis along two main paths regarding flexibility in the district energy-electricity system interface: identifying barriers through qualitative methods and evaluating the impacts of the barriers through quantitative methods.

The identification of barriers is conducted through a narrative literature review and semi-structured interviews. The review yields 40 barriers, divided into nine categories. While *absence of flexibility signals* is identified as the most important barrier, the range extends across economic, technological and behavioural categories. The interview-based study verifies the theoretical barriers against experienced barriers among US district energy systems. While conditions vary considerably between plants in the United States, common to most are some degree of optimisation behind the meter and a mostly absent incentive for flexibly buying from, and feeding into, the electricity grid. This indicates that district energy systems are an under-utilised asset in the electricity grid. The impact of barriers is analysed through quantitative methods ranging from a simple spreadsheet-based model, to a single-plant model, to an energy system model. The spreadsheet model enabled the initial impact screening of selected barriers, showing that electricity grid tariffs and taxes reduced the competitiveness of power-to-heat technologies relative to other district heating technologies. This finding is nuanced, but maintained, in more advanced single plant model-based analyses of the levelised cost of heat under various electricity grid tariff structures and tax/subsidy levels. Among the findings is that time-of-use electricity grid tariffs are unproblematic as district energy plants can flexibly dispatch according to these. This underscores the interplay and potential contribution of district energy to electricity systems, including local grids. The large-scale energy system analysis shows the impact of heat source substitution between biomass and power-to-heat on flexibility and sector coupling – constraining competing heat sources may not lead to the desired results from integration between heat and electricity.

This study finds a pervasive presence of barriers to flexibility, even in well-developed district energy sectors. The barrier impacts show especially reduced heat electrification. Addressing such barriers reveals potentially undesired consequences in the form of increased emissions or costs. Increasing flexibility is thus a means, not a goal, which should be analysed case by case.

Resumé (Danish)

I overgangen til stadig mere miljømæssigt og økonomisk bæredygtige energisystemer, er fleksibilitet og sammenkobling af energisektorer veldokumenterede tiltag. Den termiske del af energisektoren, forstået som varme og køling, er af betydelig størrelse (f.eks. udgør den halvdelen af det endelige energiforbrug i EU). Potentialerne og fordelene ved at integrere fjernvarme- og kølesystemer med elsektoren er ligeledes veldokumenterede, særligt i Europa. Udfordringen for beslutningstagerne er at forstå rammebetingelserne for fleksibel integration i grænsefladen mellem fjernvarme og -køling og elsystemet. Denne afhandling bidrager til besvarelse af det spørgsmål, ved at præsentere analyser af rammebetingelserne for fjernvarme og -køling, og hvad disse betyder for fleksibilitet i grænsefladen mellem fjernvarme og -køling og elsystemet.

Det primære forskningsspørgsmål (*Hvilke rammebetingelser hindrer fleksibilitet i grænsefladen mellem fjernvarme og -kølingssektoren og elsystemet, og hvad er konsekvenserne?*) besvares gennem seks forskningsartikler (fem fagfællebedømte; et arbejdspapir). I disse identificeres barrierer gennem litteraturstudie, undersøges rammebetingelser i den virkelige verden og analyseres deres indflydelse gennem modelbaseret analyse.

I besvarelsen af forskningsspørgsmålet følger afhandlingen to hovedstier med hensyn til fleksibilitet i grænsefladen mellem fjernvarme og –køling og elsystemet: Identificering af barrierer ved hjælp af kvalitative metoder og evaluering af barriererens virkninger gennem kvantitative metoder.

Identificering af barrierer er udført gennem litteraturstudie og semistrukturerede interviews. Litteraturstudiet identificerede 40 barrierer fordelt på ni kategorier. Mens *fravær af fleksibilitetssignaler* blev identificeret som den vigtigste barriere, spænder feltet af barrierer på tværs af økonomiske, teknologiske og adfærdsmæssige kategorier. Den interviewbaserede undersøgelse verificerede de teoretiske barrierer mod oplevede barrierer blandt driftsledere i fjernvarme- og –kølingssystemer i det østlige USA. Forholdene varierede mellem værker, men fælles for dem var en vis grad af optimering af drift bag elmåleren og et fraværende incitament til fleksibelt køb og salg af el. Dette indikerer, at fjernvarme og -kølingssystemer er et underudnyttet aktiv i elsystemet.

Virkningen af barrierer analyseres gennem kvantitative metoder, der spænder fra en simpel regnearksmodel over en enkeltanlægsmodel til en energisystemmodel. Regnearksmodellen muliggjorde indledende indikative studier af udvalgte barrierer, hvilket viste, at elnettariffer og elafgifter reducerede konkurrenceevnen for kraftvarme- og el-til-varmeteknologier ift. konkurrerende fjernvarmeteknologier. Denne konklusion blev nuanceret, men bekræftet i en mere avanceret modelbaseret analyse af varmeomkostninger under forskellige eltarifstrukturer og skatte- og subsidieniveauer. Blandt resultaterne var, at eltariffers niveau og design i betydeligt omfang kunne påvirke brugen af el-til-varmeteknologier (tidsdifferentierede tariffer var mest attraktive). Dette understreger samspil og potentielt bidrag fra fjernvarme og –køling til elsystemet, inklusiv lokale distributionsnet. Den bredere energisystemanalyse viser virkningen af udvalgte rammebetingelser. Analysen på energisystemniveau viser virkningen af substitution mellem varmekilder på fleksibilitet og sektorkobling: Begrænsning af konkurrerende varmekilder fører muligvis ikke til den ønskede effekt af integration mellem varme og elektricitet.

Den eksisterende viden på området udvides med denne afhandling særligt på to felter. For det første defineres en taksonomi for barrierer for fleksibel fjernvarme og -køling. For det andet kvantificeres indvirkningen af barrierer. Fleksibilitet er et middel, ikke et mål i sig selv.

List of publications

Papers included in the thesis

Skytte, K., Olsen, O. J., Soysal, E. R., & Sneum, D. M. (2017). Barriers for district heating as a source of flexibility for the electricity system. Journal of Energy Markets, 10(2), 1-19. https://doi.org/10.21314/JEM.2017.161

Sneum, D. M., & Sandberg, E. (2018). Economic incentives for flexible district heating in the Nordic countries. International Journal of Sustainable Energy Planning and Management, 16, 27-44. https://doi.org/10.5278/ijsepm.2018.16.3

Sneum, D. M., Sandberg, E., Koduvere, H., Olsen, O. J., & Blumberga, D. (2018). Policy incentives for flexible district heating in the Baltic countries. Utilities Policy, 51, 61-72. https://doi.org/10.1016/j.jup.2018.02.001

Sneum, D. M. (2020). Barriers to flexibility in the district energy-electricity system interface – the (in)complete overview. *Submitted to* Renewable and Sustainable Energy Reviews

Sneum, D. M. (2020). Flexibility of US campus district energy systems in the electricity grid. Working paper published in DTU Orbit.

Sneum, D. M., Garzón González, M., Gea-Bermúdez, J. (2020). Increased heat-electricity sector coupling by constraining biomass use? *Submitted to* Energy

Publications not included in the thesis

Sneum, D. M., Sandberg, E., Soysal, E. R., Skytte, K., & Olsen, O. J. (2016). Framework conditions for flexibility in the district heating-electricity interface.

Soysal, E. R., Sneum, D. M., Skytte, K., Olsen, O. J., & Sandberg, E. (2016). Electric Boilers in District Heating Systems: A Comparative Study of the Scandinavian market conditions. In Swedish Association for Energy Economics Conference 2016

Skytte, K., Sneum, D. M., Sandberg, E., Soysal, E. R., & Olsen, O. J. (2016). District heating as a source of flexibility in the Nordic electricity market. In Swedish Association for Energy Economics (SAEE) conference 2016

Sneum, D. M., & Münster, M. (2017). DTU-forskere: Forsyningsstrategi er risikabel for samfundsøkonomien. Altinget.dk.

Sneum, D. M., Blumberga, D., Katz, J., & Olsen, O. J. (2017). Framework conditions for flexibility in the individual heating-electricity interface.

Sandberg, E., Sneum, D. M., & Trømborg, E. (2018). Framework conditions for Nordic district heating - Similarities and differences, and why Norway sticks out. Energy, 149, 105-119. https://doi.org/10.1016/j.energy.2018.01.148

Münster, M., Sneum, D. M., Pedersen, R. B., Bühler, F., Elmegaard, B., Giannelos, S., ... Iliceto, A. (2020). Sector Coupling: Concepts, State-of-the-art and Perspectives. European Technology and Innovation Platform.

Acknowledgements

The people and institutions who I would like to thank include the following:

- Present and former colleagues in DTU's Sustainability Division, for good company (and abundant amounts of cake). Particularly our indispensable secretaries, Vivi Morsing and Julie Nyborg, for their everlasting preparedness to fix problems and answer questions. Prof. Emeritus Ole Jess Olsen also deserves special thanks: I continuously enjoy our discussions and friendly (dis)agreement on various subjects related to district heating.
- Research Scientist Eli Sandberg, formerly NMBU now SINTEF, for her tireless work during our collaboration and mutual understanding of life as a PhD researcher (and parent).
- The co-authors of my publications, with whom I have very much enjoyed collaboration.
- Prof. Elizabeth Wilson for being the kindest and most generous host, personally and professionally, for my family and me during our stay at Dartmouth College, USA. Including not laughing too hard at our Danish outfits in the -25 °C New Hampshire winter.
- The people at Danish District Heating Association and the think tank Green Energy for regular professional back-and-forth. Especially Chief Consultant John Tang (while in China for the Danish Energy Agency), Analyst Christian Hansen and Economic Consultant Anders Jespersen.
- The International District Energy Association, particularly Senior Director Laxmi Rao and President Rob Thornton, for kindly sharing US knowledge and access to their CampusEnergy conference.
- Energy Advisor Niels Malskær and Energy Attaché Bo Riisgaard Pedersen, Danish Energy Agency/Ministry of Foreign Affairs for good company, drinks and an introduction to district energy in the United States.
- The team in the Flex4RES project, Postdoc Katinka Johansen, Aalborg University, and all the people who have provided feedback for the research during interviews – which are too many to mention here.
- The foundations which have supported my research. This support opened many new opportunities:
    - P.A. Fiskers Fond
    - Marie & M.B. Richters Fond
    - Otto Mønsteds Fond
- My supervisors, Senior Researcher Lena Kitzing (DTU MAN), CEO Klaus Skytte (Nordic Energy Research) and Chief Analyst Nina Detlefsen (Green Energy) for combining freedom with to-the-point advice.
- My family, including my in-laws (Bente + Helge), sister-in-law (Signe), aunt (Helle), cousin (Lene) and not least my parents (Jacob + Lone). Finishing the thesis would have been impossible without your and Thora's help during the last few months' nights, weekends, birth and broken ankle.
- Thora, my sweet, wise and very patient girlfriend, for keeping me, our everyday life and our home anchored during tumultuous times.

I think and hope that all of you will be equally kind when other people need your help.

List of contents

List of tables

List of figures

Abbreviations

CHP: Combined heat and power/cogeneration
Cogen: Cogeneration plant
DE: District energy (local networks generating heating and/or cooling and possibly electricity)
DH: District heating
EB: Electric boiler
GHG: Greenhouse gas
HP: Heat pump
LCOH: Levelised cost of heat, similar to the more commonly used term levelised cost of electricity
(M)tCO_2: (Mega) tons of carbon dioxide
MW: Megawatt. $_{EL}$ and $_{TH}$ indicate, respectively, electric and thermal capacity.
NEITG: Non-electricity interfaced thermal generator (often a natural gas or biomass boiler for heating or chiller for cooling). This term is used in place of the more commonly applied term 'heat-only boiler' to encompass cooling and to exclude electric boilers.
PtH/C: Power-to-heat/cold
PURPA: Public Utilities Regulatory Policy Act
TS: Thermal storage (typically a cold/hot water heat accumulator)
(V)RE: (Variable) renewable energy

1. Introduction

It has been shown, perhaps most prominently by Stern [1], that it pays to save the planet from severe climate change. This has strong support from other parts of the scientific community, which have continuously over the last few decades underscored the urgency of addressing the issue of climate change (e.g. IPCC [2,3]). Along with pure economic forces (unsubsidised solar and onshore wind power are expected to be the least-cost sources of new electricity in 2020 [4]), this focus on the environment drives an increased deployment of renewable energy, including technologies with variable generation, such as wind power and solar photovoltaics.
In electricity markets, as well as other markets, liquidity depends on sufficient numbers of buyers and sellers. Thus, an increased number of actors on both sides improves the matching of demand and supply. Another economic aspect is the existence of substitute goods, that is, different goods which can be used interchangeably to serve the same purpose. Within the domain of energy, this relates to Lovins's [5] concept of customers wanting services (hot showers, etc.) rather than kilowatt hours. Liquid markets, the notion of energy as a service and the need to address climate change converge in the concepts *flexibility* [6], *sector coupling* [7], *system integration* [8] and *smart energy systems* [9] (explained in 2.2). Common to these are that they acknowledge the economic and environmental benefits of coupling energy sectors through monetary as well as energy streams.
The electricity sector is commonly perceived as the unifying hub between the different energy sectors. Additional sectors include transport, gas and heating and cooling. Heating and cooling alone accounts for half of the final energy consumption in the EU [10].
Energy-as-a-service applies to heating and cooling since thermal energy can be produced in multiple ways. One such way is district heating (DH) and cooling, that is, the production and distribution of heating or cooling to serve thermal needs in a local area. Aggregating district DH and cooling, the term *district energy* (DE) is applied in this thesis. In summary, electricity can be *used* in many energy conversion processes, whereas heat can be *derived* from many energy conversion processes – respectively power-to-X and X-to-heat.
Sector coupling between the electricity system and DE is not a new concept. It has existed for decades through the application of, for example, combined heat and power (CHP) plants or heat pumps (HP). These are characterised by their respective cogeneration of heat and electricity and consumption of electricity to generate heat. Thus, they act in the interface of the heating and electricity sectors.
In some cases, the sector coupling of DE and the electricity system is flexible, such as when the DE plants respond to needs – signals – in both sectors (heating and electricity). This is typically the case in Danish CHP plants (e.g. seen in the operation of the Svendborg district heating plant [11]). In other cases, DE plants may disregard signals from one sector, generating solely according to signals from the other sector. This inflexibility generates inefficiencies, such as feeding electricity to a grid that is already saturated.
Numerous studies have asked – and answered – questions regarding the benefits of coupling DE and the electricity system (e.g. [12–14]), and some have proposed long-term plans regarding how much there should be at which point (e.g. Europe: [15] Denmark: [16,17]). Yet, there is an absence of insights in regard to the concrete factors that drive or hinder flexibility in the DE-electricity system interface. This thesis attempts to address exactly this issue – firstly, by collecting an array of framework conditions that are perceived as barriers to flexibility in the DE-electricity system interface; secondly, by identifying the quantitative impacts of those barriers.

To extend the theoretical knowledge with real-world empirical data, flexibility and DE are explored in a variety of case studies. These include the following:

- The Nordics (Denmark, Finland, Norway, Sweden) since DH and flexibility are generally well deployed. Aim: Identify barriers in areas with well-developed flexibility conditions and DE deployment.
- The Baltics (Estonia, Latvia, Lithuania) since DH is well deployed but flexibility appears limited. Aim: Identify barriers in areas with limited flexibility conditions and well-developed DE deployment.
- The eastern United States (Connecticut, New Hampshire, New Jersey, New York, Massachusetts, Pennsylvania, Vermont) since DE and flexibility appear limited. Aim: Identify barriers in areas with limited flexibility conditions and limited DE deployment.

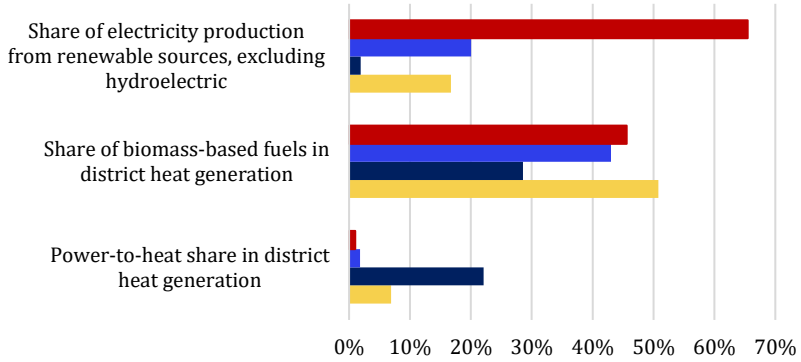
The relevance of these and other regions of the world will be discussed in the following.

1.1 The broader relevance of district energy

Heating and cooling – the themal sector – is of considerable size in terms of energy produced and consumed. In a global 2014 estimate, Gadd and Werner [18] counted 80 000 DH systems, supplying 11 EJ. For Europe, these numbers were respectively 6 000 systems and 2 EJ[1]. As noted in section 1, heating and cooling demand corresponds to half of the EU's final energy consumption, while the share of the EU's heat supply from DH in 2012 was 9% [10]. In China, 200 million people are supplied by DH [19]. In 2015, Northern China's primary energy consumption for heating was 5.4 EJ, while cooling across China accounted for 0.9 EJ [20]. Projections for China describe a possible expansion to 400-600 million consumers approaching 2050 [19], or an expansion of heating and cooling to 9 EJ by 2050 [20]. With 0.6 EJ [21] in 2012 in the US, the share of DH and cooling is comparatively moderate but still significant. The renewable energy share of heating and cooling supply in the EU was 21% in 2018 [22]. In Denmark, this number was 62% in 2018 for DH [23].

As the Nordics represent energy systems with a high share of renewables, a long track record for flexibility signals (electricity markets) dating back to 1993 [24] and large DH deployment, these deserve special attention. The numbers for 2017 (*Figure 1*) show high shares of non-hydro renewables in Danish electricity generation. While biomass is widely used for DH, power-to-heat (PtH) is mostly limited although expected to increase beyond 2017 in Denmark [25].

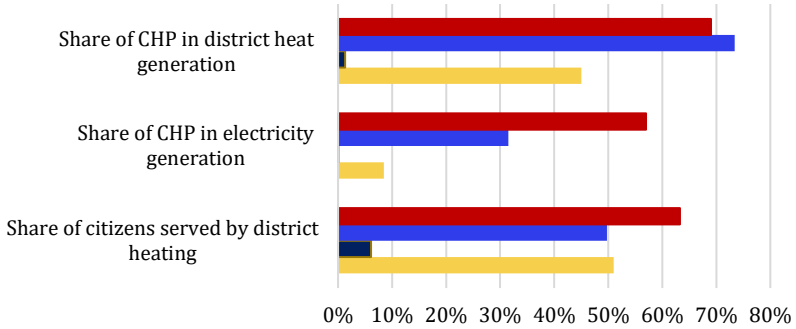
[1] Euroheat [128] counts 1.4 EJ in sales in 2013, meeting 12% of Europe's heat demand.



	Power-to-heat share in district heat generation	Share of biomass-based fuels in district heat generation	Share of electricity production from renewable sources, excluding hydroelectric
Denmark	1%	46%	65%
Finland	2%	43%	20%
Norway	22%	29%	2%
Sweden	7%	51%	17%

Figure 1 Shares (2017) of PtH, biomass and renewable sources in the Nordics. Numbers based on data by Sandberg [26].

Further, except for hydropower-dominated Norway, DH deployment and CHP use is considerable, as seen in *Figure 2*. We have described these differences in more detail in Sandberg et al. [27].



	Share of citizens served by district heating	Share of CHP in electricity generation	Share of CHP in district heat generation
Denmark	63%	57%	69%
Finland	50%	32%	73%
Norway	6%	0%	1%
Sweden	51%	9%	45%

Figure 2 Shares (2017) of CHP and citizens served by DH in the Nordics. Numbers based on data by Sandberg [26].

The motivation for exploring how heating and cooling is and can become a flexible part of the energy system extends beyond the abovementioned cases. Indeed, the motivation is to extract

general knowledge about the mechanisms that are broadly at play regarding flexibility in the DE-electricity system interface.

1.2 Research interest

Not without irony, Boulding's First Law states, '*anything that exists is possible*' [28]. Whereas Boulding's statement was targeted at peace studies, it is equally applicable to flexibility in the DE-electricity system interface. Variation in the degree of DE systems' flexibility motivates the following main research question:

Which framework conditions hinder flexible operation in the district energy-electricity system interface, and what are their consequences?

– and the following sub-research questions:

1. How can barriers to flexibility in the DE-electricity system interface be identified, structured and addressed in a systematic manner?
2. How does the systematic overview correspond to experiences in real-world DE systems?
3. What consequences do selected identified barriers to flexibility in the DE-electricity system interface have for certain typologies of DE plants?
4. On a larger scale, what consequences do selected barriers to flexibility in the DE-electricity system interface have for the energy system?

Paper A answers sub-research question 1 by defining a taxonomy for barriers. Paper B answers sub-research question 2 by reviewing barriers among 10 US university DE systems. Papers C-E answer research question 3 by exploring the business economic impacts of barriers on individual DE plants. Paper F answers research question 4 by analysing selected barriers in a Nordic energy system context. In aggregate, the papers and this thesis answer the main research question.

In this thesis, flexibility in the DE-electricity system interface is considered a relevant measure to obtain efficient and renewables-based energy systems. For instance, if a country wants to transition its DE systems into an active part of the energy system, then the value of such a transition must be evaluated and a comprehensive set of barriers identified. This thesis provides the tools necessary for initiating such an analysis.

Finally, the overall premise for the thesis is that flexibility in the DE-electricity system interface is a desirable characteristic, enabling a transition to more sustainable energy systems. Flexibility can be delivered from other sectors beyond DE. While these alternative sectors are sometimes superior and often interacting, the analyses in this thesis are limited to DE only.

1.3 Research context

The thesis draws upon qualitative and quantitative data combined. Qualitatively, the thesis builds on qualitative analyses of the literature and stakeholder interviews and quantitatively on the techno-economic modelling of barriers in individual DE plants and energy systems. While the qualitative methods are applied to identify structures and barriers, the quantitative techno-economic modelling analyses the business-economic plant and energy system impacts of selected barriers.

Identifying and analysing barriers to flexibility in the DE-electricity system interface requires an interdisciplinary approach which draws on engineering, economics and policy analysis.

Specifically, this involves the physical infrastructure of cooling, heat and electricity supply; energy system modelling and regulatory frameworks in different countries.
The general foundation in the thesis builds on the literature from several fields. Within economics, Baumol [29] and Demsetz [30] provide theoretical background for the concept of barriers to market entry. Comprehensive theoretical overviews on DE regulation are limited apart from Wissner [31], but some concepts can be drawn from Pérez-Arriaga [32] within the field of electricity. DE is the core technological subject, treated in aggregate by Frederiksen and Werner [33] and supplemented, among others, by Gadd and Werner [18] (thermal storages [TS]) and Blarke [34] (PtH). Some readers may recognise elements of new institutional economics (originating from especially Coase [35]), with related subjects such as limited rationality, transaction costs and limited information [36]. I acknowledge similarities as it is difficult to avoid an institutional scope when dealing with the inherently context-specific concept of DE. That said, no effort has been made to stringently follow approaches determined by this economic branch.
Of particular relevance in this thesis is the body of interdisciplinary literature on respectively DE and flexibility. IEA [6] provided a foundational study for structuring and addressing flexibility. Lund et al. [37] extended this work with an extensive overview of applications, technologies and concepts related to flexibility in energy systems. Lund [38] laid the foundation for the academic analysis of coupling in the interface between heat and electricity. Lund et al. [39] expanded on this with a definition of *smart energy systems*, showing that extended use of DH would enable further coupling in the DE-electricity system interface, subsequently enabling the integration of VRE. Identifying and addressing barriers within the field of energy has been treated in a wide array of applied studies, where Blumstein et al. [40], Cagno et al. [41] and Good et al. [42] have provided useful background. While the collective body of literature shows the overall benefits of flexibility and DE and even the potential in combining these through flexible DE, no comprehensive study of barriers to flexibility in the DE-electricity system interface has been identified. What comes closest are IEA's review of barriers to cogeneration and DE [12]; Ropenus and Skytte's review of barriers to distributed generation in the EU [43]; the Danish transmission system operator Energinet's modelling of the flexibility of various Danish energy assets, including varying the degree of flexibility from DH [44] and Ma et al.'s literature review of energy flexibility in DH [45]. This thesis was conducted in the auspices of the Flex4RES project, which included studies of flexibility in DH. The body of literature on flexibility in the DE-electricity system interface has thus grown since initiating the studies, leading to publications by me and others on the subject. Many of these results are summarised by Skytte et al. [46].
I interpret the absence of focused research on the field of barriers to a flexible DE-electricity system interface to be the result of two things. Firstly, the research community of DE and flexibility is relatively small, leaving few resources to widen the field. Second, there may be a belief that the inherent context-specificity of DE makes it a subject for civil service, industry and consultants rather than academia. The former is a limitation in research capacity, while the latter is a cultural limitation. I venture beyond these limitations to close a gap that, I will argue, indeed is possible and pertinent to address from a research perspective, firstly, by adding this research into the scattered ranks of studies on barriers to flexibility in the DE-electricity system interface and, secondly, by expanding the field of research by extracting general knowledge from the studies on flexibility in the DE-electricity system interface.

The articles in Part II provide further context within the respective field of energy analysis covered.

1.4 Structure of the thesis

The thesis is structured in two parts; Part I is the thesis synopsis, and Part II collects the research articles conducted for the thesis.

Paper A is a journal article submitted to Renewable and Sustainable Energy Reviews. It reviews the literature on barriers to flexibility in the DE-electricity system interface and constructs a taxonomy based on the findings.

Paper B is a working paper published online. It applies the taxonomy from Paper A to collect perceived barriers to flexibility in the DE-electricity system interface from 10 US university DE systems.

Paper C is a journal article published in the Journal of Energy Markets. It presents an initial scoping of barriers to the use of CHP and PtH in Nordic countries based on economic framework conditions.

Paper D is a journal article published in Utilities Policy. It provides a model-based analysis of the economic framework conditions in the Baltic countries with respect to investment incentives in DH systems with and without CHP and electric boilers (EB).

Paper E is a journal article published in the International Journal of Sustainable Energy Planning and Management. The approach is similar to that in Paper D but with the Nordic countries in scope.

Paper F is a journal article submitted to Energy. It provides a model-based analysis of selected framework conditions for flexibility in the DE-electricity system interface with Denmark as a case.

The articles are described in more detail in 4.1. *Figure 3* provides an overview of the papers and how they contribute to answering the research questions through different analytical and methodological fields.

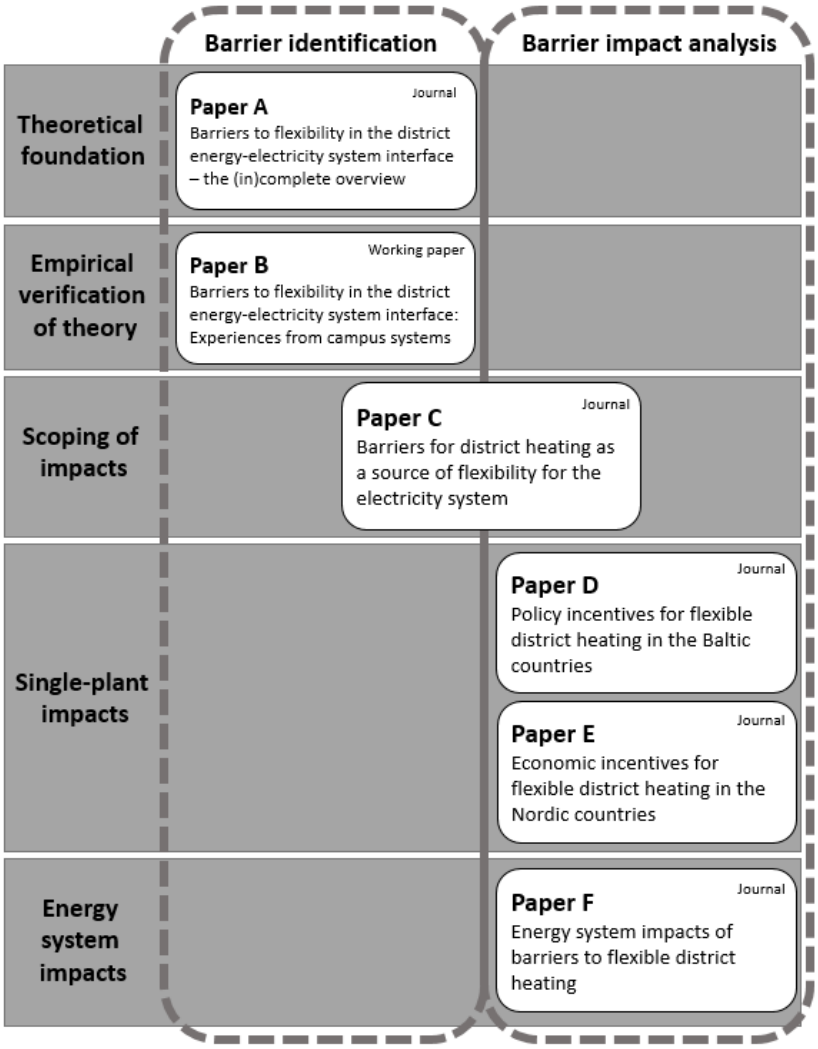


Figure 3 Structure of articles.

Chapter 2 provides background and elaborates on key concepts. Chapter 3 provides details and discussion on the methods applied. Chapter 4 provides the results of each scientific paper and a discussion of these. Chapter 5 provides the conclusion.

2. Background

2.1 Flexibility

'Flexibility' in this thesis describes the ability to respond to signals, internal as well as external, of a consumer and/or producer of energy. This is in line with similar definitions [6,37] although these commonly only deal with electricity. This thesis expands the perspective to thermal energy as well. To nuance this definition, and as it tends to go with popular subjects, flexibility currently covers an extensive array of qualities in an energy system. This includes technological flexibility (e.g. storage, generation, demand, transmission [6]), geographical flexibility (i.e. drawing on a geographically larger pool of resources [6]) and temporal flexibility (ranging from sub-seconds, to hours [6], to the yearly displacement of energy generation and demand [47]). The focus of the thesis directly applies the technological scope by addressing demand, generation and storage and the temporal scope by addressing the decoupling of energy demand from energy production through storage. Indirectly, the geographical scope is included by the nature of DE, which is decentralised and geographically disperse. A caveat is that flexible is not necessarily integrated (and vice versa, as discussed in 2.1) since a DE plant can remain un-integrated but operate flexibly according to internal needs. This is what justifies the term flexibility *in the DE-electricity system interface*.

The purpose of focusing on flexibility (and sector coupling, explained in 2.2) can be summarised in the benefits these concepts bring based on work by IEA [6] and IEA and NREL [47], as follows:

- Resource efficiency and reduced emissions in energy systems through increased integration of VRE
- Liquid markets through flexibility-induced increased ability to respond to signals
- Resilient energy systems through increased ability to respond to uncertainty
- Deferred infrastructure investments through utilising existing resources more efficiently

2.1.1 Flexibility's role in sustainable energy systems

With help from selected theories, this section presents flexibility in the overall concept of a sustainable[2] energy system. This explains the profound purpose of flexibility in addition to the more specific and traditionally applied definitions and benefits of flexibility (treated in 2.1). Starting all the way from fundamental human necessities, Maslow's hierarchy of needs [48] states that an individual's functioning depends on the satisfaction of fundamental physiological needs. This *homeostasis*, that is, the boundary within which the organism can function properly, includes physical (temperature) as well as societal (safety) conditions. These environmental and social conditions are potentially affected by climate and other environmental impacts. Returning to Lovins's concept of services [5], thermal comfort and environmental safety can be interpreted as desired services along with electricity-based services such as lighting.

One way to structure these needs and services into specific criteria is The Energy Trilemma's three pillars of *equity* (broadly available energy at a reasonable cost), *security* (reliable energy

[2] In the Brundtland Report's understanding of sustainability [129] and UN Sustainable Development Goal 7 '*Ensure access to affordable, reliable, sustainable and modern energy for all*' [51].

supply) and *environmental sustainability* (low environmental impact of energy) [49]. Jamasb and Llorca [8] propose a similar link between sector coupling[3] and the Energy Trilemma.
Engineering and economic principles dictate that the above criteria and energy services must be translated into demand signals for them to be met by energy supply. This can be through signal-providing schemes such as electricity markets or environmental indicators. As noted in the introduction, such schemes benefit from the broad availability of actors (such as flexible DE plants), where sector coupling indeed increases the number of actors [7,8]. As seen in the smart energy system concept ([50] – see 2.2), these actors must not only be coupled but also be nimble in their response to signals – actors must be flexible.
With the needs and services defined, along with a signal-providing scheme to communicate these needs, Lund's choice awareness theory [38] can be applied to identify the array of options (such as appropriate technologies) to achieve the desired services and the subsequent selection of solutions that best fits the context. Thereby, awareness is followed by informed choice.
In summary, flexibility is here perceived as the grease in the machinery that improves especially the environmental and economic aspects of a sustainable energy system. Flexibility framed in the terminology of the targets 7.1 and 7.2 of the UN Sustainable Development Goal 7 [51]:

- *7.1. By 2030, ensure universal access to affordable, reliable and modern energy services*:
    - By making energy systems more flexible, these and their related goods become more efficient, subsequently reducing costs, all things being equal.
- *7.2 By 2030, increase substantially the share of renewable energy in the global energy mix.*
    - The integration of especially VRE is facilitated by flexible energy systems.

2.2 Smart grid, sector coupling, integration and smart energy systems

Flexibility is one term among many which relates to the ability to respond to signals and to integrate across sectors. In this section, I present a selection of these related terms and discuss flexibility in relation to them.
Smart grids typically describe the ability of the electricity system to accommodate variations in generation and demand [50]. A criticism of this term has been that it leaves out other sectors, that is, that it is too narrow in scope to efficiently utilise the capabilities of other sectors [50].
This brings us to the terms *integration* and *sector coupling*, which are here understood as interchangeable terms. They describe connecting energy sectors to enable a more optimal energy system by converting energy to an adjacent sector where it is, for example,

- Stored more easily (shifting in time) [7];
- Transported more easily (shifting in space) [7];
- A substitute good, displacing other sources temporarily (shifting in fuel – optimised operation) or permanently (e.g. full electrification of the heating sector) [7], thereby moving towards energy as a service [8].

[3] *Sector integration* in their terminology.

Smart energy systems bridges the above terms. This term was coined to expand the narrow scope of smart grids to also include other sectors, and to clarify the purpose of integration and related terms, in that integration only makes sense if done flexibly [52].
Smart energy systems as a concept is in line with the analyses and understanding in this thesis. When *flexibility in the DE-electricity system interface* is used instead, it is because it describes the concrete focus of the thesis and because the scope of the thesis does not include sectors beyond heating and cooling and electricity (e.g. gas).

2.3 District energy

DE is a term used with various definitions, covering some or all of the following: electricity generation, heat generation and cooling generation. The end uses of heating and cooling include tap water, home heating and comfort cooling but possibly also industrial purposes. In this thesis, DE is understood as the thermal generation of heating and/or cooling, optionally combined with electricity generation (further discussed in Paper A).
Whereas the subject of barriers to DE in itself is an interesting one, it is not included in the scope of this thesis. It is thus assumed that DE is chosen as the preferred way to satisfy the services desired through the process defined in section 2.1.

2.3.1 DE technologies

Heating or cooling can be generated using many different technologies. Since the thesis's scope is the interface of the DE and the electricity grid, the choice of technologies is narrowed down to a set corresponding to IEA [12] and Lund et al. [37]: '*combining different technologies in a CHP plant (e.g. gas engines, heat pumps, heat storage, peak-load gas boilers, electric boiler) could increase the inherent flexibility*'. In summary:

- Cogeneration/CHP
- PtH/C (EB, HP, electric chillers)
- Non-electricity interfaced thermal generator (NEITG – biomass boilers, natural gas boilers and similar)[4]
- TS (e.g. tank and seasonal)

Whereas NEITGs are by definition not active in the DE-electricity system interface, they are important to include since they are the alternative option which may improve or hinder flexibility, depending on framework conditions. TS is not a generation technology but can offer significantly increased flexibility of DE systems, as seen in [53] and Papers D, E and F.
Figure 4 illustrates the energy flows between the energy sources, technologies and energy services.

[4] This abbreviation is as bulky as it is necessary: The more commonly applied terms – thermal-only, heat-only, boilers, etc. – are not sufficiently clear since they may be interpreted as including EB and may exclude cooling-generation in non-electric chillers.

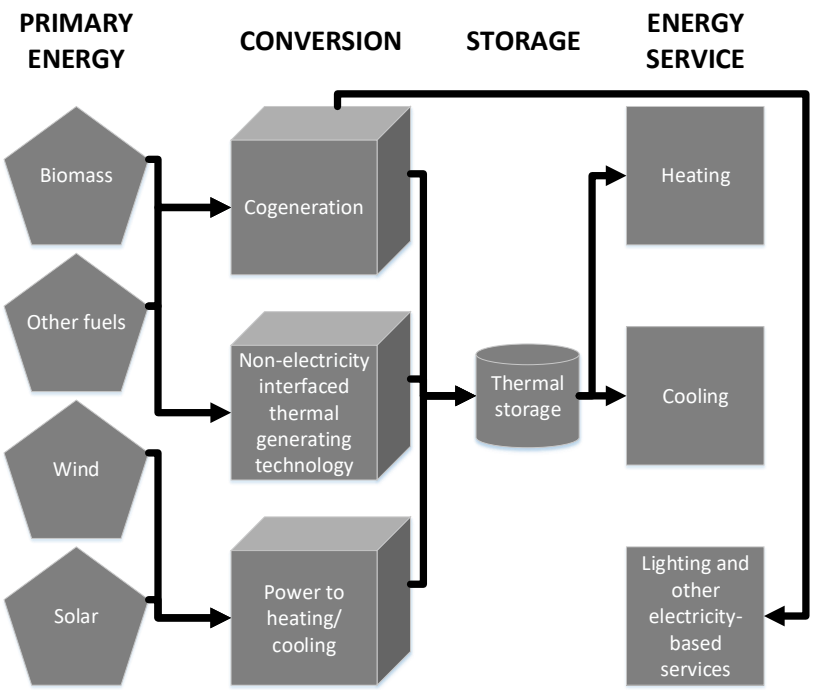


Figure 4 Flowchart with examples of primary energy, conversion, storage and energy services.

The choice of technologies at individual DE plants depends on several factors, including the size of the plant, such as in Denmark, where larger systems can support the scale of extraction turbine-based CHP generation capacity, while smaller DE systems may choose reciprocating engine-based backpressure generators. Likewise, the source of energy for HP may determine their size, efficiency and availability. The concept of fourth-generation DH (i.e. low temperature heating in smart energy systems) enables the expanded use of HP due to the increased resource base of heat sources, which can be efficiently utilised by HP [54]. Put another way, HP is a desired technology since it is generally better to generate heat by moving it from where it already is (e.g. ambient heat) than by combusting valuable resources. The use and size of storages are dependent on the medium of heating/cooling transfer (steam from steam-based systems is not feasible to store, while water from hot/cold water-based systems is). DE is thus inherently dependent on local conditions. Subsequently, some framework conditions and barriers will apply in certain cases while not being applicable in other cases.

2.3.2 Flexible district energy

In their definition of DH, Frederiksen and Werner [33] argue that the main idea of DH is '*to use local fuel or heat resources that would otherwise be wasted*'. While this is true under many circumstances, I will argue that DE's raison d'être now extends beyond the focus on only utilising otherwise wasted energy due to the extended possibilities for electrification and the subsequent flexibility. This section describes such flexibility in DE.

While the perspective of the analyses in this thesis is that of DE systems, the purpose is not to optimise those systems' position in the energy system. Rather, it is to explore whether DE plants have incentives to be flexible for the benefit of the energy system as a whole.

In the same vein, it should be made clear that I, for analytic reasons, apply a 'flexibility for flexibility's sake' perspective in the extensive analyses of barriers to flexibility in the DE-electricity system interface (Papers A-F). Transferring this myopic approach to real-world policy

risks leading to sub-optimal solutions. Rather, the results should be used to provide the tools for identifying barriers and solutions if flexibility is deemed desirable for society as a whole, for example, based on specific energy system analyses. In other words, flexibility should be about striking the right balance between electrons and molecules.

Flexible district energy defined

Full flexibility in the DE-electricity system interface is the practical ability to simultaneously respond to at least hourly varying signals from the thermal side (heat/cooling demand) and electricity system (typically electricity prices):

- Practical, because, as this thesis examines, there can be multiple barriers between technically or theoretically being able to operate flexibly and doing it in practice;
- Simultaneously because responding flexibly to signals from only one side is considered only a partial flexibility of DE;
- Hourly because a defined threshold is necessary. Time-resolution can vary, but hours are a practical proxy for signals in electricity markets (e.g. the hourly Nord Pool Spot market), variations in VRE generation and variations in heat demand. As long as the condition of hourly flexibility is maintained, daily, weekly or seasonal flexibility are additional desirable capabilities (as seen in Paper F, seasonal flexibility is, indeed, a highly valuable ability offered by seasonal hot water storages).

DE flexibility in practice: Economic or environmental dispatch

There are plenty of signals to which a DE plant can respond (prices, weather, regulation, etc.). In this thesis, the potential signals are local thermal demands (heating/cooling), electricity price and emissions.

Figure 5 shows the simplified principle of economic dispatch – specifically, the least-cost heat dispatch[5] of a plant with PtH, NEITG and back-pressure CHP. With the outset in economic dispatch, the Y-axis is the cost of generating heat and the X-axis the electricity price. A plant optimising towards the least cost of heating/cooling will switch generation between units, depending on the price on the electricity market. Thus, the least cost of heat will be at the PtH during low electricity prices (1), at the NEITG (and/or TS) during intermediate prices (2) and at the CHP during high electricity prices (3). This concept applies when operation minimises thermal generation cost according to electricity prices, that is, when electricity is sold to an external market. One finding from Paper B is that this concept of DE operation does not apply (at least not without modifications) in US DE systems supplying local thermal *and* electricity demand *behind-the-meter*.

[5] In Papers C and D this is called "*preferred unit for dispatch*" – that is, the technology with the lowest cost of heat production under the given electricity price.

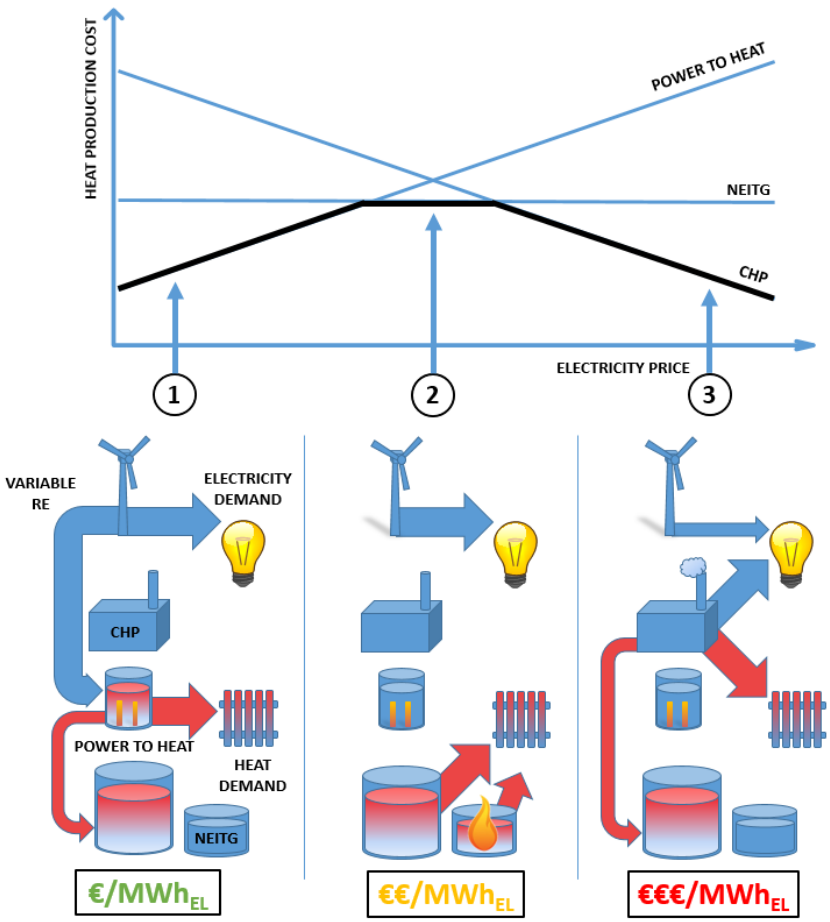


Figure 5 Economic and environmental (VRE-based) dispatch of a generic DE system. Own illustration based on [55], [56] *and* [46].

While economic dispatch is commonly adopted in some form at many DE plants, environmental dispatch has not been identified in real-world operation (Paper B provides examples of it being examined in US plants). *Figure 6* shows that dispatch can also happen according to the environmental impact/share of VRE. Dispatch according to environmental impact is applied in the modelling of DE by Lund [52] and Thellufsen et al. [57], both minimising fuel use by maximising the use of VRE. *Figure 6* illustrates the concept as understood in this thesis, with tons of CO_2 (tCO_2) as the measure for the environmental impact.

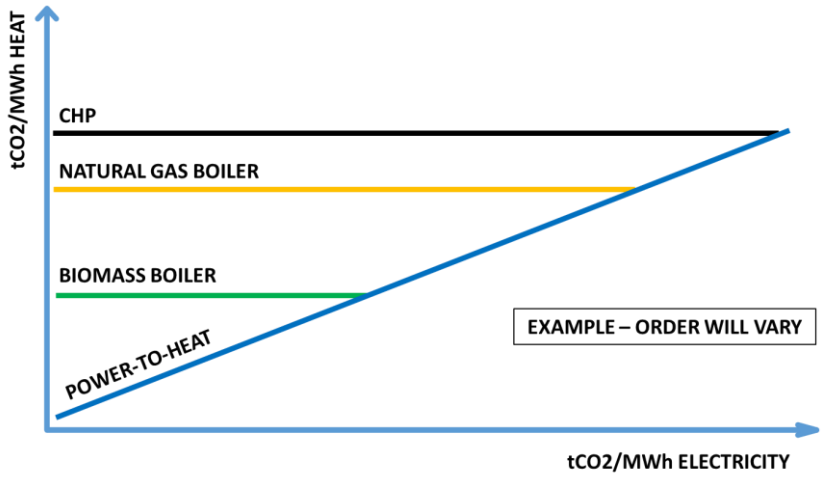


Figure 6 Concept of environmental dispatch, with heat as an example.

When the target is to generate heating/cooling with the least environmental impact, the order of dispatch will fill up from below. That is, in this example, the PtH will be dispatched if the renewable share of imported electricity is lower than the natural gas boiler's fixed emission rate. It is worth noticing that the top unit (CHP in this example) will only be dispatched in cases where capacity need exceeds the less-emitting technologies. Thus, this type of dispatch risks optimising locally, leading to energy system sub-optimisation. In other words, CHP will not necessarily help displace more polluting electricity generators on the grid if the plant is optimised according to its own emissions, unless the displacement of high CO_2/MWh electricity with CHP electricity is rewarded by, for example, certificates or something similar. For DE systems optimising both on heat and electricity (such as the campus systems described in Paper B), CHP will remain a relevant part of the dispatch to displace high CO_2/MWh electricity from the grid.

Potentially, additional dimensions to the flexibility can apply if more inputs are variable, such as variations in fuel price or variations in renewable gas content in the gas used by the CHP. Such extra dimensions are not considered in the thesis.

2.4 Energy policy relating to flexibility in the district energy-electricity system interface

The geographical span of the thesis's analyses ranges from the Baltics (Estonia, Latvia, Lithuania), across the Nordics (Denmark, Finland, Norway, Sweden) to the United States (Connecticut, New Hampshire, New Jersey, New York, Massachusetts, Pennsylvania, Vermont). This section presents key policies and regulations on the European, Nordic, Danish and US levels. Individual papers provide more comprehensive overviews of taxation (Papers C and D) and US energy regulation (Paper B). The scope in this section is DE, unless otherwise indicated.

2.4.1 European energy policy

This section presents a selection of key EU policies from the early 2000s onwards.

Energy efficiency

In 2012, the European Energy Efficiency Directive included a separate article (Article 14) on the promotion of efficiency in heating and cooling. This called for an assessment and the facilitation

of feasible DH, cooling and CHP by 2015 [58], which is to be re-assessed every five years [59]. In the 2018 amendment, a requirement of at least 0.8% annual savings in final energy demand was introduced, with DH and cooling specified as one measure to reach this [60].

Climate and energy

On energy and climate, the *2020 Climate and Energy Package* (a set of binding legislation) was enacted in 2009, with targets of 20% greenhouse gas (GHG) reduction compared to 1990, 20% energy from renewables and 20% energy efficiency (compared to projected 2020 use) [61]. In 2014 (and updated in 2018), this was supplemented with 2030 targets in the *2030 Climate & Energy Framework* on, respectively, at least 40%, at least 32% and at least 32.5% [62]. Towards 2050, the European Commission's target is a climate-neutral EU [63]. In 2019, the European Green Deal stated ambitions of increasing the 2030 GHG reduction target to 50-55% [64]. In March 2020, the Commission disseminated its draft for a European climate law. This does not focus on technologies but on climate targets. [65].

Integration and flexibility

Clean Planet for All, the European Commission's strategic vision from 2018, laid out pathways that included the integration of energy sectors, specifically including electricity, heating and cooling [63]. In 2019, the European Green Deal underscored this, having the integration of energy sectors, including heating, cooling and electricity, as one of the measures to achieve its goals [64]. Furthermore, this is a concrete task in the mission letter to the 2019-elected Energy Commissioner [66].

Renewable energy

With the 2018 Renewable Energy Directive, Member States are for the first time required to increase the share of renewable energy in heating and cooling by 1.3 percentage points per year from 2020, capped at 60%. Ambient energy (e.g. extracting heat from the surrounding environment) is recognised as renewable energy [67].

Resilience and security of supply

In 2015, the Energy Union initiative was launched to provide Europeans with '*secure, sustainable, competitive and affordable energy*'. This coupled the concepts of security of supply and resilience with heating and cooling, specifically, due to heating/cooling's significant share of EU energy demand and its derived import dependence of especially gas [68].

Access to grids and markets

The first Electricity Market Directive from 1996 established the framework for the 1999 opening of the European electricity market [69]. This enabled access for generators, including independent producers such as CHP units, to price signals from the market – a key proxy for the flexibility needs of the energy system in this thesis.

Whereas market access for independent producers (which includes CHP) was enabled by the first Electricity Market Directive, the access of such generators to the grid – non-discriminatory network access – was not always certain. Subsequent revisions to the initial Electricity Market Directive addressed this issue – especially the revised Electricity Directive, as part of the Third Energy Package in 2009, where the unbundling of vertically integrated utilities was intended to remove the incentive from incumbents to block the grid access for new entrants such as CHP units. As a side-note, system operators were allowed to provide priority dispatch to CHP, which

indicates a priority to the resource as an energy efficiency measure rather than a flexible producer of electricity in the market. [70]. Priority dispatch was later limited to include only facilities which were eligible prior to 4 July 2019 or less than 400 kW [71].
Other signals for dispatch, including environmental dispatch, are not currently legal for non-demonstration projects [71].

District heating and cooling
In 2016, for the first time the EU addressed heating and cooling comprehensively in the Heating and Cooling Strategy. The strategy aggregates the concepts of the policies described above and relates these to DE, particularly regarding the role of DE in the future European energy system – the promotion of CHP, TS and the potentials for flexibility from integration with the electricity system. This role is much in line with the subject of this study. Indeed, the strategy requests Member States to address barriers related to DE, a request to which this thesis is a small contribution. Specifically, it is intended that DE should be more integrated with the electricity system, that it should be more flexible, that it should rely on renewable energy and that DH systems in general should be expanded across the EU. [10].

EU energy policy summary
In summary, the paths of heating and cooling, renewables and flexibly integrated energy sectors are converging in the European energy policy. The findings in this thesis, specifically in Papers C-E on taxation, Paper A on barriers to flexible DE and Paper F on the quantitative impacts of selected barriers, contribute in identifying how the above European policy can be facilitated.

2.4.2 Nordic energy policy

Nordic climate and energy policy
The Nordics (Denmark, Finland, Norway, Sweden) have various energy mixes but common targets on energy and climate. These include the following:

- Climate and energy
  - Denmark: '*Net-zero emissions*' by 2050 [72]
  - Finland: '*Carbon neutrality*' by 2035 [73]
  - Norway: '*Climate neutrality*' by 2030 [74]
  - Sweden: '*Zero GHG emissions*' by 2045 [75]
  - Common Nordic target for carbon neutrality [76]

- Flexibility and sector coupling: full inclusion of all flexible assets in the market, clear price signals and a '*Nordic vision for sector coupling*' [77]

As these are government policies, the targets are not necessarily legally binding. Additionally, with the 2020 revisions of the Nationally Determined Contributions (NDCs) in the Paris Agreement [78] coming up, the above targets may quickly become obsolete.

Nordic district heating
The deployment of Nordic DH started in Denmark in 1903 [79], followed by very limited deployment in Norway in 1950 (beyond this, DH was almost absent in Norway until the 1980s) [80] and Finland and Sweden in 1953 [33]. Common to these initial deployments was the

utilisation of waste or waste heat. The oil crises of the 1970s were a turning point for all Nordic countries (except Norway, utilising electric heating instead) regarding the utilisation of DH as a measure for energy efficiency.
DH is regulated in various ways across the Nordics (discussed in Paper E and in more detail by Sandberg et al. [27] and especially Sandberg [26]). Denmark and Sweden have dedicated acts addressing DH, while in Norway, DH is incorporated in the general Energy Act. Finland has no dedicated regulation of DH, which instead is regulated through, for example, consumer protection and competition rules.

Nordic electricity markets
The Nordic countries were among the pioneers in the deployment of electricity markets. Norwegian transmission system operator Statnett initiated the Nord Pool power exchange in 1993. Sweden joined in 1996 and thereby created the first day-ahead electricity market. Finland joined in 1998 and Denmark in 2000. [24].

Nordic energy policy summary
In summary, the Nordic energy policy has for a long period focused on the use and deployment of especially DH. The climate and renewables ambitions towards 2050, combined with the long tradition of electricity markets, set a firm framework for DH to be electricity market-coupled and decarbonised.

2.4.3 Danish energy policy on district heating

This summary of Danish energy policy on DH provides concrete insight into the background for the development of a DH sector, which is among one of the most flexible – yet far from perfect (as discussed regarding results in 4.2).
After the shock from the oil crisis in 1973 (and 1979), the first comprehensive plan was made for Danish energy in 1976 – 'Dansk Energi 1976'[6]. It focused on decreased dependency on energy imports (which were 98% in 1970 [81]) through a reduced use of oil by increasing the efficiency of the heat supply – specifically by proposing the physical planning (zoning of DH through a national heat plan) and utilisation of excess heat from existing power plants but only a limited deployment of new DH systems based on CHP [82].
When the Ministry of Energy was created in 1979, it was in part to administer the provisions in the newly enacted Heat Supply Act of 1979 by managing the deployment and regulation of DH and CHP [83,84]. Subsequent plans and policies have targeted increasing the deployment of DH and CHP, including the Danish CHP Agreement of 1986, which prescribed the deployment of 450 MW_{EL} CHP in Denmark [85]. Beyond the energy efficiency perspective, this should also be seen as an effort to save the Danish oil and natural gas project in the North Sea when oil and gas prices fell in the 1980s, specifically by mandating the deployment of 'decentral' (small) natural gas-based CHP units to ensure a stable off-take of natural gas. [79].
Small, decentralised CHP units were from 1990 to 2005 subject to a 'triple tariff', which was a time-of-production subsidy allocating remuneration by time of day [86]. With the triple tariff, the decentral CHP units were incentivised to introduce TS since electricity generation during certain hours paid better. For large and small CHP units, economic optimal operation was the motivation for installing TS, which then and now enable Danish DH plants to decouple DH production from electricity consumption and production [52]. With the liberalisation of the

[6] English: Danish Energy 1976.

electricity sector, the large CHP units started participation in the Nord Pool electricity market around 2000. In 2005, the small Danish CHP units were also obliged to trade their electricity on the market [87]. All actors, including CHP units, are required to act through a balance responsible party. The balance responsible party is responsible for the electricity balance in the measurement points of consumption and production. [88]. Typically, to minimise the business process costs of having internal staff, smaller CHP units will apply an external expert balance responsible party.

In the Danish case, regulation which had previously been aligned with policy can now be problematic in the transition of the energy system. One example is the requirement on the co-production of heat and electricity in the large cities, which makes the deployment of large-scale HP illegal [89].

In the Nordic and Danish cases, the motivation for DH has varied over time. Each of these periods has coincidentally increased the potential for flexibility. Where the first Nordic plant addressed the issue of getting rid of waste in a space-constrained city, the subsequent period until the 1970s saw deployment mainly as a least-cost way of supplying heat (flexibility contribution: initial deployment of DH systems). In the 1970s and through the 1980s, motivation shifted towards security of supply, obtained through efficiency and fuel-shift (flexibility contribution: increased deployment of DH systems). The 1990s saw a growing focus on environmental impact (flexibility contribution: deployment of CHP and TS), followed by a focus on competition and marketisation in the late 1990s and 2000s (flexibility contribution: price signals reaching DH systems) [79]. Since the early 2010s, the focus has shifted from generation to the use of electricity for heating through PtH (flexibility contribution: electricity demand flexibility).

For the future Danish energy system, several paths have been laid out, including goals by the present Danish Government and its supporting parties (70% GHG reductions by 2030 compared to 1990 [90]). In 2018, a broad political agreement set out a target of a RE share of 100% of electricity consumption and at least 90% in DH by 2030. Additionally, this agreement [91] targeted '*the most integrated, market-based and flexible energy system in Europe*' with intentions, including the following:

- reduced electricity taxes for heating purposes
- termination of the mandatory use of natural gas in small CHP units (*brændselsbinding* – mandatory fuel use) and of the cogeneration of heat and electricity (*kraftvarmekrav* – mandatory cogeneration)
- increased competition with individual heat sources through the lifting of a mandatory connection to DH systems for consumers in DH areas
- regulatory 'sandboxes' – free zones for testing regulation
- dynamic electricity taxes

The Danish District Heating Association estimates that Danish DH companies by 2030 can contribute with 2.8 $MtCO_2$ for heat and 6.7 $MtCO_2$ for electricity (CO_2-neutral CHP plants) under current and new policies [92]. While numbers are not directly comparable, the Danish Council on Climate Change estimates 2.2 $MtCO_2$ reductions from DH and electricity, considering only new policies towards 2030 [93].

2.4.4 US energy policy

> *I've compared the formation of energy policy in this country to peewee soccer* […] *Nobody plays their position. Nobody even knows how to play a position. It would be nice if we could just form energy policy with a deliberate end in this country and it would be nice if we could try to execute it in a deliberate way instead of trying to jam it all through the tax code which seems to me like a really weird way to go about doing anything but that's how we do energy policy in this country*. – Chris Nelder [94]

The above description of US energy policy provides a harsh, humoristic and somewhat accurate summary of US policy on energy. Federal regulation addresses mostly issues that are of inter-state relevance. There is, for instance, no renewable heat policies at the federal level, while these exist on the state level [95]. This means that much of the energy policy is left to the discretion of individual states, leading to, for example, promoting policies on biomass-based thermal energy supply in Vermont while streamlining permitting for CHP in Washington State [96]. Therefore, a brief summary, not a full overview, is the purpose of this section.
Regarding cogeneration, an executive order in 2012 targeted the deployment of 40 GW industrial cogeneration by 2020 [97]. This was the first national goal for cogeneration [98], while the Public Utilities Regulatory Policy Act (PURPA) is among the most important policies for cogeneration deployment [98]. PURPA was introduced in 1978 in an effort to reduce US dependence on foreign oil [99] and energy efficiency in general by requiring utilities to buy electricity from small power producers (‘qualifying facilities’ such as CHP) at ‘avoided cost’ [100]. A 2005 revision exempted utilities in wholesale markets from this mandate [98]. It is worth noting that the principle of the Danish triple tariff and the principle of avoided cost in PURPA are very similar. Cogeneration is eligible for a 10% investment tax credit until 2021 [101]. Biomass projects had been eligible for a production tax credit until 2017 [102].
Renewable portfolios standards is another key regulatory measure. This enables states to define renewable shares of total energy supply to be met by energy suppliers. Traditionally, this has focused on electricity, but as of 2014, New Hampshire was the first to implement standards for heat [95]. This subsequently creates a market for renewable energy certificates, which are tradeable among, for example, suppliers who cannot meet the renewable portfolio standard. Several states beyond New Hampshire now include thermal energy in their renewable portfolio standard, with specific qualifications varying from state to state. For instance, biomass-based heat qualifies in New Hampshire, while the District of Columbia only allows solar thermal [103].

3. Methods: Analysing flexible integration in the district energy-electricity system interface

Answering the research questions takes the thesis along the following two main paths regarding flexibility in the DE-electricity system interface: *identifying* barriers and *evaluating the impacts* of these barriers. The identification of barriers is conducted through the qualitative methods narrative literature review and semi-structured interviews. The impact of barriers is analysed through quantitative methods, ranging from a simple spreadsheet-based model, to a single-plant model, to an energy system model. This methodological triangulation enables a thorough analysis.

3.1 Literature and expert reviews: Identifying barriers to flexibility in the DE-electricity system interface

In the words of Painuly, [104] '[T]*he advantage of decomposition of a barrier into its elements is clarity on causes for presence of a barrier*'. Such clarity is required in sub-research question 1 (*Can barriers to flexibility in the DE-electricity system interface be identified, structured and addressed in a systematic manner?*). The answer is provided by the initial definition of the key characteristics of barriers and a subsequent comprehensive review of the barriers to flexible DE, their emerging categories and their solutions. This combination of characteristics, categories and barriers form a taxonomy fundamental to making informed decisions regarding the analysis of flexible DE.

Barrier characteristics are those which inform on the type of technology and at which decision level and which point in the lifecycle the barrier is present. The characteristics are not identified through the comprehensive literature review but, rather, initially defined by the author and verified against other references.

3.1.1 Narrative review

Initially, a systematic review was intended. Searches were conducted during October 2018 through the university research portal DTU Findit, which includes the Scopus and Web of Science databases [105]. Search terms and results are given in *Table 1*.

Table 1 Search terms and results of the systematic review.

Search term	Gross results	Useful results
categorization, flexibility, renewable	90	3
barrier, flexibility, renewable, district	14	2
barrier 'smart energy'	75	3
barrier flexibility renewable	500+	9

Based on the limited amount of results from the systematic review, the research design was revised to include a narrative review. This enabled an expansion into concepts similar to – or overlapping with – flexible DE, such as barriers to flexibility, renewable heat and demand response. Additionally, this allowed an expansion of the resource base, including the following:

- The identification of references through lists of references in related research;
- Web searches;

- The use of personal archives;
- Targeted searching in key stakeholders' literature databases (IEA and similar).

This is in line with Sovacool et al. [106], who define the narrative review as follows: '*to synthesize insights from a variety of perspectives and disciplines, or areas where insufficient data exists to conduct a systematic review or meta-analysis*'.

3.1.2 Expert elicitation

To provide what Creswell [107] calls *peer debriefing*, that is, requesting feedback from peers to identify errors and enable that the study '*will resonate with people other than the researcher*' [107], the initial draft of the study was sent to 15 energy experts. Nine of these provided feedback. Additionally, this measure helped triangulate the findings with data sources other than those in the initial narrative literature review. While the feedback is not an approval of the study by the experts, it has helped address author bias by letting the narrative review be subject to additional perspectives.

3.2 Analysing flexibility

A key element is the definition and measurement of flexibility. At which level is an energy system flexible? When is a DE system sufficiently flexible? The answers here are normative, not descriptive, since flexibility can be measured in a myriad of ways. This illustrates the inherent weakness of applying *flexibility*, a term which is broadly well understood but applied in disparate ways. Flexibility is in this thesis addressed from different angles.

- Papers A and B analyse flexibility by proxy of *DE systems' ability to receive and respond to electricity grid-based signals.* Capuder and Mancarella take a similar perspective for DH [108], and Cochran et al. for demand response [109]. Paper A applies a narrative review of the literature on related fields within energy (further detailed in 3.1). Paper B applies the taxonomy from Paper A to identify barriers through interviews with DE stakeholders.
- Paper C analyses flexibility by proxy of *the relative operational competitiveness of grid-integrated technologies to non-grid-integrated technologies.* Green Energy has applied a similar approach for DH [110]. The analysis is a simple calculation of the percentage of hours during 2014 and 2015 where, respectively, EB and HP had the lowest heat production cost compared to biomass CHP, biomass boiler, natural gas CHP and natural gas boiler. This is conducted by calculating the electricity price at which the heat production costs are at parity – that is, where cost levels intersect. Subsequently, the hours with electricity prices lower than this intersect (i.e. where the EB is the least-cost technology) are summarised, and the shares of the technologies are calculated.
- Papers D and E analyse flexibility by proxy of *the relative investment incentive between combinations of grid-integrated technologies and non-grid-integrated technologies.* This is measured by modelling different combinations of DH technologies and their resulting levelised costs of heat. This indicates which combination of technologies will yield the lowest cost under the given framework conditions. Trømborg et al. [111] have applied a similar perspective on DH technologies and flexibility.
- Paper F analyses flexibility by proxy of *a set of evaluation criteria, including the deployment of PtH, renewables and CO_2-emissions.* Kirkerud et al. [112] and

Hedegaard and Münster [113] have applied a similar perspective regarding PtH and the integration of RE in respectively DH and individual heating.

3.3 Discussion of methods applied

Common to Papers A and B is that they identify perceived barriers. While these barriers may indeed be present, neither methodology can quantify their impact. Quantified impact is instead indicated in Papers C-F.

The narrative review was initiated as a systematic review. A systematic review may indeed have been possible to conduct later in the process – knowing what I did, after iterating through the extensive narrative review, where search terms and subjects stood out clearer.

Narrative reviews can be subject to researcher bias and can be difficult to replicate due to the lack of structure inherent in this method [106]. A further challenge with this study is that I was the single author. More authors could have expanded the scope by sheer number of references reviewed but also regarding the perspectives taken and interpretations made. It was thus a conscious and necessary choice to include the expert elicitation as a means to mitigate those weaknesses. Additionally, the study explicitly underscores these weaknesses and invites corrections and additions from peers.

The research design required choices regarding cut-off criteria for barriers. By *cut-off criteria* is meant the extent to which a barrier pertains to flexible DE or to other realms. One main example is the boundary between barriers to flexible DE and barriers to DE in general. This boundary is indistinct since anything that affects DE can subsequently affect flexible DE. By determining whether the barrier directly relates to flexibility or to DE more broadly, the line has been drawn sharper.

The interviews in Paper B identify perceived barriers. While this approach may initially seem problematic since the difference between perception and reality may be substantial, the approach was intentional – perception is exactly what is important in this particular study (an approach described by Sovacool et al. [106] and applied by, e.g., Golove et al. [114]). As the interviewees are managers at specific DE plants, their *perception* of barriers is decisive for operation and investment at their plants – both determining factors for flexibility in the DE-electricity system interface. Subsequent studies would be relevant to verify whether perceived barriers are also actual barriers, which is also part of the recommendations in Paper B.

Regarding the quantitative studies in Papers C-F, these are based on input data regarding taxes, subsidies and electricity grid tariffs. Such data are characterised by a relatively short 'best before date' since they are subject to frequent regulatory change or revised structures. In practice this means that, for example, since Danish taxes have been revised since 2015-2016, the exact numbers become obsolete, but the general message is unchanged.

Paper C is a simple study with a simple method, yielding indications of barriers rather than detailed energy system modelling. This worked well as an initial screening, setting the basis for the more detailed analyses in Papers D and E. The latter papers' total 144 scenario variations expands the findings in Paper C by exploring a considerably broader range of framework conditions. As the scenarios were mostly defined manually, this was very time-consuming. In addition to time-saving automation (which has subsequently been developed in the energy modelling software used in Papers D and E), the results could further benefit from the following:

- Providing results as ranges rather than individual values. Using stochasticity in, for example, electricity prices could mitigate the perfect foresight of the modelling, and include risk and uncertainty;

- Investment optimisation to expand beyond operational optimisation;
- The inclusion of ancillary services in the revenue stream of the DE plant. By only including spot market prices, an important source of revenue specifically for EB is omitted, as indicated by Detlefsen [115];
- Specifically regarding the assumption on constant price levels of green certificates in Paper E, this would have benefitted from a sensitivity analysis with a less optimistic assumption.

Regarding the energy system modelling in Paper F, the intention is to show the impact of constraining a particular potential barrier (biomass) in the Danish energy system. While this analysis extends beyond other similar studies in its detail on regulatory conditions and system representation, later iterations could be improved in especially the following two areas: the representation of regulatory conditions in surrounding countries and the geographical resolution of heat demand among the heat demands represented (DH and industrial and individual heating).

Important to note is that the qualitative studies are equally subject to variations in framework conditions as the quantitative studies. Acknowledging the fleeting relevance of all such specific results of regulatory and policy studies, the focus should less be on the decimals and more on the general relevance of results. The analyses in this thesis will thus hopefully find value as generic indicators of potential relevance, making the results transferable to other contexts and timeframes.

4. Results and discussion: Flexibility in the district energy-electricity system interface

This section presents the highlights of the research conducted in the research papers forming the thesis.
The thesis takes its starting point in a review of barriers to flexibility in the DE-electricity system interface (Paper A). This theoretical taxonomy is subsequently tested against real-world DE systems to mirror the taxonomy in real DE systems (Paper B). With this qualitative foundation, single-plant impacts of barriers to the flexibility of DH is conducted in Papers C-E. Having established a clear indication of impacts regarding the incentive to operate and subsequently invest in flexible technologies, the scope is broadened to the whole energy system in Paper F. At this energy system level, heat source substitution is explored as a means to address barriers and analysed against several criteria (system cost, PtH deployment, electricity grid tariff revenue, etc.).

4.1 Results of Papers A to F

Paper A presents a review of the literature on barriers to flexibility in the DE-electricity system interface. Based on the findings, a taxonomy is developed. Barriers share common characteristics regarding technologies affected, the part of DE lifecycle affected and at which decision level the barrier originates. A total of 40 barriers are identified and placed in the following nine emerging categories:

1. Operational signalling – flexibility requires signals on which to respond;
2. Investment – flexibility depends on investment in specific assets;
3. Permitting – flexibility depends on accommodating permitting processes and related regulation;
4. Ownership – flexibility depends on alignment with ownership conditions especially for taxation;
5. DE technology conditions – flexibility depends on the capability of technologies;
6. Grid access – flexibility depends on integration with the electricity grid;
7. Physical environment – flexibility depends on the availability of resources and land;
8. Bounded rationality – flexibility depends on awareness among stakeholders;
9. Acceptance – flexibility depends on prioritisation among stakeholders.

The main barrier is identified to be the absence of signals on which to respond flexibly. In addition, primary barriers (barriers that are decisive for the use of flexible DE) include limitations from organisational bounded rationality, which can hinder investments in flexible technologies during the planning phase. Discriminatory grid codes can be another primary barrier since this can hinder access to the electricity grid of an otherwise potentially flexible DE plant. Secondary barriers, referring to barriers reinforcing or stacking on top of other barriers, include operational taxes and levies on flexible DE technologies. Such taxes may not in themselves hinder flexibility but can make flexible technologies uncompetitive by shifting their marginal production cost upwards. Solutions beyond enabling DE access to signal-providing schemes include increased information on flexibility benefits and regulation incentivising flexibility according to energy

system needs. Paper A's identification of potential barriers serves as a basis for the subsequent research analysing the presence and impact of those barriers.
In Paper B, I explored the perceived framework conditions for flexibility at 10 US university campus DE systems. The analysis found that most operation happens as behind-the-meter optimisation of thermal and electric needs, in contrast to how market-integrated systems are acting. Paper B additionally serves as a basis for testing Paper A's findings against real-world cases. The taxonomy was found to be applicable as an analytical tool, resulting in identification of 18 barriers out of the 40 identified in Paper A.
In Paper C, we screened whether economic framework conditions (2015) pose barriers to DH flexibility in Denmark, Norway and Sweden – specifically, how the economic framework conditions impact the relative competitiveness of grid integrated technologies (CHP and PtH) against NEITG. We found that untaxed biomass-based technologies generally have the lowest levelised cost of heat (LCOH). Natural gas CHP is generally uncompetitive against biomass boilers, as exemplified for Denmark in *Figure 7*[7].

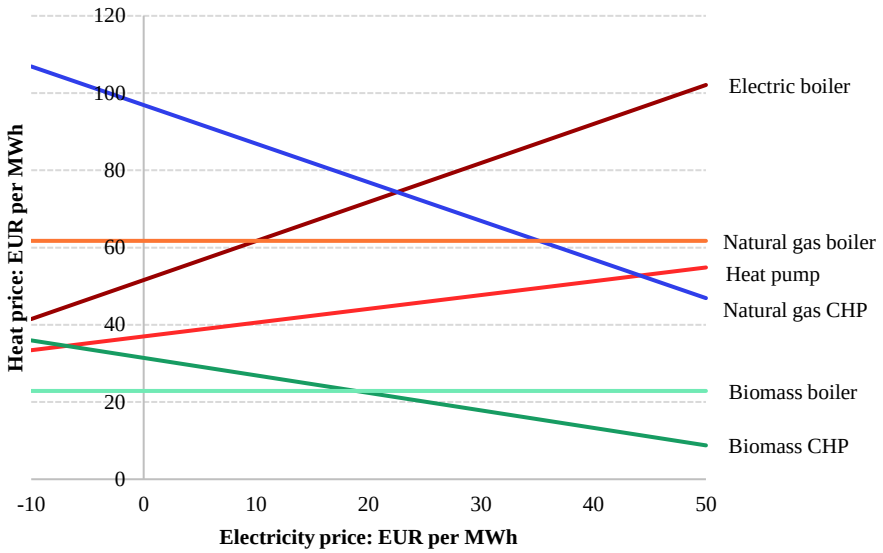


Figure 7 Least-cost dispatch chart, showing DH technologies under 2015-Danish framework conditions.

The results are mixed regarding HP, which appears more competitive in Norway and Sweden, as indicated by the percentage of hours that HP would be the optimal dispatch over the biomass boiler in the electricity spot-price time series of 2014-2015

- 0% in Denmark
- 99.6% in Norway
- 12.5% in Sweden

The difference can be attributed to the electricity grid tariffs, higher electricity tax and public service obligation that PtH faced in Denmark. Overall, the results indicate an indirect impact of economic framework conditions on flexibility – namely, on the economic incentive to operate

[7] See *Figure 5* for an explanation of the least-cost dispatch concept.

flexible technologies and subsequently to invest in them. Paper C serves as a basis for the more detailed analyses of the economic framework conditions in Papers D and E.
Paper D develops the analyses in Paper C with more detailed DH modelling and an expanded dataset and geographical scope (Baltics). The following four different plant configurations were tested for a small (40 GWh_{TH}/year) DH plant:

1. Wood chip CHP + EB
2. Wood chip CHP + wood chip boiler
3. Wood chip boiler + EB
4. Wood chip boiler

Testing these configurations regarding the impact of taxes, subsidies and electricity grid tariffs as well as with and without TS yields a total of 48 scenario variations. In Estonia and Latvia, we found that investment incentives from economic framework conditions motivate a combination of wood chip boiler and EB, that is, an option with potential for demand flexibility but no electricity production flexibility. For Lithuania, CHP + EB has slightly lower LCOH (41 EUR/MWh) than wood chip boiler and EB (45 EUR/MWh). The significantly larger investment that the CHP requires in combination with the uncertainties from the electricity revenue means that wood chip boiler and EB in all three cases is found to be the most attractive investment. TS is in all cases a no-regrets solution, providing lower heat prices and reducing the use of peak load capacity (with storage in CHP + EB, LCOH is 59-77% of non-storage LCOH). EB's share of heat production was 0-3%. Taxes and subsidies are not prohibitive to the operation of EB, which indicates a fundamental inability to compete against untaxed biomass assets under the given electricity prices. Paper D serves as a verification and elaboration of the results in Paper C, demonstrating the existence of economic barriers to the operation of, and investment in, flexible technologies at single DH plants.
In Paper E, the motivation and methodology is the same as in Paper D but with the Nordics as the geographic scope – Denmark, Finland, Norway and Sweden – totalling 96 scenario variations. This was done to explore a plant configuration similar to that in Paper D under different (Nordic) regulatory framework conditions. We found that investment incentive is largest for biomass CHP with EB in all countries but Denmark (where a wood chip boiler is the best investment). This is largely driven by investment and operation subsidies. The subsidies' share of LCOH is up to 68% in Norway and 51% in Sweden. TS is again a no-regrets solution in all cases (with TS scenarios' LCOH 18-86% of non-storage scenarios). Biomass is the major energy source in all scenarios (around 90% in all scenarios with HS, with Norway as the single exception at 64%). Electricity-based heat generation from EB is limited. While EB use is completely eliminated in scenarios with Finnish and Norwegian capacity-based tariffs, it reaches a maximum of 35% in the Norwegian wood chip boiler + EB scenario. Thus, electricity grid tariffs have significant impacts. Taxes and subsidies have limited impact on the operation but significantly impact the investment incentive for CHP.
In Paper F, we analysed the impacts of fuel substitution (biomass-based sources to other heat sources) on the flexibility and sector coupling in a large energy system. By constraining a biomass use, considered a competitor to especially PtH, we found that sector integration was inversely impacted between PtH and CHP – when one would increase, the other would decrease. Also, provided an increasing CO_2 price, intervening by constraining biomass led to increased emissions (293-2 244 kton/year). Compared to the base case, the constraints induced a shift away from biomass use, resulting in increased PtH capacity (122%-491%), tax-

(222%-647%) and electricity tariff revenue (105%-165%) as well as end-user heat cost (108%-151%). The study showed that while competing heat sources can reduce especially the electrification of heating, constraining these would benefit from other simultaneous measures (e.g. draw on tax surplus to reduce emissions), to mitigate the downsides (e.g. increased heat costs, increased emissions).

4.2 Discussion of results

4.2.1 Precondition for the analysis

The thesis is founded on an assumption of transitioning energy systems. With increasing amounts of VRE, the energy system requires increased flexibility. Even beyond transition, electricity markets become increasingly liquid as the number of participating flexible actors increases. Such flexibility can be obtained in many different ways, where DE is the one analysed here. DE plants are not always perceived as flexible (discussed in e.g. [116–118]) since they may disregard broader energy system needs in their operation according to thermal demand. In contrast, the Nordics are known for flexible DH plants. This discrepancy was the initial motivation for the thesis: Why are not all DE plants flexible? If interpreted normatively – meaning that DE *should* always be based on flexible technologies – the question can be criticised: flexible DE may not always be necessary, such as in the case of abundant thermal energy from non-flexible resources such as geothermal or industrial excess heat, or if the energy system is simply saturated with flexible resources that make DE flexibility irrelevant. As stated in 2.3.2, 'flexibility for flexibility's sake' is applied for analytic purpose in this study, while not the intention in all real-world cases. This approach has proved relevant in especially Paper A, to address the research gap regarding a systematic overview of a wide array of barriers. Paper F extends beyond the myopic view to show the impacts of implementing flexibility measures, impacts which may not always be desirable for the energy system broadly.
Finally, it is worth noting that a purely economically focused study of barriers to the flexibility of DE in an electricity market would essentially be a study of barriers to a perfect market (i.e. market failures). Since the thesis takes a broader view of a sustainable energy system (section 2.1), such framing is only partially true.

4.2.2 Framework conditions for flexibility in the DE-electricity system interface

Quantitative analyses of heat prices as a proxy for the most attractive investment in DH is performed in Papers C-E. Similarity in data and methodology enables a comparison of LCOH between Papers D and E. For CHP + EB, the considerable difference in labour costs are reflected in the investment share of LCOH (49-57 EUR/MWh in Nordics; 33 EUR/MWh in Baltics). Another factor is fuel cost, where wood chips in the Baltics are around half the price of those in the Nordics (11.5 EUR/MWh vs 19-22.8 EUR/MWh). Taxes are generally lower in the Baltics. Despite this, Finnish, Norwegian and Swedish LCOHs are on par with – or lower than – the Baltic prices (Nordics: 12-56 EUR/MWh; Baltics: 41-62 EUR/MWh). This is attributed to the significant share of Nordic subsidies.
Paper B identified 18 barriers among the surveyed US DE systems out of the total 40 identified in Paper A. While Nordic DE plants are actively participating in the electricity markets, the same is not the case in the US plants. While they may have similar generation and consumption assets (CHP and PtC), the US systems are mainly dispatching outside the electricity market. If perceiving electricity markets as contestable markets, lowering the barriers to entry for these existing CHP plants would enable hit-and-run entry (a type of market participation where entry and exit are free – discussed by Baumol [29]). In the existing US DE systems, some plants have

already invested in CHP and other infrastructure due to internal needs. Policy enabling hit and run, along with other types of response, would promote flexibility in the DE-electricity system interface.

Papers D and E show biomass CHP with TS operating close to baseload at a 75-80% capacity factor. Paper C shows a similar tendency for Denmark and Sweden. Biomass CHP units would in these cases contribute to the flexible energy system by abstaining from generation rather than feeding into the grid. Similar findings have been made by Blarke [34] regarding HP, in both cases due to the low marginal cost of heat. CHP may be less favourable in the real world than the modelled in Paper E since the analyses have been made on the assumption of generous subsidies, which may not be the case in the longer term.

The initial screening regarding the Nordic countries indicates an impact of electricity grid tariffs (Paper C). This is verified in Paper E, indicating that monthly revised capacity-based electricity grid tariffs can remove all incentive for PtH. Letting the capacity threshold be set on a yearly maximum instead can mitigate this. Such a design is similar to the ratcheted demand charges that US plants are facing, where their consumption during annual grid peak hours sets the level of their subsequent demand charges (described in Paper B). While such peaks can be forecast, and plant operation adjusted to avoid those peaks, the question is whether DE should be subject to such charges at all, given a track record of reliable flexibility (as, e.g., proposed by Selecky et al. [119]).

Skytte et al. [46] calculated the flexibility need as a function of electricity price variations. This indicated '*that there is no 'flexibility emergency' in the Nordics and Baltics as of 2018*' [46]. In this regard, a distinction should be made between a saturated flexibility demand and a completely absent need for flexibility. While the former is likely, the latter is hardly realistic in a system with VRE. Whether DE provides flexibility in this system depends on its ability to compete in the electricity system interface. The strength and weakness of DE as a flexibility provider is that there are many ways to *produce* thermal energy, while for electricity there are many ways to *use* it – or *X-to-heat* vs *power-to-X,* as coined by Eldrup et al. [120]. If uncompetitive in the electricity interface, DE will opt for other options, potentially leading to reduced energy system flexibility. Despite large increases in VRE, Paper F indicates a need for CHP even in the long term (3 GW by 2045 in the base case). Likewise, PtH is deployed extensively (also 3 GW [thermal] by 2045 in the base case) but is to some degree limited by the alternative heat source from biomass-based CHP (while not so much by boilers). Thus, by consuming and generating electricity, DE is able to contribute to satisfying the flexibility need in the long term.

4.2.3 Consequences of addressing framework conditions

Since DH is evidently a precondition for flexibility in the DH-electricity system interface, I will briefly treat this in the following. The regulatory environments in which DH has been deployed in the Nordics have varied between competition with other heat sources (Sweden) and a physically planned heat supply (Denmark). The overall existence of DH in the Nordic context is thus driven by different framework conditions (as explored by Sandberg et al. [27]). Future conditions for DH will thereby determine the ability to deliver flexibility in the energy system. In the Danish case, there has been a longstanding tradition of striving for the energy system with the best economy for society – what the Danes typically call socio-economy [121]. Since the 2000s, economic efficiency has become increasingly in focus, as seen in authorities' and consultants' work on the subject [122,123]. While economic efficiency is desirable, the

methodology for analysing and obtaining this goal should not be reduced to a simple analysis of least-cost heat supply for the end consumer for the following two reasons:

1. As all papers in this thesis show, there is currently a multitude of framework conditions that should be taken into consideration before it can be argued that a level playing-field is present
2. The holistic approach regarding the energy system is important to maintain. This is important since optimisation within a single sector may be a sub-optimal solution for the energy system as a whole. A prime example is a business-economically optimal investment in biomass boilers, which limits the possibility for integration with the electricity system

The use of TS is a no-regrets solution, providing better LCOH (Papers D and E) and a more flexible energy system (Paper F). This is supported by several studies, including Østergaard [124]. In the US, the presence of steam-based systems hinders this on the heat side, while it is to some degree utilised on the cold side. This underscores the relevance of feasibility studies of conversion projects in contexts such as the US to clarify whether the collective benefits are high enough to justify conversion – not just at the plant level but also on a system scale. The latter could justify state or federal subsidies, according to the societal benefits.

Electricity grid tariffs are both in the Nordics and the US shown to have impact on the flexible operation of DE. A tariff design based on real costs (except cable lengths, which can be socialised to give indiscriminatory access – what Reneses et al. calls a '*super shallow cost-based connection charge*' [125]) – would be the preferred solution in both cases. Indeed, as proposed by Skytte et al. [126], making these tariffs dynamic according to relevant signals would enable further utilisation of DE flexibility.

Although conceptually fascinating, environmental dispatch may be challenging in combination with the economic signals currently in place. Instead, taxation according to externalities is a relevant way to align signals for environmental impact (e.g. tCO_2/MWh) with electricity market signals (e.g. EUR/MWh). This is to some degree already the case, but the question is whether the tax levels (or similar externality costs) are updated to current externalities or, indeed, whether the taxes are simply a fiscal source for government budgets. One option, as recommended in the Flex4RES and Energylab Nordhavn projects, is to make the taxes dynamic according to climate impact [46,127].

Whereas the barrier created by competition from substitute goods – grid-integrated and NEITG heat sources – has been proven (Paper F), the consequence of addressing this by constraining one source is not a win-win scenario (CO_2 emissions increase and heat consumers bear the cost increase). If the purpose is to increase flexibility in the DE-electricity system interface, the remaining set of potential barriers identified in Paper A should be analysed before proceeding with implementation. This should be self-evident but is not always the case (cf. Lund's [38] choice awareness theory). Subsequently, mitigation measures could be applied, such as redesigning the constraints (e.g. targeting non-climate-friendly biomass) to moderate impacts, cost-sharing among electricity and heat consumers or applying economic surplus to finance CO_2 reduction in other areas.

Finally, while the impacts of barriers and possible solutions have been analysed, the details in the implementation of solutions have not been addressed. Thereby, future work remains regarding rolling out possible changes to facilitate flexibility in the DE-electricity system interface.

4.3 Summarised contributions of the thesis

The existing scientific body is expanded by this thesis in two ways. First, it identifies and lays out a taxonomy of barriers to flexible DE. Second, it quantifies the impact of selected barriers and the consequences of mitigating these.

4.3.1 Contributions to barrier understanding

The first comprehensive overview of barriers to flexible DE is here conducted. Subsequently, the barriers are organised in a proposed taxonomy. Common characteristics are suggested for all types of barriers, indicating which technologies they affect, at which point in the project life they occur and at which decision level they originate. Furthermore, the taxonomy divides the barriers into nine categories, intended to cover everything from technical, to economic, to behavioural aspects. While much of the knowledge had already been available, it was tacit, unstructured and scattered among academia and professionals. The taxonomy enables further scientific work to transcend into systematic approaches in addressing flexible DE. Likewise, policy makers and project owners tasked with deploying flexible DE have been provided with a concrete checklist of matters to address in such a process – and proposed solutions. It is the hope and intention that this will make the process of enabling flexibility in the DE-electricity system interface smoother and more likely to reach the desired outcome. Perhaps most useful for the broader energy research community is that the structure of the taxonomy, with few adaptations, is broadly applicable to the flexibility (and other desired characteristics) of technologies in energy systems.

4.3.2 Contributions to policy analysis

The thesis quantifies substitution among heat sources, thereby indicating the impact on flexibility in the DE-electricity system interface. It does so with a focus expanded to the energy system broadly, such as revenue from electricity grid tariffs and taxes. The thesis thereby provides a systematic analysis of heat source substitution as a measure to address the potential barrier of competition between flexible, grid-integrated thermal sources and especially biomass-based resources such as NEITG. This provides policy makers with an initial indication of ‘hotspots’ to address. Secondly, the methodological approach can serve in analysing concrete systems since DE systems are inherently context-specific.

5. Conclusions and outlook

The overall research question of the thesis is: *Which framework conditions hinder flexible operation in the district energy-electricity system interface, and what are their consequences?* This question is posed since increasingly flexible and coupled energy sectors will benefit markets and the transition to an efficient and renewables-based energy system. DE and the electricity grid are the sectors in focus, having shown considerable potential for flexibility. Such flexibility is not always present in DE systems, which motivates the following sub-research questions that collectively constitute the main research question:

1. *How can barriers to flexibility in the DE-electricity system interface be identified, structured and addressed in a systematic manner?*
    a. Paper A defines common characteristics of barriers to flexible DE. It identifies 40 such barriers and their proposed solutions. Each barrier is placed in one of nine categories. In aggregate, this forms a taxonomy for barriers to flexible DE.

2. *How does the systematic overview correspond to experiences in real-world DE systems?*
    a. Paper B applies the developed taxonomy to 10 US university campus DE systems. This real-world reflection of the taxonomy identifies 18 of the taxonomy's total 40 barriers. As expected, the study shows different barriers in different places, underscoring the context-specific character of DE systems and their related barriers to flexibility. Common is that supply flexibility is almost absent, while demand flexibility is present.

3. *What consequences do selected identified barriers to flexibility in the DE-electricity system interface have for certain typologies of DE plants?*
    a. Applying 2015-2016 data for micro-economic analyses, Paper C screens for barriers to flexible DE in the Nordic economic framework conditions and finds challenges within taxes and tariffs, reducing the competitiveness of CHP and PtH against alternative technologies. Papers D and E extend this study to a detailed LCOH analysis of generic plants. The latter studies show that subsidy policies in Nordic countries (except Denmark) drive investment towards CHP and EB. Danish framework conditions incentivise wood chip boiler, thus limiting sector coupling. The Baltic countries land in between, with a combination of wood chip boiler and EB as most feasible. Economic framework conditions thus drive investments differently, depending on place. The large reliance on subsidies for CHP is noteworthy, considering that lower electricity prices may drive DH towards an electricity consumer role rather than towards electricity production.

4. *On a larger scale, what consequences do selected barriers to flexibility in the DE-electricity system interface have for the energy system?*
    a. Paper F studies interactions between substitutable heat sources with different flexibility potentials and sector coupling characteristics. Introducing a constraint to a potential barrier to flexibility in the DE-electricity system interface does not

yield positive results for all criteria analysed (increased CO_2 emissions and heat costs) but increases the electrification of heat, VRE deployment and reduces system costs. The findings underscore that barriers and their mitigation measures should be carefully analysed for adverse impacts before implementation. This analysis provides a method for doing so.

The thesis adds to the existing research through its development of a comprehensive overview of barriers and its related structure – a taxonomy for barriers to flexible DE. Also, by quantifying the impacts of barriers through a techno-economic analysis, a comparison of barriers is conducted, providing indications of the 'lowest-hanging fruit', if such barriers should be addressed.
Overall, it can be concluded that it is indeed possible to identify and analyse which framework conditions drive and hinder flexible operation in the DE-electricity system interface – specifically, that at least 40 different barriers can be present and that anything from outright bans, to stifling investment incentives from taxes and tariffs, to the behaviour and knowledge among plant staff can hinder investment in, and the operation of, flexible DE technologies. The consequences of the reduced flexibility in the DE-electricity system interface include less utilisation of PtH to integrate increasing amounts of VRE, less energy-related tax revenue and higher use of biomass.

Weighting barriers and identifying those with the largest impact should be done with caution, again respecting the context-specificity of DE systems. What can be concluded regarding the most important barrier is that the provision of flexibility from a DE system depends on signals. The absence of signal-providing schemes, such as market prices, is a primary barrier. Importantly, even in the presence of signals, each of the other 39 identified barriers can alone hinder flexibility in the DE-electricity system interface. Whether and how much is a matter of context.

The next steps, enabled by the research in this thesis, can involve two analytic approaches – explorative and normative.

- In an explorative approach, an external framework condition is applied to a set of barriers – from a single barrier to all 40 – to examine the impact of barriers under the given framework condition.
- A normative approach is similar to Liebig's law of the minimum, where a minimum threshold determines the overall development of a system – in this case, how flexible DE is. Here, barriers are screened to identify the lowest threshold, that is, which barrier is limiting flexibility. This can subsequently be addressed (and the process reiterated).

In both analytic approaches, relevant framework conditions to explore include

- 100% (V)RE systems;
- Regulatory regimes for DE and utilities, such as incentives-based (as discussed in Denmark) and performance-based (as discussed in the US) regulation;
- Technologies such as digitalisation, artificial intelligence, carbon capture, high-temperature thermal energy storages and power-to-X;

- Climate plans (e.g. targets for Denmark in 2030, the EU in 2050 or US universities in 2050);
- Pertinent countries such as China with a large deployment of DE and the US with unmapped DE potential;
- Shifting role of electricity grids and roles of distribution system operators and transmission system operators, especially distribution-level flexibility markets and the contribution of DE;
- Sustainability studies extending beyond the traditional areas of economics and energy to environmental and social factors;
- Consumer-side flexibility in DE systems.

In summary, the field of DE, flexibility and regulation holds great potential for interesting and relevant future analyses.
Science and ethics lay out the necessary path of a persisting effort towards an increasingly sustainable world. Albeit a small piece of the puzzle, striking the right balance between molecules and electrons in the DE-electricity system interface can contribute to such development. No barrier identified in this study was found to be insurmountable. Hopefully, neither will the transition to a sustainable energy system.

6. References

[1] Stern N. The Economics of Climate Change. Cambridge: Cambridge University Press; 2007. doi:10.1017/CBO9780511817434.
[2] IPCC. Climate Change 2014 Synthesis Report. Geneva: 2014.
[3] IPCC. Global Warming of 1.5°C. 2018.
[4] IRENA. Renewable Power Generation Costs in 2018. Abu Dhabi: 2019.
[5] Lovins AB. The Negawatt Revolution. Conf Board Mag 1990;27:18–23.
[6] IEA. The power of transformation. Paris: IEA; 2014. doi:10.1007/BF01532548.
[7] Münster M, Iliceto A, Berger M, Bramstoft R, Bühler F, Elmegaard B, et al. Sector Coupling: Defitions, state-of-the-art and perspectives 2020.
[8] Jamasb T, Llorca M. Energy Systems Integration: Economics of a New Paradigm. Cambridge: 2019.
[9] Lund H, Andersen AN, Østergaard PA, Mathiesen BV, Connolly D. From electricity smart grids to smart energy systems – A market operation based approach and understanding. Energy 2012;42:96–102. doi:10.1016/j.energy.2012.04.003.
[10] The European Commission. An EU Strategy on Heating and Cooling 2016.
[11] EMD International A/S. Svendborg District Heating. EMD Website 2020. http://www.energyweb.dk/svendborg/?english&history (accessed March 28, 2020).
[12] IEA. Linking Heat and Electricity Systems: Co-generation and District Heating and Cooling Solutions for a Clean Energy Future. Paris: 2014.
[13] Energinet.dk. Nordic Power Market Design and Thermal Power Plant Flexibility. Fredericia: 2018.
[14] Klinge Jacobsen H, Zvingilaite E. Reducing the market impact of large shares of intermittent energy in Denmark. Energy Policy 2010;38:3403–13. doi:10.1016/j.enpol.2010.02.014.
[15] Mathiesen BV, Bertelsen N, Schneider NCA, Garcia LS, Paardekooper S, Thellufsen JZ, et al. Towards a decarbonised heating and cooling sector in Europe: Unlocking the potential of energy efficiency and district energy. 2019.
[16] Mathiesen BV, Lund H, Hansen K, Ridjan I, Djørup SR, Nielsen S, et al. IDA's Energy Vision 2050. Department of Development and Planning, Aalborg University; 2015.
[17] Danish Energy Agency. Energiscenarier frem mod 2020, 2035 og 2050 [Energy scenarios towards 2020, 2035 and 2050]. Copenhagen: 2014.
[18] Gadd H, Werner S. Thermal energy storage systems for district heating and cooling. Adv. Therm. Energy Storage Syst. Methods Appl., Halmstad: Woodhead Publishing Limited; 2014, p. 467–78. doi:10.1533/9781782420965.4.467.
[19] Tang J. District Heating in China. Hot Cool 2019:15–8.
[20] IEA, Tsinghua University. District energy systems in China. 2017.
[21] US Energy Information Administration. U.S. District Energy Services Market Characterization. Washington: 2018.
[22] Eurostat. Renewable energy for heating and cooling. Eurostat Website 2020. https://ec.europa.eu/eurostat/web/products-eurostat-news/-/DDN-20200211-1 (accessed March 2, 2020).
[23] Danish Energy Agency. Figurer - Energistatistik 2018 [Figures - Energy statistics 2018] 2019.
[24] Danish Energy Agency. European Experiences on Power Markets Facilitating Efficient Integration of Renewable Energy 2018.
[25] Bernth M. Antallet af varmepumper i fjernvarmen vokser eksplosivt i år [The amount of heat pumps increases with explosive growth this year]. Ingeniøren 2020. https://ing.dk/artikel/antallet-varmepumper-fjernvarmen-vokser-eksplosivt-aar-232316 (accessed March 30, 2020).
[26] Sandberg E. Nordic district heating and energy system flexibility : challenges and opportunities = Nordisk fjernvarme og energisystemfleksibilitet : muligheter og

utfordringer. Norwegian University of Life Sciences, 2019.
[27] Sandberg E, Sneum DM, Trømborg E. Framework conditions for Nordic district heating - Similarities and differences, and why Norway sticks out. Energy 2018;149:105–19. doi:10.1016/j.energy.2018.01.148.
[28] Boulding KE. Stable peace. Austin, Tex.: University of Texas Press; 1978.
[29] Baumol WJ. Contestable Markets: An Uprising in the Theory of Industry Structure. Am. Econ. Rev., vol. 72, 1982, p. 1–15.
[30] Demsetz H. Barriers to Entry. Am Econ Rev 1982;72:47–57.
[31] Wissner M. Regulation of district-heating systems. Util Policy 2014;31:63–73. doi:10.1016/j.jup.2014.09.001.
[32] Pérez-Arriaga IJ. Regulation of the Power Sector. 1st ed. Springer-Verlag London; 2013. doi:10.1007/978-1-4471-5034-3.
[33] Frederiksen S, Werner S. District Heating and Cooling. 1st ed. Lund: Studentlitteratur; 2013.
[34] Blarke MB. Towards an intermittency-friendly energy system: Comparing electric boilers and heat pumps in distributed cogeneration. Appl Energy 2012;91:349–65. doi:10.1016/j.apenergy.2011.09.038.
[35] Coase RH. The Nature of the Firm. Economica 1937;4:386–405. doi:10.1111/j.1468-0335.1937.tb00002.x.
[36] Simon HA. Behavioural Economics. New Palgrave Dict. Econ., London: Palgrave Macmillan UK; 1987, p. 1–9. doi:10.1057/978-1-349-95121-5_413-1.
[37] Lund PD, Lindgren J, Mikkola J, Salpakari J. Review of energy system flexibility measures to enable high levels of variable renewable electricity. Renew Sustain Energy Rev 2015;45:785–807. doi:10.1016/j.rser.2015.01.057.
[38] Lund H. Renewable Energy Systems. 2nd ed. Academic Press, Incorporated; 2014.
[39] Lund H, Østergaard PA, Connolly D, Mathiesen BV. Smart energy and smart energy systems. Energy 2017;137:556–65. doi:10.1016/j.energy.2017.05.123.
[40] Blumstein C, Krieg B, Schipper L, York C. Overcoming social and institutional barriers to energy conservation. Energy 1980;5:355–71. doi:10.1016/0360-5442(80)90036-5.
[41] Cagno E, Worrell E, Trianni A, Pugliese G. A novel approach for barriers to industrial energy efficiency. Renew Sustain Energy Rev 2013;19:290–308. doi:10.1016/j.rser.2012.11.007.
[42] Good N, Ellis KA, Mancarella P. Review and classification of barriers and enablers of demand response in the smart grid. Renew Sustain Energy Rev 2017;72:57–72. doi:10.1016/j.rser.2017.01.043.
[43] Ropenus S, Skytte K. Regulatory review and barriers for the electricity supply system for distributed generation in EU-15. 2005 Int Conf Futur Power Syst 2005:6 pp. – 6. doi:10.1109/FPS.2005.204261.
[44] Energinet. Model Analysis of Flexibility of the Danish Power System. 2018.
[45] Ma Z, Knotzer A, Billanes JD, Jørgensen BN. A literature review of energy flexibility in district heating with a survey of the stakeholders' participation. Renew Sustain Energy Rev 2020;123. doi:10.1016/j.rser.2020.109750.
[46] Skytte K, Bergaentzlé C, Fausto F, Gunkel P, Flex4RES. Flexible Nordic Energy Systems - Summary Report. Lyngby: 2019.
[47] IEA, NREL. Status of Power System Transformation 2018. Paris: 2018.
[48] Maslow AH. A theory of human motivation. Psychol Rev 1943;50:370–96. doi:10.1037/h0054346.
[49] World Energy Council. World Energy Trilemma Index 2019. London: 2019.
[50] Mathiesen B V., Lund H, Connolly D, Wenzel H, Ostergaard PA, Möller B, et al. Smart Energy Systems for coherent 100% renewable energy and transport solutions. Appl Energy 2015;145:139–54. doi:10.1016/j.apenergy.2015.01.075.
[51] UN General Assembly. Transforming our world: the 2030 Agenda for Sustainable Development 2015.
[52] Lund H. Renewable Energy Systems. 2nd ed. Aalborg: Academic Press; 2014.
[53] Danish Energy Agency. Regulation and planning of district heating in Denmark.

Copenhagen: 2015.
[54] Lund H, Werner S, Wiltshire R, Svendsen S, Thorsen JE, Hvelplund F, et al. 4th Generation District Heating (4GDH). Integrating smart thermal grids into future sustainable energy systems. Energy 2014;68:1–11. doi:10.1016/j.energy.2014.02.089.
[55] Connolly D. Finding and Inputting Data into the EnergyPLAN Tool. Aalborg: 2015.
[56] Sneum DM, Sandberg E, Soysal ER, Skytte K, Olsen OJ. Framework conditions for flexibility in the district heating-electricity interface. Lyngby: 2016.
[57] Thellufsen JZ, Nielsen S, Lund H. Implementing cleaner heating solutions towards a future low-carbon scenario in Ireland. J Clean Prod 2019;214:377–88. doi:10.1016/j.jclepro.2018.12.303.
[58] The European Parliament, The European Council. Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency 2012.
[59] The European Commission. Commission Recommendation (EU) 2019/1659 on the content of the comprehensive assessment of the potential for efficient heating and cooling 2019.
[60] The European Council, The European Parliament. DIRECTIVE (EU) 2018/2002 on Energy Efficiency. Off J Eur Union 2018;328:210–30.
[61] European Commission. 2020 climate & energy package. Eur Comm Website n.d. https://ec.europa.eu/clima/policies/strategies/2020_en (accessed January 17, 2020).
[62] European Commission. 2030 climate & energy framework. Eur Comm Website n.d. https://ec.europa.eu/clima/policies/strategies/2030_en (accessed January 17, 2020).
[63] European Commission. A Clean Planet for all. Com(2018) 773 2018:114.
[64] European Commission. A European Green Deal 2019.
[65] The European Commission. The Commission's proposal for the first European Climate Law 2020.
[66] von der Leyen U. Mission Letter to Energy Commisioner Kadri Simson 2019.
[67] The European Parliament, The Council of the European Union. Directive (EU) 2018/2001 of the European Parliament and of the Council on the promotion of the use of energy from renewable sources. Off J Eur Union 2018.
[68] The European Commission. Energy Union Package - A Framework Strategy for a Resilient Energy Union with a Forward-Looking Climate Change Policy 2015:1–21.
[69] The European Parliament, The Council of the European Union. Directive 96/92/EC concerning common rules for the internal market in electricity. Off J Eur Communities 1997:20–9.
[70] The European Parliament, The European Commission. Directive of 2009/72/EC Concerning Common Rules for the Internal Market in Electricity. Off J Eur Union 2009:55–93.
[71] The European Parliament, The Council of the European Union. Regulation (EU) 2019/943 of 5 June 2019 on the internal market for electricity 2019:54–124.
[72] Danish Government. Energiaftale af 29. juni 2018 2018:19.
[73] Finnish Government. Programme of Prime Minister Sanna Marin's Government 10 December 2019 2019.
[74] Norwegian Government. Norway's Climate Strategy for 2030: a transformational approach within a European cooperation framework 2017;41:252.
[75] Swedish Environmental Protection Agency. Sweden's Climate Act and Climate Policy Framework. Website 2019. http://www.swedishepa.se/Environmental-objectives-and-cooperation/Swedish-environmental-work/Work-areas/Climate/Climate-Act-and-Climate-policy-framework-/ (accessed January 20, 2020).
[76] Sipilä J, Jakobsdóttir K, Solberg E, Lövin I, Lilleholt LC. Declaration on Nordic Carbon Neutrality 2019.
[77] Nordic Council of Ministers. Roadmap for reaching the Nordic electricity market vision 2019.
[78] United Nations Framework Convention on Climate Change. Paris Agreement 2015.
[79] Skov A, Petersen JÅ. Dansk fjernvarme i 50 år: 1957-2007. Kolding, Denmark: Dansk Fjernvarme and Odense Stadsarkiv; 2007.

[80] Norsk Fjernvarme. Kort historikk. Nor Fjernvarme's Website n.d. https://www.fjernvarme.no/fakta/kort-historikk (accessed January 20, 2020).
[81] The World Bank. Energy imports, net (% of energy use) - Denmark | Data. IEA Stat 2014. https://data.worldbank.org/indicator/EG.IMP.CONS.ZS?end=2015&locations=DK&most_recent_year_desc=false&start=1960&view=chart (accessed January 20, 2020).
[82] Ministry of Commerce. Dansk energipolitik 1976 [Danish Energy Policy 1976]. Copenhagen: 1976.
[83] Rasmussen U, von Rosen W. Energiministeriet | Gyldendal - Den Store Danske. Den Store Danske n.d. http://denstoredanske.dk/Samfund%2C_jura_og_politik/Samfund/Ministerier%2C_styrelser%2C_udvalg_og_råd/Energiministeriet (accessed January 20, 2020).
[84] Nielson P. En hel Nielson. Rødovre: Sohn; 2011.
[85] Danish Energy Agency. Heat supply in Denmark, Who, What, Where, and Why. Copenhagen: 2005.
[86] Elsam. Decentrale kraftvarmeværker på markedsvilkår - teori 1 2002.
[87] Danish Government. Aftale om vindenergi og decentral kraftvarme mv. [Agreement on wind energy and decentralised CHP etc.] 2004.
[88] Energinet. Forskrift C1: Vilkår for balanceansvar [Regulation C1: Conditions for balance responsibility] 2016:1–27.
[89] Danish Energy Agency. Projektbekendtgørelsen [Announcement on approval of projects for collective heat supply]. Denmark: 2018.
[90] Frederiksen M, Østergaard M, Olsen Dyhr P, Skipper P. Politisk forståelse mellem Socialdemokratiet, Radikale Venstre, SF og Enhedslisten: Retfærdig retning for Danmark 2019.
[91] The Danish Parliament. Energy Agreement of 29 June 2018 2018:1–19.
[92] Danish District Heating Association. CO2-neutral fjernvarme i 2030 [CO2-neutral DH in 2030] 2019.
[93] The Danish Council on Climate Change. Kendte veje og nye spor til 70 procents reduktion [Known pathways and new paths to 70 percent reduction]. Copenhagen: 2020.
[94] Nelder C. [Episode #81] – Principles of Energy Transition 2018.
[95] IEA. Renewable Heat Policies 2018.
[96] U.S. Department of Energy. Energy Efficiency and Energy Security Benefits of District Energy. Washington, DC: 2019.
[97] Obama B. Executive Order 13624 of August 30, 2012 - Accelerating Investment in Industrial Energy Efficiency. Pres Doc 2012;77:54779–81. doi:10.4324/9780203122273.
[98] Chittum A, Farley K. Utilities and the CHP Value Proposition. Washington, DC: 2013.
[99] Beck F, Martinot E. Renewable Energy Policies and Barriers. Encycl Energy 2004;5:365–83. doi:10.1016/B0-12-176480-X/00488-5.
[100] FERC. FERC: Industries - PURPA Qualifying Facilities. FERC Website 2020. https://www.ferc.gov/industries/electric/gen-info/qual-fac.asp (accessed March 15, 2020).
[101] DSIRE. Business Energy Investment Tax Credit (ITC). DSIRE Website 2020. https://programs.dsireusa.org/system/program/detail/658 (accessed March 16, 2020).
[102] DSIRE. Renewable Electricity Production Tax Credit (PTC). DSIRE Website 2018. https://programs.dsireusa.org/system/program/detail/734 (accessed March 16, 2020).
[103] Donalds S. Renewable thermal in state renewable portfolio standards. 2018.
[104] Painuly JP. Barriers to renewable energy penetration: A framework for analysis. Renew Energy 2001;24:73–89. doi:10.1016/S0960-1481(00)00186-5.
[105] Bøgh Pedersen K. List of content in DTU Findit - DTU Library. DTU Libr Website 2018. http://www.bibliotek.dtu.dk/english/servicemenu/find/about_dtu_findit/content/content_list (accessed February 14, 2019).
[106] Sovacool BK, Axsen J, Sorrell S. Promoting novelty, rigor, and style in energy social science: Towards codes of practice for appropriate methods and research design. Energy Res Soc Sci 2018;45:12–42. doi:10.1016/j.erss.2018.07.007.
[107] Creswell JW. Research design : qualitative, quantitative, and mixed methods

approaches. 4th ed. Thousand Oaks: SAGE Publications; 2014.
[108] Capuder T, Mancarella P. Techno-economic and environmental modelling and optimization of flexible distributed multi-generation options. Energy 2014;71:516–33. doi:10.1016/j.energy.2014.04.097.
[109] Cochran J, Miller M, Milligan M, Ela E, Arent D, Bloom A. Market Evolution: Wholesale Electricity Market Design for 21 st Century Power Systems. Golden: 2013.
[110] Grøn Energi. The competitiveness of district heating compared to individual heating. Kolding: 2018.
[111] Trømborg E, Havskjold M, Bolkesjø TF, Kirkerud JG, Tveten ÅG. Flexible use of electricity in heat-only district heating plants. Int J Sustain Energy Plan Manag 2017;12:29–46. doi:10.5278/ijsepm.2017.12.4.
[112] Kirkerud JG, Bolkesjø TF, Trømborg E. Power-to-heat as a flexibility measure for integration of renewable energy. Energy 2017;128:776–84. doi:10.1016/j.energy.2017.03.153.
[113] Hedegaard K, Münster M. Influence of individual heat pumps on wind power integration - Energy system investments and operation. Energy Convers Manag 2013;75:673–84. doi:10.1016/j.enconman.2013.08.015.
[114] Golove WH, Eto JH. Market Barriers to Energy Efficiency : A Critical Reappraisal of the Rationale for Public Policies to Promote Energy Efficiency. Energy Environ 1996;26:66. doi:10.1177/0042098011427189.
[115] Detlefsen N. Specialregulering i fjernvarmen. Kolding: 2016.
[116] EWIS. European Wind Integration Study (EWIS) - EWIS Final Report-Appendix 3.1. 2010.
[117] IEA. Harnessing Variable Renewables: A Guide to the Balancing Challenge. Paris: International Energy Agency; 2011. doi:612011171P1.
[118] IRENA. Long-term modelling and tools to expand variable renewable power in emerging economies. 2017.
[119] Selecky J, Iverson K, Al-Jabir A. Standby Rates for Combined Heat and Power Systems. Montpelier: 2014.
[120] Eldrup A, Bendtsen B, Bjerregaard J, Frost Rasmussen J. Opråb fra varmesektoren: Grøn varme i 2030 er muligt, hvis regulering baseres på tillid - Altinget: forsyning. Altin Forsyn 2020. https://www.altinget.dk/forsyning/artikel/varmesektoren-groen-varme-i-2030-er-muligt-hvis-regulering-baseres-paa-tillid (accessed March 6, 2020).
[121] Danish Ministry of Finance. Manual in socioeconomic impact assessments 2017.
[122] Ib Larsen-udvalget. Moderniseret regulering i fjernvarmesektoren [Modernised regulation of the DH sector]. Copenhagen: 2015.
[123] McKinsey&Company, Struensee & co. Forsyningssektorens effektiviseringspotentiale [The utility sector's potential for increased efficiency]. 2016.
[124] Østergaard PA. Comparing electricity, heat and biogas storages' impacts on renewable energy integration. Energy 2012;37:255–62. doi:10.1016/j.energy.2011.11.039.
[125] Reneses J, Rodríguez MP, Pérez-Arriaga IJ. Electricity tariffs. London: Springer London; 2013. doi:10.1007/978-1-4471-5034-3.
[126] Skytte K, Bergaentzlé C, Rosenlund Soysal E, Olsen OJ. Design of Grid Tariffs in Electricity Systems with Large Shares of Variable Renewable Energy. EEM17, Eur Energy Mark 2017.
[127] Energylab Nordhavn. Recommendations and main results 2019.
[128] Euroheat & Power. District Heating and Cooling - Country by Country 2015 Survey. Brussels: 2015.
[129] World Commission on Environment and Development. The Brundtland Report: "Our Common Future." 1987.

Part II

SUBMITTED TO *RENEWABLE AND SUSTAINABLE ENERGY REVIEWS*

Barriers to flexibility in the district energy-electricity system interface – the (in)complete overview

Author

Møller Sneum, Daniel[*1]

1 = DTU Management, Sustainability Division, Produktionstorvet building 426, DK-2800 Lyngby, Denmark

Abstract

Sector-coupling, specifically flexibility in the interface between district energy (systems based on district heating and/or district cooling) and electricity systems has shown to be beneficial. The question is why, then, this flexible integration is not universally applied in district energy? By reviewing 100+ pieces of literature, this study identifies 40 barriers (and related solutions) to flexibility in the interface between district energy and the electricity system. Furthermore, a taxonomy is proposed for these barriers. While expansive, the taxonomy is inherently incomplete, as more barriers are likely to exist and develop. The primary barrier is *lack of signal-providing scheme*, which hinders signals of energy system needs to reach flexible DE systems.

Word count: 9 992

Keywords

Barriers

Cooling

Distributed generation

District energy

District heating

District heating and cooling

Flexibility

Heating

Integration

Microgrids

Renewable energy

[*] Corresponding author details, dasn@dtu.dk +4593511642.

Sector coupling

Smart energy systems

Solutions

Variable renewable energy

Abbreviations

BPC: Business process costs

CHP: Combined heat and power/cogeneration

Cogen: Cogeneration plant

DE: District energy (generation of electricity, heating and cooling)

DE-ESI: District energy-electricity system interface

ESI: Electricity system interface

HP: Heat pump

NEITPU: Non-electricity interfaced thermal producing unit (typically a natural gas or biomass boiler for heating or chiller for cooling). Used instead of the more commonly applied term ”heat-only boiler”, to encompass cold as well, and to clearly exclude electric boilers.

PTH/C: Power to heat/cold

TS: Thermal storage (typically a cold/hot water heat accumulator)

(V)RE: (Variable) renewable energy

1 Introduction

The challenge of flexibility in the district energy-electricity system interface (DE-ESI) is to establish the right balance between the molecules in the thermal grid and the electrons in the electricity grid. This study identifies the barriers for working towards this balance.

1.1 Problem statement

IEA [1] and many others [2–5] have outlined the need for flexibility in energy systems when integrating more variable renewable energy. Coupling of district energy (DE - local plants and distribution grids for cold and heat) and electricity, is a measure for improving overall energy- and economic efficiency [1,6,7]. Among the benefits can be counted the ability to use the least cost technologies to satisfy energy demands [3], resilience [8,9] and the ability to flexibly balance and integrate the electricity production from variable renewable energy (VRE) [10].

Despite this, DE is not necessarily fully integrated nor flexible under real-world conditions (e.g. Baltics [11], Germany [12], UK [13]), due to identifiable and addressable barriers.

An absence of systematic identification, characterisation and categorisation of barriers to flexibility in the DE-ESI entails a research gap. Closest to filling this gap are

- IEA’s review of barriers to cogeneration and DE [10]

- IEA and NREL's structure for flexibility of *what* (hardware and infrastructure), *how* (market, policy and regulatory frameworks) and *who* (institutional roles and responsibilities) [14]
- The reviews of barriers for flexibility of DE in the Nordic and Baltic countries by Skytte et al. [15] and Sneum et al. [11,16,17]

The research gap can be closed with a taxonomy for barriers to flexibility in the DE-ESI, useful for research, policy making and at plant level.

1.2 Research questions

With the taxonomy as a useful measure to structure barriers to flexibility in the DE-ESI, the question then is how it can be defined, reviewing literature for

- categories of barriers?
- barriers themselves?

Additionally, what the solutions are to the identified barriers?

2 Methodology

2.1 Literature review

The study is built upon a narrative review, as defined by Sovacool et al. [18]: "*to synthesize insights from a variety of perspectives and disciplines, or areas where insufficient data exists to conduct a systematic review or meta-analysis*".

To identify barriers and their categories, the review surveys literature in areas which include (or overlap with) flexibility in the DE-ESI: flexibility, demand response, DH and DE, renewable heat and distributed generation.

2.1.1 Narrative review

The narrative review produced an array of literature from internet searches, own archives, energy institutions' databases of literature and references in already-identified literature.

Since narrative reviews are based on the eyes that see, an inherent weakness in this methodology is in defining which categories, barriers and solutions to include. The narrative review offers no stringent reply to this, other than to see this study as a first contribution to a field of so far limited coverage. Thus, with this study comes an open invitation to peers, warmly welcoming any suggestions and additions to the taxonomy.

2.1.2 Expert review

Methodological triangulation has been applied to mitigate the shortcomings of a narrative review. Concretely, by requesting 12 energy experts to comment on the initial review. Of these, 9 experts responded with feedback - Table 1.

Table 1 Experts providing feedback to initial review. For names and affiliations, please see Acknowledgements. Parenthesis indicate no response within deadline.

NAME	ACADEMIA	ENERGY AUTHORITY	INDUSTRY	INTERGOVERNMENTAL ORGANISATION	TRANSMISSION SYSTEM OPERATOR	UTILITY
Aalborg University (two	X					

experts, one responded)						
Danish Board of District Heating			X			
Danish Energy Agency (two experts, one responded)		X				
Danish Energy Association			X			
Energinet					X	
Green Energy			X			
(IEA - two experts, neither responded)				X		
(iEnergi)			X			
International District Energy Association			X			
Norwegian University of Life Sciences	X					
(NW Natural)						X
Ørsted						X

Expert feedback foremost included comments to the framing of the study, i.e. clarity; not content. These comments were accommodated, e.g. elaborating that the study was not about barriers to DE, but to *flexibility* of DE. Second, two ([19] and [20]) references were suggested and added to the study. The expert feedback is neither an approval nor a kind of contribution that can hold the experts responsible for any contents in this study; this responsibility rests fully on the author, including any mistakes that may be.

2.2 Definition of flexibility

Flexibility has many definitions. Common for many of these is that they assign an *ability* to an *asset* in the energy system within a given *time-frame* [1,14,20–23], e.g. short term operational response by generation or demand in the electricity system. *Flexibility* is in this study understood as the ability to respond to external signals (sub-hourly and upwards) by technologies capable of electricity demand or generation in the DE-ESI. This definition aligns with definitions by Nuytten et al. [24], Andersen and Østergaard [25] and Sneum et al. [17].

2.3 Definition of a flexible district energy system

The term district energy is by some [26–29] used interchangeably with the term *district heating and cooling*, i.e. systems generating and distributing heating and cooling. Adding to this definition, the generation and use of electricity is included by others [30,31]. DE is thus in this study defined as local energy systems based on thermal networks, with the ability to generate and consume any combination of heating, cooling and electricity. Size of plants and scale of systems range from small-scale industry/consumer clusters, over town-size to large-scale metropolitan systems. Common for all DE systems are that they are geographically confined, due to the loss-induced limitations of transporting thermal energy in pipes. This is an important difference from the electricity system's ability to transmit electricity across continents.

Figure 1 illustrates a flexible DE plant, responding to signals of either renewables-share (top) and/or electricity prices (bottom - in Denmark, both situations regularly apply simultaneously).

1. High electricity prices; low VRE share. Cogeneration supplies heat and electricity
2. Medium electricity prices; medium VRE share. TS (or other source) supplies heat
3. Low electricity prices; high VRE share. PTH consumes electricity and supplies heat

Cost drivers other than pure electricity cost play a role in the dispatch of a plant. One such is *spark spread*, i.e. the gross margin between revenue from sold electricity compared to cost of fuel for generating that electricity. This study concerns flexibility in the DE-ESI, i.e. flexibility regarding use and generation of electricity; not flexible use or generation of fuels such as natural gas.

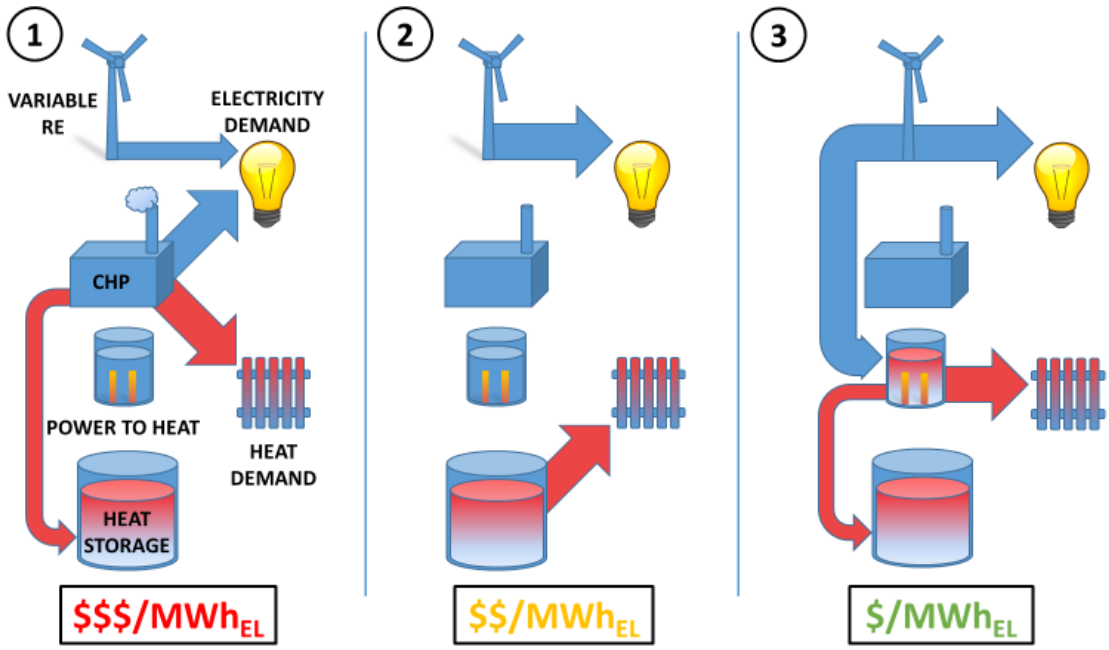


Figure 1 Three operational modes of the flexible DH plant. Own illustration based on [1] *and* [32].

2.4 Definition of barriers

In dictionary form, a barrier is "*A circumstance or obstacle that keeps people or things apart or prevents communication or progress*" [33]. Within energy efficiency, Sorrell et al. [34] defined a barrier as: "*a mechanism that inhibits a decision or behaviour that appears to be both, energy efficient and economically efficient*". Disregarding the energy efficiency perspective, the definition is useful in its brevity – encompassing decisions and behaviour. The term *mechanism* is in this study expanded to the broader *framework condition*. Thus, a barrier in this present study is considered a framework condition that inhibits a function, decision or behaviour that promotes flexibility in the DE-ESI.

As exemplified by Demsetz [35], defining barriers with outset in a narrow focus on insiders and outsiders in a market, omits other important barriers such as legal restrictions. Thus, in identifying barriers the attempt is to balance a comprehensive scope with the limitations of a practicable taxonomy.

Just like resilience or low-cost heat can be desired attributes of DE plants, so can flexibility – on societal and plant scale. If analysis on the societal scale indeed show that flexibility in the DE-ESI positively impacts society, while at the same time this is not reflected at plant-level, then there are split incentives, which should be addressed (Østergaard et al. [36] exemplifies this). The assumption in this study is that flexibility

in the DE-ESI is a desired attribute and that barriers should be identified and possibly addressed. While existence of DE systems is fundamental for any subsequent consideration on flexibility, this study is limited in scope to the barriers for flexible DE; not for DE broadly.

3 Developing the taxonomy for barriers to flexibility in the DE-ESI

"[T]*he advantage of decomposition of a barrier into its elements is clarity on causes for presence of a barrier.*" [37]. A taxonomy of barriers to flexibility in the DE-ESI is developed to do exactly that. This initially allows identification of the barrier; subsequently solutions to overcome the barrier. The taxonomy is developed by

- 3.1.1: definition of characteristics applying generally to relevant barriers
- 3.1.2: review-based identification of barrier-categories
- 3.2: review-based identification of barriers and solutions for flexibility in the DE-ESI

3.1 Taxonomy structure

3.1.1 Characteristics of barriers to flexibility in the DE-ESI

Three common characteristics apply to all identified barriers: *Type of technology* affected by the barrier, when in the *project life cycle* the barrier affects and the barrier's *origin*.

3.1.1.1 Technology type

Different technologies can be impacted by barriers regarding flexibility in the DE-ESI. These include cogeneration, electric chiller, heat pump (HP), electric boiler, non-electricity interfaced thermal producing unit (NEITPU – e.g. a gas boiler) and thermal storage (TS). Aggregated into four: cogeneration, power to heating/cooling (PTH/C), NEITPU and TS. This selection is in line with IEA [10] and Lund et al. [2]: "*combining different technologies in a CHP plant (e.g. gas engines, heat pumps, heat storage, peak-load gas boilers, electric boiler) could increase the inherent flexibility*". Here, supplemented with the equivalent cold side.

When *Technology type* includes the non-grid connected technology NEITPU, it is because this is the main competitor to cogeneration and PTH/C. Finally, while TS is not a generation technology, it is crucial in enabling flexibility by low cost storage [38].

3.1.1.2 Project life cycle

Project life cycle describes the phases in the life of a DE system, from the initial idea to the point where the DE system is retired

1. Requirements specification
2. Scoping/pre-feasibility study
3. Feasibility study
4. Tendering and construction
5. Operation
6. Decommissioning

The first four phases can be aggregated into the *investment phase*, determining if the technology will be physically available. Subsequently, the *operation phase* explores whether the technology operates as flexibly as desired. This definition bears elements from Rao et al.'s [28] definition of a lifecycle for deployment of DE and IEA's [10] for cogeneration and DE. Whereas e.g. operation will already be

considered during the early phases, the barriers are assigned to the conceptually closest phases in the taxonomy (section 4) – in this case *Operation*.

3.1.1.3 Level of origin

Cagno et al. [39] apply two overall categories of barriers: Internal and external. Expanding on this and on Sandberg et al. [40], six levels of origin are applied

1. Service and technology providers
2. Plant
3. Local
4. Regional
5. National
6. International

3.1.2 Categories of barriers to flexibility in the DE-ESI

Categories are the second dimension of the taxonomy. These are identified, by reviewing barriers and categorisations within other fields of energy where barrier-studies have been conducted

1. Operation signalling
2. Investment
3. Permitting
4. Ownership
5. DE technology conditions
6. Grid access
7. Physical environment
8. Bounded rationality
9. Commitment

3.1.2.1 Operational signalling

Flexible technologies need signals in order to respond. Barrier-impacts can be dampening/removing signals entirely or skew the playing-field between technologies, whereby the flexible technology becomes less attractive. Operational signals are typically provided by electricity markets [1,37,39,41–49], but also environmental dispatch signals can be applied [40]. The level and structure of taxes on operation [29,41,49–54] and tariffs can potentially impact the degree of level playing-field or signals [43,49,50].

3.1.2.2 Investment

Both Collier [55] and Sandberg et al. [40] define *economy* as one of two overall barrier categories regarding heating (*"economic/non-economic"* and *"economic/other"*). In this study, economy is subdivided into different categories, where this section addresses investment. Investment incentives can be impacted by limited access to capital [29,37,39,41,44,45,47,53,54,56–58], subsidies for competing technologies [50,53], cost of capital and risk-related issues [34,37,46,51,52,54], where subsequent requirements on pay-back time, discount rate or internal rate of return can influence the investment decision [34,37].

3.1.2.3 Permitting

"[I]*f a cost-effective measure conflicts with existing codes or standards, its implementation will be difficult or impossible*" [45]. Projects typically undergo a permitting phase, before they are installed and operated. Permitting relates to technology bans and mandates [37,45,50], spatial planning and siting [43,49]. Another aspect is the process of permitting itself, where the duration [47], consenting and licensing process during the project life cycle can impact the project [51], e.g. by outdated and inadequate regulation [44,54].

Permitting is here considered a subset of the broader term *regulation* (regulation as a term is addressed in 5.5).

3.1.2.4 Ownership

Whereas ownership may not be an issue in an energy system largely comprised of professional generators, the decentralised character of smaller DE makes this subject relevant. Ownership and taxation can influence decisions on operation and investment, since expenditures can be treated differently depending on the applicable tax code [58].

3.1.2.5 DE technological conditions

In the investment phases, technological conditions deal with technology types, their associated costs and maturity, while they in the operation phase relate to the technical ability to operate flexibly. Adjustability (span between minimum and maximum generation level), ramping (the speed at which generation can be changed) and lead time (the advance notice required to be available) is based on IEA's [1] definition of flexible operation. A fundamental challenge is if the technology is adequate to satisfy the desired operational capabilities [39,48,57]. The pure/endogenous cost of procurement impacts the choice of technology [39,52]. Desired capabilities of the technologies might come at a cost, either because the capability is bundled with other options, or because a trade-off is necessary between flexibility and other desirable features [59]. Different technological options can entail different costs in the daily operation (known as business process costs, indirect costs or soft costs), e.g. "*legal, accounting and other financial costs, as well as overhead and administrative costs*" [60]. The supply chain may be lacking [51] if workforce [54,58] or suppliers are under-developed [39]. The ability to meter, control and communicate with the technologies may be limited [58] and lack standards and procedures [44]. When technologies connected to the grid are "*not fully visible or controlled at the system level, and most have no economic incentive to respond to either system level or more local distribution level flexibility needs*" [7], they fail to bring the potential benefits of integration in the system. Finally, water as an energy transport medium is a major enabler for flexible DE, since water is easily stored in TS. Steam-based DE is considered 1st generation technology, while liquid water is used in more modern generations 2 through 4 [61].

3.1.2.6 Grid access

Grid infrastructure is a necessity for grid-connected technologies. Constraints can lie within the availability and capacity of this infrastructure [37,44,51,52,58], costs of connecting to the grid [47], and the related grid codes determining a framework for operation [62].

3.1.2.7 Physical environment

IRENA [29] points out that resource availability is essential; access to fuels, ambient temperatures or other energy sources needed for DE generation. Physical availability of land can be determined by impacts on the natural environment and ownership of physical premises [41,43,56].

3.1.2.8 Bounded rationality

Organisations and individuals make decisions under bounded rationality. Awareness of optimal solutions according the priorities of the organisation can be limited [44,54], caused by lack of information and knowledge [34,39,46,51,52,54,57]. Capability to include unknown technologies as an alternative in new projects can be limited [56], caused by constraints on time and ability to process information [34,46], and by lack of trust [48,50].

3.1.2.9 Acceptance

The same actors as mentioned above (3.1.2.8) can have varying degrees of acceptance to address conditions for flexibility in the DE-ESI. The social license to operate is thus granted by the stakeholders.

While an actor can have the knowledge and capabilities to address an issue, the interest in doing so is determining the further progress. In some cases, actors can even have incentives for maintaining status quo [45]. Firstly, there must be certain degree of value [45,54,58], status [39], interest [39,54] and priority [57] for the problem. This in turn leads to a commitment to address the problem, e.g. by addressing additional workload [57], decision-making power [58], culture [37], inertia, customs [50] and behavioural patterns. [45,54].

3.1.3 Taxonomy structure: Characteristics and categories combined

The overall taxonomy structure with a set of common characteristics and categories is seen in Table 2.

Table 2 Taxonomy structure indicating how barriers are characterised *and* categorised.

Characteristic / Category	Technology type	Project life cycle	Level of origin
Operational signalling			
Investment			
Permitting			
Ownership			
DE technology conditions			
Grid access			
Physical environment			
Bounded rationality			
Acceptance			

3.2 Identification of barriers for flexibility in the DE-ESI

While the previous section defined a taxonomy structure, this section identifies specific barriers to flexibility in the DE-ESI. The scope of the study necessitates brevity within each category, which will perhaps frustrate experts in the individual categories. Bear in mind that this study attempts exactly to be broad, enabling an overview of the field.

Barriers are identified in literature and referenced in the text. Solutions are mostly referenced, but in some cases, the author infers and proposes solutions without references to literature.

3.2.1 Barriers: Operational signalling

3.2.1.1 Dispatch signals

3.2.1.1.1 Absence of signal-providing scheme

Evidently, responding to signals requires the existence of a signal-providing scheme. Such scheme is typically an electricity market, where physical and financial products are traded among actors. Such markets can be considered absent for DE, in case they do not reward flexibility from cogeneration and DE [10], e.g. if electricity services are covered by a vertically integrated utility (companies where transmission, distribution and supply are bundled within the same utility, e.g. south-eastern US), in contrast to competitive markets with multiple suppliers (e.g. north-western Europe). No large-scale deployment of purely environmental dispatch signals has been identified (hybrid solutions exist, e.g. the EU Emissions Trading System and European power markets).

Solutions firstly include the establishment of a signal-providing scheme – market [10,14] or other. It can additionally be argued that the character of an electricity generating technology should be included to account for its reduced need for transmission and distribution, i.e. its locational value (locational-marginal-pricing) [63] or ability to provide system services [14]. In regions with vertically integrated utilities, performance-based regulation could include regulated return and incentives for the utility, depending on the integration (and flexible operation of) non-utility DE technologies.

3.2.1.1.2 Electricity market: Absence of flexibility-need (involatile prices)

Price volatility in electricity markets is necessary to incentivise a production-shift among technologies [64]. A saturated demand for flexibility (e.g. by overcapacity) can lead to limited price spreads in the market [65,66]. Related to the lack of volatility in prices is the level of prices. A generally low electricity price can disincentivise investment in, and flexible operation of, cogeneration [15,25,41,67]; vice versa for PTH [25,66,68–70].

Solutions in a well-functioning market must focus on the DE-level. This includes introducing flue gas cooling through heat exchangers and absorption HP to increase the efficiency of the cogeneration, subsequently lowering its bidding price on the electricity market [71]. Or over-dimensioning PTH/C units (e.g. based on winter load) to shift operation from baseload to become more price-responsive. This may come with a cost [36], 50-100% more expensive than not over-dimensioning [70]. Solutions to an imperfect market is a whole separate field of study. Regarding volatility, solutions include improving price-reflective signals by higher granularity geographically or temporally (e.g. bids based on minutes instead of hours) [1].

3.2.1.1.3 Electricity market: Fixed electricity prices

Fixed electricity prices remove the ability to respond to real-time signals [72]. End-consumers, such as industry, are typically subject to this through flat or seasonal prices [7,49,58,73]. For entities with both generation and consumption, such as a plant with cogeneration and PTH, an additional aspect can be low time-resolution (e.g. annual instead of hourly) net metering, which "*reduces the value of flexibility as the self-producer will not face the true value of the electricity and thus not have incentives to be flexible*" [73]. Solutions include introducing signals by shifting (part of) the fixed price to become variable. Additionally, shifting from net metering to real-time pricing is possible for DE systems.

3.2.1.1.4 Physical vs. financial dispatch: Must-run operation

Must-run operation reduces flexibility, regardless of technology. Dispatch according to physical contracts disregards flexibility needs [1]. Similarly, dispatching according to heat-demand (e.g. due to absence of TS) hinders DE response to signals [14,66], as seen in power plants in China [74,75] and in the Baltics through fixed-price must-take schemes for electricity from cogeneration [11]. Take-or-pay contracts (i.e. where the supplier and consumer agree to trade energy or pay a penalty) and maintenance contracts may lock plants into inflexible operation or put a limit on the amount of starts and stops [14]. Finally, uninterruptable thermal energy sources such as solar heating may limit the operation of cogeneration and PTH/C, if storage capacity or heat demand is insufficient to accommodate both [19].

Solutions (beyond introducing TS) can be to apply more advanced control strategies that take into account both heat demand and other signals [76]. Additionally, shifting from physical contracts to financial ones [1] can allow response to a larger set of signals, including interruptibility contracts with grid operators where operation can be interrupted under certain conditions [62].

3.2.1.2 Operational taxes and subsidies

3.2.1.2.1 Operational taxes on flexible DE

Taxes on the use of flexible DE technologies will reduce their competitiveness. Taxation on electricity use by PTH has been classified as a barrier in Denmark [41,62,75,77–79], Germany [80], the Nordics [15,81],

Norway [68], Sweden [69] and in general [29,66].
Solutions include adjusting the level of taxation to a point where the desired technologies are competitive or by applying production tax credits [82], provided that the tax credits are tied to requirements of flexible operation. Or even implementing dynamic electricity taxes, adjusted according to the electricity price [83].

3.2.1.2.2 Favourable operational taxes on NEITPU

Since the least-cost generation option is always chosen at economically rational plants, technologies on such plants compete internally. If a NEITPU, e.g. a biomass boiler, supplies cheaper heating, it will be dispatched. It can be problematic if flexible technologies are generally not competitive. This has been identified as a case in the Baltics [16,53], Denmark [41,79] and the Nordics [15,17].
Solutions for levelling the playing-field include levelling the playing field by levelling taxes for electricity and biomass for heating [79], e.g. by introduction of taxes on NEITPU, as suggested regarding fossil fuels vs. renewable fuels [55]. In Denmark fuel taxation in the 1980s was used to maintain an incentive for use of biomass, when the oil and gas prices dropped [38]. A similar approach could be taken regarding DE-ESI.

3.2.1.2.3 Inflexible operational subsidies for flexible DE

Operational subsidies can distort signals by dampening them or removing them entirely. This has been the case for feed-in-tariffs as seen in CHPs in Denmark in the 2000s [4,42], in Chinese CHPs [75], for renewables [2,62,84] and generation technologies broadly [73]. Subsidising through certificates, has in UK been disconnected from short-term signals [62].
Solutions include switching to signal-providing schemes such as feed-in-premiums; providing the subsidy as a capacity payment ensuring a certain income [40,42], directed towards renewable fuels for CHP and/or DE as tax exemptions; or green certificates. [40]. Green certificates are perhaps the best-known type of tradeable credits based on a desired technology. Another type of tradeable certificates is seen in Denmark, where HP have been included in the Danish energy savings agreement, enabling sales of energy savings credits deriving from the HP [85]. In another example, subsidies were from 1992 provided for deployment of small-scale CHP in Denmark, supplemented with a tax reduction from 2003 [38]. These examples show a shift in subsidies from the operational side to the investment-side, which avoid distortion of operational signals, as also indicated by Sandberg et al [40].

3.2.1.2.4 Operational subsidies for NEITPU

Whereas no references have been identified regarding operational subsidies (apart from tax-exemption, treated in 3.2.1.2.2) for inflexible resources, it is deducted from the notion that inflexible resources, such as biomass boilers, can potentially be subject to subsidies that reduce variable costs. Such reduction would decrease the relative competitiveness of flexible DE technologies.
Solutions could be to adjust or remove subsidy [86], according to social benefits and, possibly, giving equal subsidy status to other DE technologies.

3.2.1.3 Electricity grid tariffs

Like taxes, electricity grid tariffs can make PTH/C less competitive. Issues regarding volumetric tariffs (on MWh) have been identified for the Baltics [16], Denmark [77,78], Nordics [15,17,42,81,87], Norway [68], Spain [62] and DE broadly [66,88]. Furthermore, capacity tariffs (on MW) can have significant impacts on the incentive to operate PTH [16,17,87]. Utilities can charge for energy and its delivery in periods where the DE plant's internal production is insufficient on undesirable. This is the case with standby rates in US, which can be a barrier if the cost of rates outweigh the benefits of cogeneration [89], e.g. if standby charges are set according to an unlikely worst-case [90]. Finally, a case of tariff-induced unlevel playing field between technologies acting as electricity storages in different electricity areas: When Danish wind power is produced, it can be exported abroad or used nationally. A Danish DE must pay system- and local grid tariffs

to consume electricity in PTH and subsequently produce electricity with cogeneration. If exporting the wind power to Norwegian reservoir hydro, this is subject to significantly lower Norwegian grid tariffs. Exporting the stored electricity back into Denmark is not subject to tariffs due to market rules, making the cost of "storing" electricity lower through exports/imports than from local utilization. [91].
Solutions include time-of-use tariffs as a least-bad option, and ideally dynamic tariffs [40,83]. Capacity tariffs could be settled annually to avoid perverse incentives from shorter term arrangements (see [17] for further details). Finally, in cases where retail tariffs are bundled as generation, transmission and distribution, unbundling these could enable ability for operational optimisation according to signals provided by each tariff type [63].

3.2.1.4 Signal-related standards and procedures

"[C]*onnection and then sale of generation are two different requirements and it is important to overcome barriers to both*" [82]. The two following sections (3.2.1.4.1 and 3.2.1.4.2) deal with *market* access, while section 3.2.6 deals with the *grid* access.

3.2.1.4.1 Barriers for entry into signal-providing schemes

Typically, a signal-providing scheme will be an electricity market. Discriminatory entry requirements can impact technologies otherwise capable of offering flexibility and services [42,82], e.g. by strict regulation of third party access [92], high fees for review and inspection [63], or limitations in ownership [14]. Such friction can stem from unprepared market- and regulatory frameworks, as seen in some cases of renewable heating and cooling [29], conflicts of interest in setting regulatory framework [14] and restricted market participation of DE resources [93].
Solutions include reducing transaction costs of market access (especially relevant for small generators) and removing third party access barriers regarding technology types and capacities [14].

3.2.1.4.2 Barriers for operation in signal-providing schemes

The potential for flexibility may be under-utilised with inadequate market design [2,94]. Either if the market insufficiently values electricity sales from cogeneration [10] or flexibility [58], or if participation is limited [4]. Such rules could be minimum bid sizes, high trading fees or just the sheer resources required, in order to be continuously active on a market [62,73]; all elements which are pertinent to DE due to the sometimes limited size in capacity and administration. Complexity of participation in markets can increase when there is an absence of similar regulatory frameworks among markets [95], or if the regulatory framework hinders the participation of certain actors (e.g. aggregation of flexible load) [14,65].
Solutions should follow the principle of "*fair and appropriate remuneration for all assets that can provide flexibility to the power system*" [14]. This include clearer market products [1,74]; reducing the minimum bid size as e.g. done by the Federal Energy Regulatory Commission for distributed energy sources [93]; or reduction in transaction costs by introducing aggregators as a one-stop-shop for resources not able or willing to be independently active on the market [14]. The role of aggregators can be similar to the balance responsible parties seen in the Nordics [62,73].

3.2.2 Barriers: Investment

3.2.2.1 Investment subsidies for NEITPU

NEITPU, such as biomass boilers, can be subject to subsidies that reduce investment costs. As an example, Beck and Martinot for renewable energy in general lists "*direct budgetary transfers, tax incentives, R&D spending, liability insurance, leases, land rights-of-way, waste disposal, and guarantees to mitigate project financing or fuel price risks*" [63]. Such subsidies would decrease the relative competitiveness of flexible technologies.
Solutions – see 3.2.1.2.4.

3.2.2.2 Limitations in capital for flexible DE

Large upfront investment costs are common in DE projects, making access to capital an essential issue [10,29,55,58]. Limitations in access to debt can arise from "*lack of collateral, poor creditworthiness, or distorted capital markets*" [63] (see IEA [10] for details on financing DE).

Solutions include access to low interest, long term loans, as argued for 4th generation DH [61] and decarbonised DH [50,55]. Additionally, environmental benefits [10] and regulatory analyses could justify subsidies [55,82], such as capacity payments for flexible technologies [7], investment tax credits and loan guarantees [63,82], guaranteed payback of investment as seen for electric boilers in the 1980s in Sweden [69] or any of the listed types of subsidy in Section 3.2.2.1, as long as flexibility is a prerequisite. Finally, turnkey financing and development could be enabled through third-party ownership [60], e.g. an energy service company [55].

3.2.2.3 High risk premium for financing flexible DE

Risk in energy projects can be divided into economic, political, social and technical [96]. Here, risk relates to the uncertainties of future conditions for flexible DE technologies, especially the capability to deliver the desired return on investment. Investors may assign *"risks related to overall system performance, product quality and durability, manufacturer warranty viability, long-term fuel availability, future fuel price uncertainty, and availability of ongoing maintenance services*" [60]. Additionally, risks are encountered regarding uncertainty about future revenue, and the transferring of market risk to individual plants by becoming subject to market prices [10,58]. Risk aversive behaviour might mean that organisations prefer to maintain contracts of constant price for energy supply [62]. In this case, risk will only be minimised if procured goods (e.g. gas) and sold goods (e.g. heat) are both based on fixed prices – which is rarely the case. Conversely, if one varies according to market prices, risk is increased; if both can vary, risks are mitigated. A type of risk aversive behaviour that hinders innovation, is the adherence to traditional methods to maintain a safe return on investment [44]. Risk perception can be impacted by limited experience with a technology, which can "*increase required rates of return, result in less capital availability, or place more stringent requirements on technology selection and resource assessment*" [63]. An example could be a credit rating agency, which, unfamiliar with flexible DE technologies, reduces the credit rating of the DE investor. Electricity price uncertainty has been an issue for cogeneration participation in US demand response markets [97], for renewable energy [63] and for Danish DH plants [25]. Conversely, Energinet.dk [42] points out that risk among Nordic market participants to a larger degree stems from regulatory risk than from price volatility.

Solutions regarding risk include devoting resources to make credit-assessors understand projects [98]; mitigating insufficient investment incentive from market prices by support schemes [25]; mitigating technology-risk by subsidies for pilot projects [28,29,78,99]; and reducing regulatory risk through long-term policy targets [10,14,28,60,86], e.g. long-term energy and decarbonisation commitments [28,99]. Furthermore, long-term planning of DE projects can provide certainty of a customer-base, in turn reducing risk [10,100]. Finally, shifting ownership from the system host to a third-party could limit investment risk [60], but introduce price-risk of third-party supplied energy.

3.2.2.4 Internal limitations from pay-back time and internal rate of return/discount rate requirements

Required short pay-back times can challenge investments in flexible technologies. This has been seen within renewable heating and cooling – down to a six-month threshold [60]. Similar issues apply for discount rate requirements that may prohibit the typically more long-term projects with flexible technologies, as also seen for renewable energy in general [37]. Commercial operators have been referenced to apply a 10-20% discount rate for DH projects [101,102], which may limit investment compared to more moderate rates required under public/cooperative ownership [103] (e.g. 4% for DH in

Denmark).
Solutions include an initial evaluation of the need for the strict hurdle rates or thresholds. Additionally, elements which can increase certainty, e.g. public guarantees or subsidies for flexible DE projects could reduce the need for high thresholds.

3.2.2.5 Externally imposed limitations from regulated rate of return

For regulated utilities, rate of return restrictions can disincentivise investment in flexible technologies. I.e. by setting the allowed rate of return so low that investors are repelled – as e.g. argued against a Danish decision on 1.4-2.9 % [104].
Solutions include allowing cost-recovery for investments in flexibility measures [14] and identifying investors with modest rate of return-requirements.

3.2.3 Barriers: Permitting

3.2.3.1 Technology bans and mandates

Obligations to (not) use certain technologies can limit the array of options in DE [50], e.g. by providing priority access to non-flexible technologies such as waste incineration [11]. Forced use of technology (heat supply by cogeneration (§14) in large Danish cities), or forced use of fuel (natural gas (§22)) are examples in Danish legislation [105], precluding PTH [78]. Third-party energy supply can also be limited, as formerly in Denmark, where industrial PTH was kept from supplying heat to nearby DH grids [42].
Solutions include evaluating whether existing requirements provide a desirable energy system; if not, they should be removed or exchanged with a requirement of flexibility [78]. Command and control regulation could be applied regarding desired technologies (mandates) or undesired technologies (bans) [50,60], targeting flexible and NEITPU technologies. Additionally, having third-party access to supplying heat from flexible technologies [42].

3.2.3.2 Inadequate legal framework for evaluation of DE projects

The legal framework for certain technologies can be lacking or inadequate [63], e.g. complexities arising from the "*need to comply with both electricity and heat supply regulations*" [106]. This barrier covers a broad range and will be exemplified by a case. In Denmark, mandatory guidelines for the evaluation of DE projects include socio-economic assessment of energy projects and building codes. Regarding socioeconomic assessment, assumptions on especially electricity prices can impact the analysis. This can impact flexible technologies utilising either low or high electricity prices, where adhering to average prices could distort the picture regarding societal benefits of flexible DE.
Solutions include ensuring that flexibility benefits are reflected in feasibility studies [10], e.g. by implementing the option of variability in electricity prices as seen in the 2018-revision of the Danish guidance to socio-economic analysis of energy [107].

3.2.3.3 Friction in the permitting process

Complexity and uncertainty in permitting can dampen the desire to undertake projects. This has been shown for electricity storage [95]; HP [78]; for a cogeneration project where the process of crossing a road with a cable took two years and $150 000 in legal fees [98]; time and money cost regarding zoning and inspection [60]; complex and long-duration procedures for low-voltage connection for distributed generation [92]; spatial regulation and emission constraints [49]; unprepared regulatory frameworks [29]; unfamiliarity with the technology among authorities regarding siting and construction [63]; and administrative complexity for flexible resources in general [1], e.g. in the form of absence of possibilities to change permit, license or permit conditions for existing technologies.
Solutions include streamlining the permitting process [60,86], e.g. through guidelines [78] or by introducing thresholds (e.g. MW) under which projects are subject to less stringent permitting. Improved certainty

regarding timing of actions and decisions can help in the planning process [108]. More broadly, it is recommended that the revisions in regulation should encompass a broad energy system perspective, rather than e.g. the narrow smart grid perspective [61].

3.2.4 Barriers: Ownership

3.2.4.1 Tax- and ownership regulation disincentivising grid integration

Ownership and integration in the DE-ESI can be impacted by tax regulation. As example, in a microgrid in New York State, US, a cogeneration plant would make the microgrid subject to become a regulated utility (hereunder to taxation), if the cogeneration plant would feed electricity to an external grid or cross a public road with a cable [98]. Similarly, Danish electricity producers over 25kW (incl. cogeneration) are subject to company tax [109].

Solutions include adjusting regulation to accommodate special types of generators, e.g. universities; issuing waivers to the regulatory shift [98]; or making the new regulatory conditions sufficiently attractive by bespoke conditions for certain types or sizes of organisations.

3.2.5 Barriers: DE technology conditions

3.2.5.1 Limitations in adjustability, ramping and lead time

Technical factors might limit DE flexibility. For HP, ramping and cycling can be limited to avoid wear, and due to limitations in technical capability [69]. Flexible HP operation can also be limited by ambient temperature and by confined use within certain periods of the year [66]. For cogeneration wear can be an issue in ramping [66] and general changes in generation [73]. Solutions include improvement of minimum load (China: 30% - Denmark: 15-25%) and ramping rate (China: 1%/minute - Denmark: 4%/minute) for thermal power plants [74,75,110]. Furthermore, retrofitting cogeneration to enable shifting between backpressure and turbine bypass operation (temporarily increasing heat, while reducing electricity output) [38,64], by either stopping the turbine or letting minimum turbine load feed into a PTH unit.

3.2.5.2 High technological cost

While flexible DE technologies can be considered technologically mature, investment costs can still be substantial. This matter is encountered within renewable heating and cooling [60], flexible thermal power plants [72]; PTH [80,111]; cogeneration and DE [10]; and renewable energy in general [63,86]. Another matter is the pace of replacement of technologies, where older, inflexible assets might have lifetime left [1].

Solutions to address high technology costs include support for increased innovation [86,99] and subsidies or tax rebates [86].

3.2.5.3 High business process costs

Business process costs (BPC) are associated with the fixed costs of ownership of an asset. E.g. if flexible power plants have large amounts of personnel, in turn leading to high fixed BPC and thereby uncompetitiveness [14]. Beyond this, BPC are not well-described within flexibility in the DE-ESI, as is also the case within the similar field of renewable heating and cooling [60].

Solutions include providing clarity regarding the context-specific BPC among alternatives, to improve the foundation for informed investment decisions. Digitalization can be a measure to improve asset management, with BPC as a subset [112].

3.2.5.4 Low supply chain maturity

The DE supply chain can be subject to barriers regarding availability of trained installers [55]; local contractor base and skills of actors [58,63], e.g. limitations in New York of skilled technicians for heating and cooling [113]; inventory replenishment and availability [60].

Solutions include long-term policies to allow the supply chain to grow [55], e.g. by facilitating recruitment in relevant industries [63]. This process takes time [14]. Furthermore, support for establishing human competencies [55,86,113] and for one-stop-shops. The long-term policy could apply push-pull mechanisms: push for establishing flexible technologies; pull among contractors etc. to obtain sufficient competencies.

3.2.5.5 Limitations in control and visibility

Flexibility in the DE-ESI depends on the ability to monitor, control and validate performance. Barriers can be lack of standards on the functionality and communication protocols of smart meters [62]; lack of overall information and communication infrastructure [72]; communication standards [58]; proven control- and communication software [48] and cost [1].
Solutions encompass a standardised and secure communication infrastructure between the signal provider and the DE unit [7,44,58]; smart meters for flexible resources [73], requiring other efforts to estimate operation in lieu of direct metering [93], and standardisation regarding access to data [58].

3.2.5.6 High-temperature systems

Liquid water based DE systems have a large potential for flexibility, particularly due to the ability to store energy as sensible heat in liquid water contained in TS [114,115]. Despite this, steam-based systems are still seen, e.g. on Manhattan in New York [61]. HP efficiency increases if the temperature increase from the heat source to the heat demand is small. Applying high-temperature DE (>70 C) in areas where heat sources are of significantly lower temperature (indeed, the case most places in Europe [116]) can thus limit the efficiency of HP, and thereby the incentive for this technology [116,117].
Solutions include modernisation of networks [10], especially when old steam-based systems are due to retire [61]. Policy priority could be directed to convert such systems to low temperature systems with TS.

3.2.6 Barriers: Grid access

3.2.6.1 High grid-connection cost

Whereas 3.2.1.4 dealt with access to the electricity *market*, this and the following section deals with access to the electricity *grid*. High connection charges for coupling of an asset to the grid can be prohibitive for new entrants [29,62,73,92,95,106], such as cases where DE is price-categorized on unequal terms with otherwise comparable grid connected technologies (so-called third degree price discrimination).
Uncertainty regarding duration of processing and cost of connection add risk in the planning for wind projects [118] and for CHP [106].
Solutions should improve non-discriminatory interconnection [63], e.g. by socialising the cost of cable length to accommodate for different geography [119]. Interruptible grid connection agreements (non-prioritised tariffs), where the grid operator can interrupt PTH/C-load is also a way to avoid paying twice for consumption and production connection, as seen in e.g. Denmark [120], Norway and Sweden [17].
Connection cost of DE could also be reduced if DE reduces grid costs [83], e.g. by lowering local peak demand [121].

3.2.6.2 Limiting grid codes

Connection rules can create barriers by inconsistency and non-transparency [10]; by limitations on bi-directional power flows (consumption and generation) due to absent regulations for buy-back of electricity fed to the grid, or by network protection rules [48]. Additionally, generators accessing the grid can face high transaction costs of hiring legal and technical advice [63].
Solutions include policies for standardised interconnection agreements [10,63], e.g. by applying performance-based regulation for grid operators to incentivise expedient connection [122], and by regulatory clarification regarding bi-directional flows of electricity from DE [10]. Additionally, grid codes can be applied as a measure to mandate minimum flexibility criteria of connected technologies, e.g. seen for ramp rates etc. in Denmark [74].

3.2.6.3 Limiting grid capacity

Sometimes, the grid can be a constraint, in case the capacity is insufficient in servicing the needs in the DE-ESI. This has been seen for distributed generation [92] and regarding RE in DE [29].
Solutions include initially considering whether smart use of grid along with flexible DE mitigates the problem. Subsequently, mapping grid constraints and geographically placing technologies according to these, or to create incentive for an upgraded grid with enough capacity. In addition, a right to connect can be introduced as seen in e.g. Danish and Norwegian legislation [123,124].

3.2.7 Barriers: Physical environment

3.2.7.1 Limited access to energy sources

Flexible technologies are dependent on energy sources to operate. HPs need heat sources and cogeneration needs fuel. Resource availability and resource-based constraints are related to the availability and assessment of resources available [29,86], such as heat sources [117].
Solutions include mapping of resources together with existing or potential plants [29,77,86].

3.2.7.2 Land availability

The desired technologies can take up more space than alternatives [55,111], urban environments can be constraining [29,111], and land use can generally be limited by competition with "*agricultural, recreational, scenic, or development interests*" [63]. Available space for TS can be a concern [125], increasing with the scale of the storage, where large seasonal storages may be more difficult to situate.
Solutions include integrating technologies during renovation projects [55] and in planning during new infrastructure developments.

3.2.8 Barriers: Bounded rationality

3.2.8.1 Limitations from organisational bounded rationality

Bounded rationality is here applied as a term encompassing several sub-elements described in this section. Absence of awareness [55,60] on the possibility for flexibility in the DE-ESI is a primary barrier. Even when awareness is established, knowledge and experience can be limited as seen regarding e.g. TS in China [74]; in general regarding district energy [28]; regarding own potentials for offering services to the grid [58]; regarding benefits of CHP [10]; and regarding potential environmental and financial benefits [48]. Lack of knowledge can be universal, but gaps can also be geographically distributed as e.g. argued regarding discrepancies in knowledge on DE between US and Europe [126]. Knowledge impacts trust and confidence, which can be lacking among stakeholders [55] due to unclear benefits or lack of recognition of benefits [95], low credibility [58] or poor past performance [63]. Lack of trust can result in reluctance to allow third parties to control flexible technologies [58].
Solutions include increasing awareness and knowledge through information provision [14,55,58,86,99], by campaigns [50], financing of feasibility studies [37] or capacity building schemes [28]. The latter may be particularly relevant in cases where the organization is constrained in size or capability, to deal with flexibility in the DE-ESI. Additionally, experience and trust can be increased by information exchange groups and pilot projects [78,86], certification and standards [55,63] and partnerships with experienced parties such as cities or utilities with similar projects [29]. Finally, bounded rationality among actors can on the operational side be bypassed technically, by automation of processes. Thereby decision-making is re-delegated and the human is out of the loop [58].

3.2.8.2 Limitations from community bounded rationality

DE can be dependent on a local community, as an off-taker of the thermal energy and stakeholder in the permitting process. For a local community, "*understanding the ultimate environmental and financial benefits of a microgrid can be very difficult*" [48].

Solutions include a well-managed process of information and dialogue, along with introduction of overall and local targets on environment, energy and economy [28,60].

3.2.8.3 Limitations from authority bounded rationality

Absent authority recognition of system-wide benefits has been seen for energy storage [95].
Solutions include the introduction of targets on environment, energy and economy, subsequently impacting authorities [28,60] by e.g. requirements on RE integration [50]. Furthermore, policymakers can generally engage with stakeholders, to "*strengthen technical, policy and institutional capabilities"* [14], which also applies regarding stronger inter-agency coordination [86].

3.2.8.4 Limitations from individual plant staff's bounded rationality

Individuals can be a decisive factor regarding flexibility in the DE-ESI. As phrased by Good et al. [58] regarding demand-response, the "[c]*ognitive capacity of an individual is naturally limited, which may mean that, even with the necessary information, they may not reach the optimal DR-related decision.*"
Solutions – see 3.2.8.1.

3.2.9 Barriers: Acceptance

3.2.9.1 Limitations from organisational acceptance

Lack of acceptance and priority can arise from the perception that DE is not the core business activity, e.g. in university microgrids or industry. Subsequently, that flexibility in the DE-ESI is also not a core business activity, and that associated opportunity costs are too large. [127]. Culture or values of the organisation can disregard economics of energy or environmental issues [58]. Risk is a significant part of acceptance to flexibility in the DE-ESI (treated in section 3.2.2.3). Organisational inertia is another aspect, where behaviour takes time to change, regardless of benefits [58]. Finally, adverse selection is relevant, e.g. if the organisation opts out of electricity market activity, due to concerns about being less informed – and thus likely obtain poor trades – than other actors on the market [58].
Solutions include mapping of organisational needs [86], to align information and company policies, subsequently reducing inertia. Adverse selection can be mitigated by allowing aggregators act as the organisation's well-informed agent on a power market.

3.2.9.2 Limitations from community acceptance

DE systems are subject to influence from the community, both the community covered by the DE network and outside the area. Informing about benefits and gaining the support among these actors can be challenging [48], especially if there is direct public opposition to certain flexible technologies [1], i.e. a lacking social license to operate.
Solutions – see 3.2.8.2.

3.2.9.3 Limitations from authority acceptance

There might be need of approval from several levels of policy makers and jurisdictions, before projects can be initiated. Negative perceptions on DE projects regarding monopoly supply or reputation can reduce the acceptance among authorities [28].
Solutions – see 3.2.8.3.

3.2.9.4 Limitations from incumbent acceptance

Flexibility in the DE-ESI introduces new actors and entails a shift in business models and structures [61], potentially as a direct competitor to the existing electricity supply industry [128]. This structural shift can be hampered by the asymmetry in access to capital and knowledge between incumbents and new entrants [61]. Barriers posed by incumbent utilities might be unintentional regulatory artefacts from earlier times, or deliberate obstruction tactics "*e.g. transmission or distribution system operators may claim a lack of*

capacity, charge excessive transport fees, delay access by long negotiations, litigation, and manipulation of price" [92]. Examples include limitation in US authorities' ability to plan for DE, due to the limited access to data from utilities [126]; limitations in use of the utility's installations for export of electricity (instead of just import); and the compensation paid for stranded technologies to utilities [98]. Utility cost recovery mechanisms can mean that their economic incentives are misaligned with the priority for access of new generators [52]. This is seen for especially regulated utilities [7,73]. Similar split incentives (i.e. where the benefits of the action do not fall on the stakeholder performing the action), are seen within demand response [58,65] and renewable heating [55].

Solutions include levelling the playing-field regarding knowledge among incumbents and new entrants, by facilitating organisation, consultancy and education [61]. Furthermore, regulation, can help reduce the issues related to split incentives. Especially by unbundling utilities and introducing aggregators [7] and by enabling third-party access to grids and markets [92]. Where unbundling, deregulation or third-party access is not desired, an intermediate solution is to introduce quotas or mandates similar to the US renewable portfolio standards [60,82], obliging utilities to integrate a certain share of capacity across the DE-ESI. Furthermore, introducing performance-based standards measuring the utilities on e.g. satisfaction among distributed energy resources as seen in New York, or measuring the quantities of providers and energy integrated [122].

3.2.9.5 Limitations from individual plant staff's acceptance

Individual acceptance can be hampered by absence of power bestowed on the individual charged with – or informed about – the shift away from the current situation [36]. An example can be that operational staff has identified potential savings, while high-level management is unwilling to support the project [60]. Solutions include empowerment of the individual decision-maker [58], restructuring organisational hierarchies and organisational targets on environment, energy and economy which facilitate the desired change [60]. Operator-preferences can be influenced by introduction of new norms or regulation [58].

4 Taxonomy of barriers to flexibility in the DE-ESI

Synthesising the taxonomy structure identified in section 3.1, and the barriers and their solutions identified in section 3.2, provides the taxonomy - Table 3. Within the project life cycle, all but phase 6 (Decommissioning) are represented.

Table 3 Taxonomy of barriers to flexibility in the DE-ESI. Project life cycle: 1 (Requirements specification), 2 (Scoping), 3 (Feasibility study), 4 (Tendering, construction and permitting), 5 (Operation). Level of origin: 1 (Service and technology providers), 2 (Plant), 3 (Local), 4 (Regional), 5 (National), 6 (International).

Category	Sub-category	Barrier name	#	Tech. type	Project life cycle	Level of origin
Operational signalling	Dispatch signals	Absence of signal-providing scheme	1	cogen + PTH/C	5	4-6
-	-	Electricity market: Absence of flexibility-need (involatile prices)	2	cogen + PTH/C	5	4-6
-	-	Electricity market: Fixed electricity prices	3	cogen	5	4+5
-	-	Physical vs. financial dispatch: Must-run operation	4	cogen + PTH/C	5	3-5
-	Operational taxes and subsidies	Operational taxes on flexible DE	5	cogen + PTH/C	5	4+5
-	-	Favourable operational taxes on NEITPU	6	NEITPU	5	4+5
-	-	Inflexible operational subsidies for flexible DE	7	cogen + PTH/C	5	4+5
-	-	Operational subsidies for NEITPU	8	NEITPU	5	4+5
-	Electricity grid tariffs	Electricity grid tariffs	9	cogen + PTH/C	5	3-5

-	Signal-related standards and procedures	Barriers for entry into signal-providing schemes	10	cogen + PTH/C	5	4+5
-	-	Barriers for operation in signal-providing schemes	11	cogen + PTH/C	5	4+5
Investment	-	Investment subsidies for NEITPU	12	NEITPU	2+3	4+5
-	-	Limitations in capital for flexible DE	13	cogen + PTH/C	2+3	2
-	-	High risk premium for financing flexible DE	14	cogen + PTH/C	2+3	2
-	-	Internal limitations from pay-back time and internal rate of return/discount rate requirements	15	cogen + PTH/C	2+3	2
-	-	Externally imposed limitations from regulated rate of return	16	cogen + PTH/C	2+3	5
Permitting	-	Technology bans and mandates	17	cogen + PTH/C	2+3	3-5
-	-	Inadequate legal framework for evaluation of DE projects	18	cogen + PTH/C	2+3	3-5
-	-	Friction in the permitting process	19	cogen + PTH/C	4	3-5
Ownership	-	Tax- and ownership regulation disincentivising grid integration	20	cogen + PTH/C	5	5
DE technology conditions	-	Limitations in adjustability, ramping and lead time	21	cogen + PTH/C	5	2
-	-	High technological cost	22	cogen + PTH/C	2+3	1
-	-	High business process costs	23	cogen + PTH/C	2+3	2
-	-	Low supply chain maturity	24	cogen + PTH/C	2-5	1
-	-	Limitations in control and visibility	25	cogen + PTH/C	5	1, 4-6
-	-	High-temperature systems	26	PTH/C + TS	5	2
Grid access	-	High grid-connection cost	27	cogen + PTH/C	2+3	3-5
-	-	Limiting grid codes	28	cogen + PTH/C	5	4-6
-	-	Limiting grid capacity	29	cogen + PTH/C	2+3	3
Physical environment	-	Limited access to energy sources	30	cogen + PTH/C	2+3	3
-	-	Land availability	31	cogen + PTH/C + TS	2+3	3
Bounded rationality	-	Limitations from organisational bounded rationality	32	cogen + PTH/C	1, 2, 3+5	2
	-	Limitations from community bounded rationality	33	cogen + PTH/C	3+4	3
	-	Limitations from authority bounded rationality	34	cogen + PTH/C	2-5	4+5
-	-	Limitations from individual plant staff's bounded rationality	35	cogen + PTH/C	1, 2, 3+5	2
Acceptance	-	Limitations from organisational acceptance	36	cogen + PTH/C	2-5	2
-	-	Limitations from community acceptance	37	cogen + PTH/C	3+4	3
-	-	Limitations from authority acceptance	38	cogen + PTH/C	2-5	4+5
-	-	Limitations from incumbent acceptance	39	cogen + PTH/C	2-5	3-5
-	-	Limitations from individual plant staff's acceptance	40	cogen + PTH/C	1, 2, 3+5	2

5 Discussion

5.1 Primary barrier: Signal-providing scheme

Barriers can be primary and ancillary [129]. The former is in itself a barrier, whereas the latter reinforces other barriers. DE systems and their framework conditions are inherently context specific (context specific impacts can be explored through past performance under the constraint of the barrier [130]). This means that an insignificant ancillary barrier in one DE system, may constitute a serious primary barrier elsewhere (e.g. electricity taxes affecting PTH/C). What unifies all barriers of this study, is the presumption that they hinder the flexibility of a DE system. Flexibility necessitates signals, which leads to the primary barrier: Absence of signal-providing scheme.

5.2 Internal and external competition

Flexibility in the DE-ESI must show better performance on lifecycle cost than the alternatives; a competition that is addressed in this section.

5.2.1 Internal competition: Cannibalisation

The ability to internally shift between generation technologies makes DE flexible, but can lead to cannibalisation among a plant's technologies, or "*discrepancy between substitutable goods*" [58]. Internal competitiveness is determined by marginal cost, and is in addition to the barriers described in 3.2, impacted by fuel prices [16,55,81]. This has been seen for NEITPU displacing HP [36], cogeneration displacing HP [69] and EB [29] and vice versa [87]. Cannibalisation is not a barrier per se, merely a consequence of commodity prices and ancillary barriers.

5.2.2 External competition: Electricity

External competition regarding electricity can be perceived as respectively structural and strategic barriers (discussed by West [130]). A structural barrier exists where even liquid and competitive markets have limited flexibility-need from DE. Either due to limited price volatility or to generally high/low price ranges. It can be explained by cost advantages of the incumbents [130], who can offer services to the market at a lower cost than the DE plant. Strategic barriers are raised by incumbents to limit access of new entrants to a market. Structural and strategic barriers can have similar impacts, but require different solutions.

5.3 Signals from many sources

While absence of signals is the primary barrier, the opposite situation also deserves mentioning. Signals existing simultaneously (e.g. market, grid tariffs and taxes), can distort, amplify or interact with each other.

5.4 Some barriers are also drivers for investment

Fixed electricity prices (3.2.1.1.3), must-run operation schemes (3.2.1.1.4) and inflexible operational subsidies for flexible resources (3.2.1.2.3) are drivers for investment in flexible technologies – and barriers for flexible operation. Whereas such drivers might be considered relevant in the very early phases of deployment, other measures that encompass flexibility should be applied instead.

5.5 Regulation: Dissecting an umbrella-category

Throughout the reviewed literature, *regulation* is a recurring category [29,37,39,44–49,51,52,54,57,58]. In this study it proved relevant to subdivide regulation into separate issues to increase detail in the taxonomy.

5.6 Common solutions

Many of the barriers identified can be perceived as policy and regulatory risks. Especially barriers related to investment, but also bounded rationality and acceptance. Long-term policies and targets can mitigate those risks. In addition to the solutions in 3.2, is research and development [7,29,86]. Another option is direct

regulation applying command and control solutions by government fiat. E.g. in the case of Denmark, where DE must prove a >1 500 DKK/year/consumer saving, to be allowed to choose a biomass boiler over PTH [131]. Common for all solutions are that they should correspond to the overall externalities and costs the barriers induce in the long term – i.e. levelling the playing field for DE to offer the right amount of flexibility in the ESI.

5.7 Further work

While this study has shed light on the subject on flexibility in the DE-ESI, further work within this field could shed light on areas outside the western world (literature mainly addresses western DE); consequences of implementing proposed solutions; expansion across energy sectors and quantification of barrier impact.

6 Conclusion

The purpose of this study was to define a taxonomy for barriers to flexibility in the DE-ESI: The structure (barrier characteristics and -categories) and the barriers themselves. Additionally, how these barriers can be addressed.

In the taxonomy, three main characteristics are assigned to each barrier: Technology type, project life cycle and level of origin. Each of the 40 barriers are placed within one of nine main categories. Concrete applications of the taxonomy will show, if there is redundancy among the barriers. Further, it is unlikely that all barriers will apply in a single project. This follows naturally of this study's catch-all approach. Although the list of barriers is expansive, as the title of this study modestly suggests, the taxonomy is inherently incomplete, as more barriers are likely to exist and develop over time.

The study built on review of literature, providing inputs to the categories, barriers and solutions. A common approach in the reviewed literature is a division into categories of regulation and/or economy. Whereas these categories certainly are relevant, this study applies a more detailed sub-division of categories.

The primary barrier is *Absence of signal-providing scheme* to induce flexible operation. Since DE projects are highly context-specific, the impact of barriers may vary. In all cases apply that if transaction costs are (perceived to be) too large, the threshold may be too large to engage with flexibility in the DE-ESI. That said, none of the barriers appear insurmountable.

Among the emerging patterns are the issue of competition: A flexible, integrated DE system is in competition – not only on the typical power market – but also through internal *cannibalisation* on the plant if e.g. a biomass boiler can supply heat at a lower cost than a HP.

As noted in the introduction of this study, striking the right balance between molecules and electrons in the flexibility of energy sectors is essential. The concretely applicable toolbox provided by this study, concretises the efforts to striking that balance.

7 Acknowledgements

This study has been conducted with generous support from The Otto Mønsted Foundation, P.A. Fisker's Foundation and Marie & M.B. Richters Foundation. The funding sources had no role in carrying out or designing the study. Furthermore, part of the research was conducted in the USA, with the warm hospitality of the Arthur L. Irving Institute for Energy and Society at Dartmouth College and its director, Professor Elizabeth Wilson. While all contents are the sole responsibility of the author of this study, an array of experts have been very helpful in providing comments. These include Anders B. Hansen, Energinet; Eli Sandberg, SINTEF; Laxmi Rao, International District Energy Association; John Tang, Danish Energy

Agency; Line Carlsen, Ørsted; Morten Duedahl, Danish Board of District Heating; Morten Stryg, Danish Energy Association; Nina Detlefsen, Green Energy; Peter Sorknæs, Aalborg University. The author is very thankful for these comments. Finally, the author wishes to thank Ole Jess Olsen for comments and generous sharing of historical and up-to-date knowledge.

[1] IEA. The power of transformation. Paris: IEA; 2014. doi:10.1007/BF01532548.

[2] Lund PD, Lindgren J, Mikkola J, Salpakari J. Review of energy system flexibility measures to enable high levels of variable renewable electricity. Renew Sustain Energy Rev 2015;45:785–807. doi:10.1016/j.rser.2015.01.057.

[3] Mathiesen B V., Lund H, Connolly D, Wenzel H, Ostergaard PA, Möller B, et al. Smart Energy Systems for coherent 100% renewable energy and transport solutions. Appl Energy 2015;145:139–54. doi:10.1016/j.apenergy.2015.01.075.

[4] Lund H. Technical Design of Flexible Sustainable Energy Systems. 2nd Dubrovnik Conf Sustanaible Dev Og Energy, Water Environ Syst 2003:1–10.

[5] Skytte K, Bergaentzlé C, Fausto F, Gunkel P. Flexible Nordic Energy Systems - Summary Report. Lyng: 2019.

[6] Lund H. Renewable Energy Systems. 2nd ed. Aalborg: Academic Press; 2014.

[7] Dragoon K, Papaefthymiou G. Power System Flexibility Strategic Roadmap - Preparing power systems to supply reliable power from variable energy resources. Berlin: 2015.

[8] Chittum A, Farley K. Utilities and the CHP Value Proposition 2013.

[9] Athawale R, Felder FA. Incentives for Combined Heat and Power plants : How to increase societal benefits? Util Policy 2014;31:121–32. doi:10.1016/j.jup.2014.10.005.

[10] IEA. Linking Heat and Electricity Systems: Co-generation and District Heating and Cooling Solutions for a Clean Energy Future. Paris: 2014.

[11] Sneum DM, Sandberg E, Soysal ER, Skytte K, Olsen OJ. Framework conditions for flexibility in the district heating-electricity interface. Lyngby: 2016.

[12] Sorknæs P, Lund H, Andersen AN, Ritter P. Small-scale combined heat and power as a balancing reserve for wind – The case of participation in the German secondary control reserve. Int J Sustain Energy Plan Manag 2015;4:31–42. doi:10.5278/ijsepm.2014.4.4.

[13] Toke D, Fragaki A. Do liberalised electricity markets help or hinder CHP and district heating? The case of the UK. Energy Policy 2008;36:1448–56. doi:10.1016/j.enpol.2007.12.021.

[14] IEA, NREL. Status of Power System Transformation 2018. Paris: 2018.

[15] Skytte K, Olsen OJ, Soysal ER, Sneum DM. Barriers for district heating as a source of flexibility for the electricity system. J Energy Mark 2017;10:1–19. doi:10.21314/JEM.2017.161.

[16] Sneum DM, Sandberg E, Koduvere H, Olsen OJ, Blumberga D. Policy incentives for flexible district heating in the Baltic countries. Util Policy 2018;51:61–72. doi:10.1016/j.jup.2018.02.001.

[17] Sneum DM, Sandberg E. Economic incentives for flexible district heating in the Nordic countries. Int J Sustain Energy Plan Manag 2018;16:27–44. doi:10.5278/ijsepm.2018.16.3.

[18] Sovacool BK, Axsen J, Sorrell S. Promoting novelty, rigor, and style in energy social science: Towards codes of practice for appropriate methods and research design. Energy Res Soc Sci 2018;45:12–42. doi:10.1016/j.erss.2018.07.007.

[19] Sorknæs P, Lund H, Andersen AN. Future power market and sustainable energy solutions - The treatment of uncertainties in the daily operation of combined heat and power plants. Appl Energy 2015;144:129–38. doi:10.1016/j.apenergy.2015.02.041.

[20] Hillberg E, Zegers A, Herndler B, Wong S, Pompee J, Bourmaud J-Y, et al. Flexibility needs in the future power system 2019.

[21] Cochran J, Miller M, Zinaman O, Milligan M, Arent D, Palmintier B, et al. Flexibility in 21 st Century Power Systems. vol. TP-6A20-61. Golden: 2014. doi:10.2172/1130630.

[22] Danish Energy Association, Energinet. Smart Energy - Hovedrapport [Smart Energy - Main Report]. Copenhagen: 2015.

[23] Ma J, Silva V, Belhomme R, Kirschen DS, Ochoa LF. Evaluating and planning flexibility in sustainable power systems. IEEE Trans Sustain Energy 2013;4:200–9. doi:10.1109/TSTE.2012.2212471.

[24] Nuytten T, Claessens B, Paredis K, Van Bael J, Six D. Flexibility of a combined heat and power system with thermal energy storage for district heating. Appl Energy 2013;104:583–91. doi:10.1016/j.apenergy.2012.11.029.

[25] Andersen AN, Østergaard PA. A method for assessing support schemes promoting flexibility at district energy plants. Appl Energy 2018;225:448–59. doi:10.1016/j.apenergy.2018.05.053.

[26] U.S. Department of Energy. Combined Heat and Power (CHP) Technical Potential in the United States. Washington: 2016.

[27] Euroheat & Power. District Energy Explained. Website n.d. https://www.euroheat.org/knowledge-hub/district-energy-explained/ (accessed April 8, 2019).

[28] Rao L, Chittum A, King M, Yoon T. Governance Models and Strategic Decision-Making Processes for Deploying Thermal Grids. 2017.

[29] International Renewable Energy Agency. Renewable Energy in District Heating and Cooling: A sector roadmap for REmap. Abu Dhabi: 2017.

[30] International District Energy Association. District Energy in Cities. Website n.d. https://www.districtenergy.org/topics/district-energy-cities (accessed April 8, 2019).

[31] District energy in cities initiative. What is District Energy? Website n.d. http://www.districtenergyinitiative.org/what-district-energy (accessed April 8, 2019).

[32] Connolly D. Finding and Inputting Data into the EnergyPLAN Tool. Aalborg: 2015.

[33] Oxford University Press. barrier | Definition of barrier in English by Oxford Dictionaries. Oxford Dictionaries n.d. https://en.oxforddictionaries.com/definition/barrier (accessed February 5, 2019).

[34] Sorrell S, O'Malley E, Schleich J, Scott S. The economics of energy efficiency. 1st ed. Cheltenham: Edward Elgar Publishing Limited; 2004.

[35] Demsetz H. Barriers to Entry. Am Econ Rev 1982;72:47–57.

[36] Østergaard PA, Jantzen J, Marczinkowski HM, Kristensen M. Business and socioeconomic assessment of introducing heat pumps with heat storage in small-scale district heating systems. Renew Energy 2019;139:904–14. doi:10.1016/j.renene.2019.02.140.

[37] Painuly JP. Barriers to renewable energy penetration: A framework for analysis. Renew Energy 2001;24:73–89. doi:10.1016/S0960-1481(00)00186-5.

[38] Danish Energy Agency. Regulation and planning of district heating in Denmark. Copenhagen: 2015.

[39] Cagno E, Worrell E, Trianni A, Pugliese G. A novel approach for barriers to industrial energy

efficiency. Renew Sustain Energy Rev 2013;19:290–308. doi:10.1016/j.rser.2012.11.007.

[40] Sandberg E, Sneum DM, Trømborg E. Framework conditions for Nordic district heating - Similarities and differences, and why Norway sticks out. Energy 2018;149:105–19. doi:10.1016/j.energy.2018.01.148.

[41] Hvelplund F, Østergaard PA, Meyer NI. Incentives and barriers for wind power expansion and system integration in Denmark. Energy Policy 2017;107:573–84. doi:10.1016/j.enpol.2017.05.009.

[42] Energinet.dk. Nordic Power Market Design and Thermal Power Plant Flexibility. Fredericia: 2018.

[43] Pérez-Arriaga IJ. Regulation of the Power Sector. 1st ed. Springer-Verlag London; 2013. doi:10.1007/978-1-4471-5034-3.

[44] Luthra S, Kumar S, Kharb R, Ansari MF, Shimmi SL. Adoption of smart grid technologies: An analysis of interactions among barriers. Renew Sustain Energy Rev 2014;33:554–65. doi:10.1016/j.rser.2014.02.030.

[45] Blumstein C, Krieg B, Schipper L, York C. Overcoming social and institutional barriers to energy conservation. Energy 1980;5:355–71. doi:10.1016/0360-5442(80)90036-5.

[46] Reddy S, Painuly JP. Diffusion of renewable energy technologies-barriers and stakeholders' perspectives. Renew Energy 2004;29:1431–47. doi:10.1016/j.renene.2003.12.003.

[47] González JS, Lacal-Arántegui R. A review of regulatory framework for wind energy in European Union countries: Current state and expected developments. Renew Sustain Energy Rev 2016;56:588–602. doi:10.1016/j.rser.2015.11.091.

[48] Soshinskaya M, Crijns-Graus WHJ, Guerrero JM, Vasquez JC. Microgrids: Experiences, barriers and success factors. Renew Sustain Energy Rev 2014;40:659–72. doi:10.1016/j.rser.2014.07.198.

[49] Bergaentzle C, Skytte K, Soysal ER, Boscan L, Olsen OJ. Regulatory barriers for activating flexibility in the Nordic-Baltic electricity market. Int Conf Eur Energy Mark EEM 2017. doi:10.1109/EEM.2017.7981948.

[50] Steinbach J, Popovski E, Fleiter T, Chassein E, Bedoya I. Policy recommendations to decarbonise European heating and cooling systems. 2017.

[51] Leete S, Xu J, Wheeler D. Investment barriers and incentives for marine renewable energy in the UK: An analysis of investor preferences. Energy Policy 2013;60:866–75. doi:10.1016/j.enpol.2013.05.011.

[52] Brown MA, Sovacool BK. Barriers to the diffusion of climate-friendly technologies. Int J Technol Transf Commer 2011;10:43. doi:10.1504/IJTTC.2011.038453.

[53] Bergaentzlé C, Skytte K, Soysal ER, Boscàn L, Olsen OJ, Lyngby D-. Regulatory barriers for activating flexibility in the Nordic-Baltic electricity market 2017.

[54] Mosannenzadeh F, Di Nucci MR, Vettorato D. Identifying and prioritizing barriers to implementation of smart energy city projects in Europe: An empirical approach. Energy Policy 2017;105:191–201. doi:10.1016/j.enpol.2017.02.007.

[55] Collier U. Renewable heat policies Delivering clean heat solutions for the energy transition. IEA Publ 2018.

[56] Meath C, Linnenluecke M, Griffiths A. Barriers and motivators to the adoption of energy savings

measures for small- and medium-sized enterprises (SMEs): The case of the ClimateSmart Business Cluster program. J Clean Prod 2016;112:3597–604. doi:10.1016/j.jclepro.2015.08.085.

[57] Olsthoorn M, Schleich J, Klobasa M. Barriers to electricity load shift in companies: A survey-based exploration of the end-user perspective. Energy Policy 2015;76:32–42. doi:10.1016/j.enpol.2014.11.015.

[58] Good N, Ellis KA, Mancarella P. Review and classification of barriers and enablers of demand response in the smart grid. Renew Sustain Energy Rev 2017;72:57–72. doi:10.1016/j.rser.2017.01.043.

[59] Golove WH, Eto JH. Market Barriers to Energy Efficiency : A Critical Reappraisal of the Rationale for Public Policies to Promote Energy Efficiency. Energy Environ 1996;26:66. doi:10.1177/0042098011427189.

[60] IEA-RETD. Waking the Sleeping Giant - Next generation policy instruments for renewable heating and cooling in the commercial sector (RES-H-NEXT). Utrecht: 2015.

[61] Lund H, Werner S, Wiltshire R, Svendsen S, Thorsen JE, Hvelplund F, et al. 4th Generation District Heating (4GDH). Integrating smart thermal grids into future sustainable energy systems. Energy 2014;68:1–11. doi:10.1016/j.energy.2014.02.089.

[62] Olmos L, Cossent R, Lobato E, Gómez T. Barriers to the implementation of response options aimed at mitigating the impact of wind power on electricity systems. Wind Energy 2011;14:781–95. doi:10.1002/we.439.

[63] Beck F, Martinot E. Renewable Energy Policies and Barriers. Encycl Energy 2004;5:365–83. doi:10.1016/B0-12-176480-X/00488-5.

[64] Levihn F. CHP and heat pumps to balance renewable power production: Lessons from the district heating network in Stockholm. Energy 2017;137:670–8. doi:10.1016/j.energy.2017.01.118.

[65] Eid C, Koliou E, Valles M, Reneses J, Hakvoort R. Time-based pricing and electricity demand response: Existing barriers and next steps. Util Policy 2016;40:15–25. doi:10.1016/j.jup.2016.04.001.

[66] Papaefthymiou G, Grave K, Dragoon K. Flexibility options in electricity systems. Berlin: 2014.

[67] Helin K, Zakeri B, Syri S. Is district heating combined heat and power at risk in the Nordic area?-An electricity market perspective. Energies 2018;11. doi:10.3390/en11051256.

[68] Trømborg E, Havskjold M, Bolkesjø TF, Kirkerud JG, Tveten ÅG. Flexible use of electricity in heat-only district heating plants. Int J Sustain Energy Plan Manag 2017;12:29–46. doi:10.5278/ijsepm.2017.12.4.

[69] Averfalk H, Ingvarsson P, Persson U, Werner S. On the use of surplus electricity in district heating systems. Proc from 14th Int Symp Dist Heat Cool Sept 6-10, 2014 Stock Sweden 2014:469–74. doi:10.3354/meps07474.

[70] Danish Energy Agency. Store varmepumper i fjernvarmeforsyningen [Large heat pumps in the district heating supply]. Copenhagen: 2016.

[71] de Wit J, Nagel K, Petersen AB. Der kan godt tjenes penge, selvom elprisen er faldet [Revenue is possible despite drop in electricity price]. Fjernvarmen 2017.

[72] Hu J, Harmsen R, Crijns-Graus W, Worrell E, van den Broek M. Identifying barriers to large-scale integration of variable renewable electricity into the electricity market: A literature review of market

design. Renew Sustain Energy Rev 2018;81:2181–95. doi:10.1016/j.rser.2017.06.028.

[73] SWECO. Study on the effective integration of demand energy recourses for providing flexibility to the electricity system. 2015.

[74] Clean Energy Ministerial. Thermal power plant flexibility. 2018.

[75] Danish Energy Agency. Flexibility in the Power System - Danish and European experiences. Copenhagen: 2015.

[76] Vandermeulen A, van der Heijde B, Helsen L. Controlling district heating and cooling networks to unlock flexibility: A review. Energy 2018;151:103–15. doi:10.1016/j.energy.2018.03.034.

[77] Siemens. Elektrificering af Danmarks fjernvarmesektor. Ballerup: 2018.

[78] Green Energy. Anbefalinger til markedsgennembrud for store varmepumper [Recommendations for market penetration of large heat pumps]. Kolding: 2018.

[79] Hvelplund F, Djørup S. Denmark: centralised versus decentralised renewable energy systems. In: Burger C, Froggatt A, Mitchell C, Weinmann J, editors. Decent. Energy A Glob. Game Chang. 1st ed., London: Ubiquity Press; 2020, p. 63–81. doi:10.5334/bcf.e.

[80] Ehrlich LG, Klamka J, Wolf A. The potential of decentralized power-to-heat as a flexibility option for the german electricity system: A microeconomic perspective. Energy Policy 2015;87:417–28. doi:10.1016/j.enpol.2015.09.032.

[81] Bolkesjo TF, Kirkerud JG, Tromborg E. Power market impacts of increased use of electricity in the heating sector. Int Conf Eur Energy Mark EEM 2017. doi:10.1109/EEM.2017.7981955.

[82] Intergovernmental Panel on Climate Change. Renewable energy sources and climate change mitigation: Special report of the intergovernmental panel on climate change. New York: Cambridge University Press; 2012. doi:10.1017/CBO9781139151153.

[83] Dyrelund A. Fjernvarmen er det smarte ellager [DH is the smart electricity storage]. Fjernvarmen 2017.

[84] Rosnes O. Subsidies for renewable energy in inflexible power markets. J Regul Econ 2014;46:318–43. doi:10.1007/s11149-014-9258-7.

[85] Ministry of Energy Utilities and Climate. Agreement of December 16th, 2016 on the energy companies' energy savings effort 2016:104.

[86] Yaqoot M, Diwan P, Kandpal TC. Review of barriers to the dissemination of decentralized renewable energy systems. Renew Sustain Energy Rev 2016;58:477–90. doi:10.1016/j.rser.2015.12.224.

[87] Sandberg E, Kirkerud JG, Trømborg E, Bolkesjø TF. Energy system impacts of grid tariff structures for flexible power-to-district heat. Energy 2018. doi:10.1016/j.energy.2018.11.035.

[88] Kirkerud JG, Trømborg E, Bolkesjø TF. Impacts of electricity grid tariffs on flexible use of electricity to heat generation. Energy 2016:1–9. doi:10.1016/j.energy.2016.06.147.

[89] State and Local Energy Efficiency Action Network. Guide to the Successful Implementation of State Combined Heat and Power Policies. 2013.

[90] Brown CB, Berendt CB. Comments of Microgrid Resources Coalition to order instituting rulemaking regarding microgirds pursuant to Senate Bill 1339 2019.

[91] Nagel K. Tarif payment for different electrical storage technologies [Tarifbetaling for forskellige ellagringsteknologier]. Kolding: 2015.

[92] Ropenus S, Skytte K. Regulatory review and barriers for the electricity supply system for distributed generation in EU-15. 2005 Int Conf Futur Power Syst 2005:6 pp. – 6. doi:10.1109/FPS.2005.204261.

[93] Federal Energy Regulatory Commission. Order no. 841 Electric Storage Participation in Markets Operated by Regional Transmission Organizations and Independent System Operators. Washington: 2018.

[94] Holttinen H, Tuohy A, Milligan M, Silva V, Müller S, Soder L. The Flexibility Workout. IEEE Power Energy Mag 2013;11:53–62. doi:10.1109/MPE.2013.2278000.

[95] Castagneto Gissey G, Dodds PE, Radcliffe J. Market and regulatory barriers to electrical energy storage innovation. Renew Sustain Energy Rev 2018;82:781–90. doi:10.1016/j.rser.2017.09.079.

[96] Michelez J, Rossi N, Martin JM, Mera E, Christensen D, Peineke C, et al. Risk quantification and risk management in renewable energy projects. Hamburg: 2011.

[97] Newell GJ, Garzón AIS. D.C. Circuit Decision Brings Uncertainty to CHP Participation in Demand Response Markets. Dist Energy 2015:59–60.

[98] Moynihan J. CHP Microgrids - The Realities 2018.

[99] Vivid Economics, Imperial College. International Comparisons of Heating, Cooling and Heat Decarbonisation Policies. 2017.

[100] Frederiksen S, Werner S. District Heating and Cooling. 1st ed. Lund: Studentlitteratur; 2013.

[101] Hawkey D, Webb J, Lovell H, McCrone D, Tingey M, Winskel M. Sustainable Urban Energy Policy - Heat and the city. 1st ed. Abingdon, Oxon: Routledge; 2016.

[102] Colmenar-Santos A, Borge-Díez D, Rosales-Asensio E. District heating and cooling networks in the European Union. Dist. Heat. Cool. Networks Eur. Union, 2017, p. 1–149. doi:10.1007/978-3-319-57952-8.

[103] Gullev L, Duedahl M. IRR - Internal rate of return and how it affects development of DH projects. Hot Cool 2019:7–10.

[104] Danish Energy Association. Energitilsynet hæmmer langsigtede investeringer i fjernvarmen | Dansk Energi. Website 2017. d (accessed November 28, 2018).

[105] Danish Energy Agency. Projektbekendtgørelsen [Announcement on approval of projects for collective heat supply]. Denmark: 2018.

[106] The European Commission. An EU Strategy on Heating and Cooling 2016.

[107] Danish Energy Agency. Samfundsøkonomiske beregningsforudsætninger for energipriser og emissioner, oktober 2018 [Guidance to socioeconomic analyses on energy] 2018.

[108] Swanstrom DA, Garzón AIS. FERC to reform interconnection procedures for large generators. Dist Energy 2017:64–7.

[109] The Danish Ministry of Taxation. Selskabsskatteloven [Law on company taxation]. Retsinformation 2016. https://www.retsinformation.dk/Forms/r0710.aspx?id=183480#P1 (accessed February 2, 2020).

[110] Energinet.dk. Model Analysis of Flexibility of the Danish Power System. Fredericia: 2018.

[111] Kavvadias K, Jiménez-Navarro JP, Thomassen G. Decarbonising the EU heating sector. Luxembourg: 2019. doi:10.2760/943257.

[112] DHC+ Technology Platform. Digital Roadmap for District Heating & Cooling - Version 2. 2019.

[113] Revkin A. Overcoming Inertia and Reinventing "Retreat." Urban Planet, Cambridge University Press; 2018, p. 394–6. doi:10.1017/9781316647554.033.

[114] Furbo S. Using water for heat storage in thermal energy storage (TES) systems. Woodhead Publishing Limited; 2014. doi:10.1533/9781782420965.1.31.

[115] Lund H, Østergaard PA, Connolly D, Mathiesen BV. Smart energy and smart energy systems. Energy 2017;137:556–65. doi:10.1016/j.energy.2017.05.123.

[116] David A, Mathiesen BV, Averfalk H, Werner S, Lund H. Heat Roadmap Europe: Large-Scale Electric Heat Pumps in District Heating Systems. Energies 2017;10:578. doi:10.3390/en10040578.

[117] Sayegh MA, Jadwiszczak P, Axcell BP, Niemierka E, Bryś K, Jouhara H. Heat pump placement, connection and operational modes in European district heating. Energy Build 2018;166:122–44. doi:10.1016/j.enbuild.2018.02.006.

[118] American Wind Energy Association. Petition for rulemaking of the American Wind Energy Association to revise generator interconnection rules and procedures 2015.

[119] Reneses J, Rodríguez MP, Pérez-Arriaga IJ. Electricity tariffs. London: Springer London; 2013. doi:10.1007/978-1-4471-5034-3.

[120] Kortegaard Støhchel H, Pedersen J. Playbook - Electric Boiler [Drejebog - Elkedel]. Kolding: 2017.

[121] Swing Gustafsson M, Myhren JA, Dotzauer E. Potential for district heating to lower peak electricity demand in a medium-size municipality in Sweden. J Clean Prod 2018;186:1–9. doi:10.1016/j.jclepro.2018.03.038.

[122] NREL, RAP. Next-Generation Performance- Based Regulation Next-Generation Performance- Based Regulation. 2017.

[123] Danish Ministry of Climate Energy and Utilities. Law on electricity supply [Bekendtgørelse af lov om elforsyning]. Retsinformation 2019. https://www.retsinformation.dk/Forms/R0710.aspx?id=206394#id4cc3ebe0-7483-42ec-9072-dd2caaecec48 (accessed August 1, 2019).

[124] Oil and Energy Department. Energy law [Forskrift om produksjon, omforming, overføring, omsetning, fordeling og bruk av energi m.m. (energilovforskriften) - Kapittel 4. Omsetning av elektrisk energi]. Lovdata 2019. https://lovdata.no/dokument/SF/forskrift/1990-12-07-959/KAPITTEL_4#§4-4 (accessed August 1, 2019).

[125] Sala JM. Thermal energy storage (TES) systems for cogeneration and trigeneration systems. Woodhead Publishing Limited; 2014. doi:10.1533/9781782420965.4.493.

[126] Malskær NF. US district energy in the age of Trump. HOT|COOL 2017:8–9.

[127] IEA-RETD. Waking the Sleeping Giant - Next generation policy instruments for renewable heating and cooling in the commercial sector (RES-H-NEXT) 2015.

[128] Rüdig W. Energy conservation and electricity utilities A comparative analysis of organizational

obstacles to CHP/DH. Energy Policy 1986;14:104–16. doi:10.1016/0301-4215(86)90122-9.

[129] McAfee RP, Mialon HM, Williams MA. What Is a Barrier to Entry? Am Econ Rev 2004;94:461–5. doi:10.1257/0002828041302235.

[130] West JK. Background note. Barriers to entry, Paris: OECD; 2006.

[131] Danish Energy Agency. Vejledning i brugerøkonomisk kontrolberegning januar 2019 [Guidance on user-economic control calculation January 2019] 2019.

Flexibility of U.S. campus district energy systems in the electricity grid

Working paper by Daniel Møller Sneum

April 2020

Flexibility of U.S. campus district energy systems in the electricity grid

Working paper by Daniel Møller Sneum
2020

Published by: DTU, Department of Management Engineering, Produktionstorvet, Building 424, 2800 Kgs. Lyngby Denmark
www.man.dtu.dk

Abstract

U.S. state targets on clean energy has accelerated in amounts and ambitions within the last few years. This is expected to bring increased amounts of variable renewable energy into the U.S. energy system, subsequently leading to a need for flexible assets in the electricity grid. District energy systems have a proven ability to contribute to renewable energy integration and is thus a relevant sector include the energy system transition. District energy systems are often deployed at university campuses, which increasingly also demonstrate ambitious targets regarding energy and climate. Since flexibility in the interface between district energy and the electricity system can be hindered, I explore the barriers to such flexibility using a taxonomy developed for the purpose. The results show that the taxonomy is useful for identifying barriers, among which limitation in generating to the electric grid is among the most prominent. Flexibility in consumption is more widely applied.

Abbreviations

DE: District energy
DE-ESI: district energy-electricity system interface
ESCO: Energy service company
GHG: Greenhouse gas
NEITG: Non-electricity interfaced thermal generator (typically a natural gas/biomass boiler for heating or chiller for cooling). The term is used to encompass cooling and to exclude electric boilers.
NYISO: New York ISO
PtH/C: power-to-heat/cooling
TS: Thermal storage
U.S.: United States
USD: U.S. dollars
U-: University
VRE: Variable renewable energy

1. Introduction

Despite, or possibly because of, the federal reduction in ambitions on climate change action, including the withdrawal from the Paris Agreement [1], the United States (U.S.) has seen an increase [2,3] in state targets on clean energy within recent years (*Figure 1*).

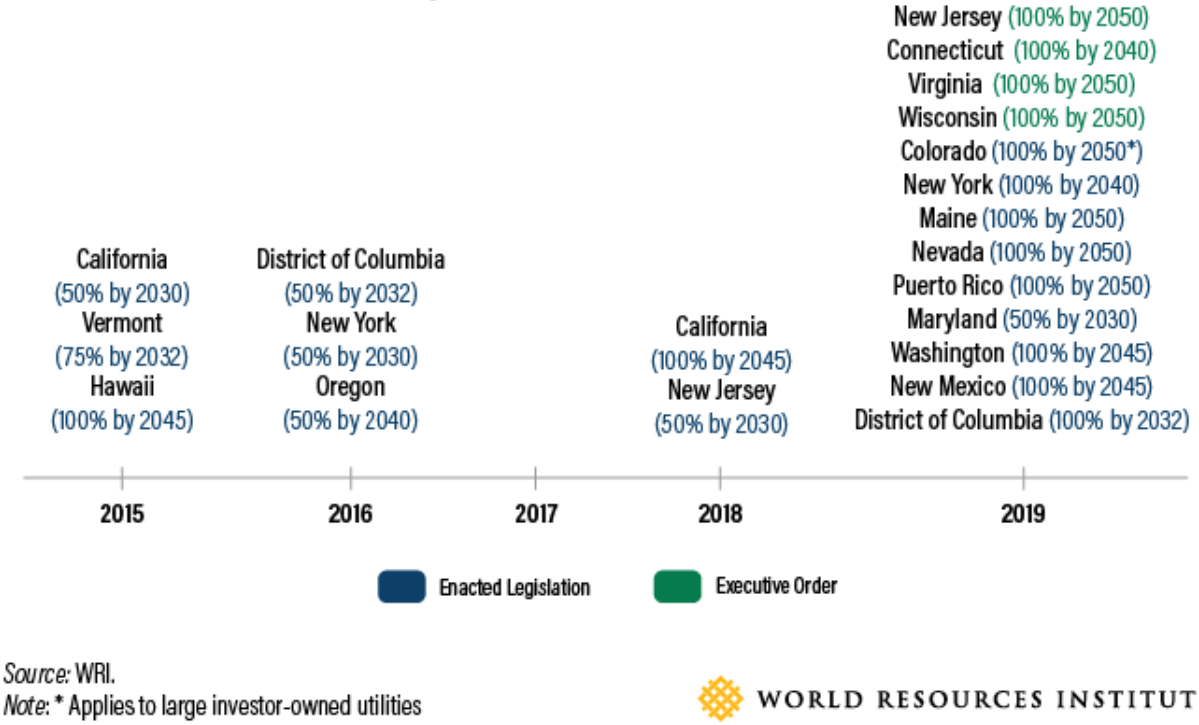


Figure 1 Clean energy commitments in U.S. states. Illustration and data by World Resources Institute [3].

Meeting such targets can lead to increased deployment of variable renewable energy (VRE) and a subsequent need for more coupling among energy sectors, such as electricity, heating and cooling [4], and increased need for flexibility [5] – in summary: smart energy systems [6].
The thermal sector, heating and cooling, is relevant in achieving such integration among energy sectors [7,8]. In the thermal sector, district energy (DE) systems supply local demands of heating, cooling and possibly electricity [9]. DE systems with electricity generation are supplied by combined heat and power plants (CHP). The U.S. Department of Energy's Combined Heat and Power Installation Database [10] counts 4 571 U.S. CHP systems as of January 2020 [1] - see *Figure 2*.

[1] Some have been verified decades ago. 3 524 plants have been verified 2005 or later.

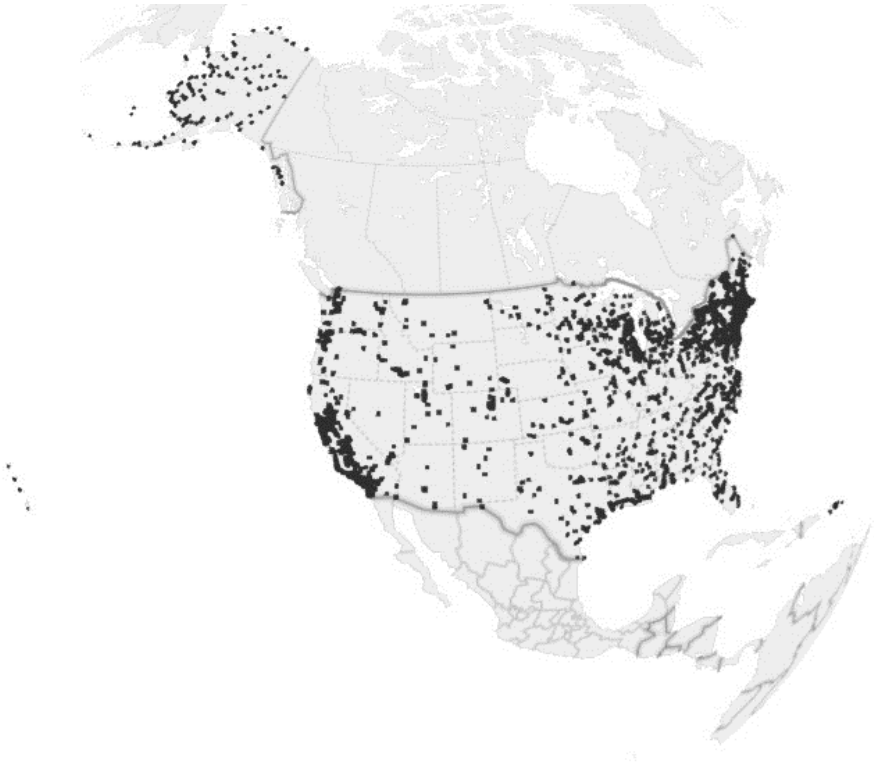


Figure 2 Overview of registered U.S. CHP plants. Own illustration, based on data from U.S. Department of Energy [10].

Compared to Europe (2 EJ district heating in 2014 [11]), U.S. district heating and cooling deployment (0.6 EJ [12] in 2012) is comparatively small, but not insignificant. The US has no policies for renewable heat at the federal level, while there are examples on state level [13].
Research by both Rocky Mountain Institute [14] and The Regulatory Assistance Project [15] has shown that residential electrification of heating in U.S. is economically attractive, reduces fossil fuel use and enables better electric grid management, but no studies have been identified regarding the electrification of U.S. DE systems more broadly, although the expected benefits are similar. Pensini et al. [16] analysed various DE configurations in a U.S. case, and found that a heat pump-based system was most efficient on cost and natural gas consumption. Konidena et al. [17] explored the interrelation between microgrids (including DE systems) and the surrounding electric grid and found that such systems can offer services to the surrounding grid – and vice versa. Sneum [9] (under review as of April 2020) proposed a taxonomy for barriers to flexibility in the interface between DE and the electricity system, but did not apply this against real-world systems. This study does exactly that, whereby existing research is expanded on two fronts. First, the applicability of Sneum's taxonomy is tested. Second, the cases analysed provides insight into barriers to flexibility faced by U.S. DE systems.

1.1 Problem formulation and research question

While the theoretical foundation for identifying barriers to flexibility in the DE-electricity system interface (DE-ESI) has been demonstrated by Sneum [9], the method has not been applied in practice on concrete cases. The academically based research question therefor is

> *Is Sneum's taxonomy on barriers to flexibility in the DE-ESI applicable as a tool for identifying barriers in real-world cases?*

The cases chosen to answer the first research question is motivated by Dragoon and Papaefthymiou [18] stating that '*District heating and cooling systems with thermal storage such as the ones existing in* […] *university campuses represent largely untapped sources of demand side energy storage in many areas of the world.*' In U.S. 280 college and university systems are registered with a total capacity of 2 582 MW_{EL} (0.2% of U.S. total capacity – total U.S. CHP capacity: 7.4%) [10]. This CHP capacity is part of DE systems which have supplied university campuses with energy for decades, even a century in e.g. the old Ivy League universities. As exemplified in *Figure 3* and noted by Malskær [19], several U.S. universities have set ambitious goals on renewable energy or climate.

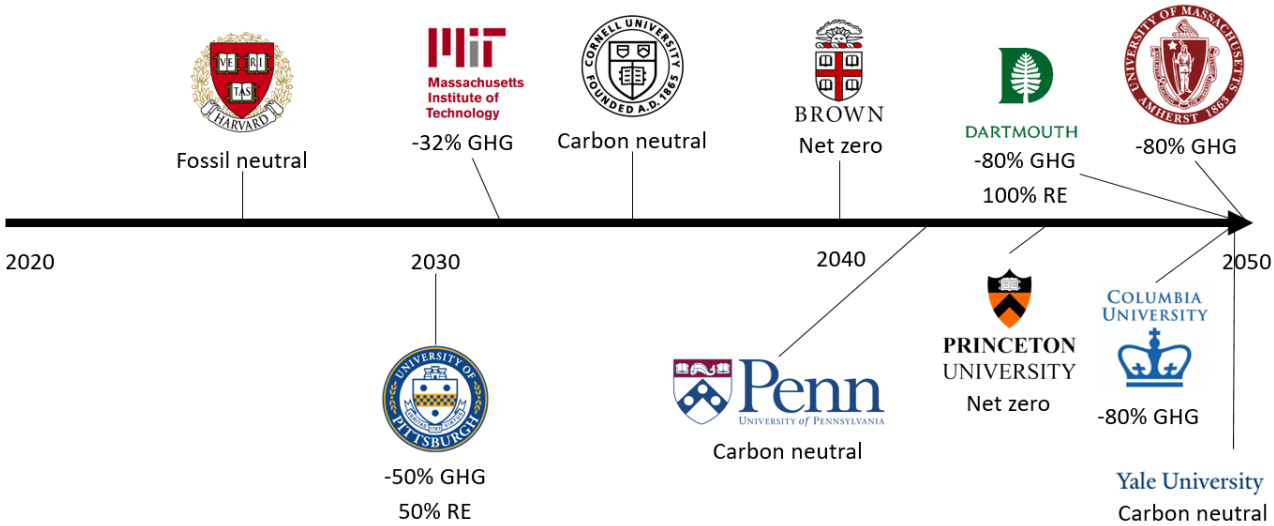
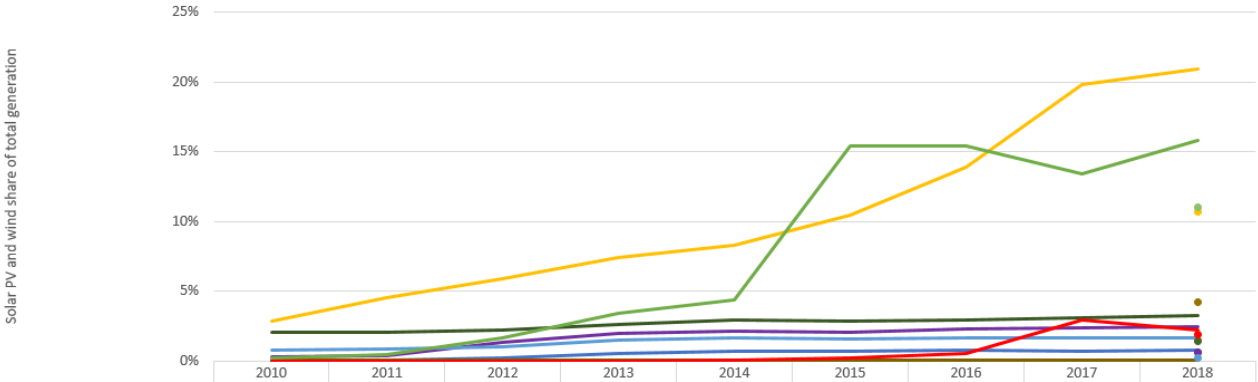


Figure 3 Selection of U.S. university clean energy and climate commitments. The selection is not equivalent to the universities in this study. Own illustration.

Using Sneum's [9] taxonomy for exploring barriers to flexibility in the district energy-electricity system interface (DE-ESI), framework conditions are studied in 10 university campus DE systems in 7[2] states. Such systems are comparable regarding energy needs and services provided, but are operating under different framework conditions, such as regulatory regimes.

As seen in *Figure 4*, the share of VRE in the studied and selected neighbouring states is mixed, with the major penetrations in Maine and Vermont. Increased penetration of VRE has for the system operator New York ISO (NYISO) and other areas in U.S., been projected to result in increased price variability and increase in the amount of hours where prices are lower than $5/MWh (NYISO: 2-11% of hours, depending on scenario) [20]. At the same time, the system operator ISO-New England explores ways to maintain dispatchable capacity during winter periods [21]. Batteries are planned for virtual power plants in New Hampshire [22]. Along with the state- and university goals, these and similar needs may benefit from flexible DE.

[2] Connecticut, Massachusetts, New Hampshire, New Jersey, New York, Pennsylvania and Vermont



	2010	2011	2012	2013	2014	2015	2016	2017	2018
Connecticut - wind	0%	0%	0%	0%	0%	0%	0%	0%	0%
Maine - wind	3%	5%	6%	7%	8%	10%	14%	20%	21%
Massachusetts - wind	0%	0%	0%	1%	1%	1%	1%	1%	1%
New Hampshire - wind	0%	0%	1%	2%	2%	2%	2%	2%	2%
New Jersey - wind	0%	0%	0%	0%	0%	0%	0%	0%	0%
New York - wind	2%	2%	2%	3%	3%	3%	3%	3%	3%
Pennsylvania - wind	1%	1%	1%	1%	2%	2%	2%	2%	2%
Rhode Island - wind	0%	0%	0%	0%	0%	0%	1%	3%	2%
Vermont - wind	0%	0%	2%	3%	4%	15%	15%	13%	16%
Connecticut - PV 2018									2%
Maine - PV 2018									11%
Massachusetts - PV 2018									1%
New Hampshire - PV 2018									1%
New Jersey - PV 2018									4%
New York - PV 2018									1%
Pennsylvania - PV 2018									0%
Rhode Island - PV 2018									2%
Vermont - PV 2018									11%

Figure 4 Solar and wind penetration measured as shares of total state electricity generation. Based on data from Berkeley Lab [23,24].

Therefore, the case-specific research question is

> *Which barriers to flexibility in the DE-ESI can be identified in U.S. DE systems, and what are the implications of these barriers?*

The analysis is relevant for plant managers and authorities (concrete experiences among the surveyed DE systems and measures to address barriers) as well as academia (the application and usefulness of the taxonomy).

2. Methodology

2.1 Taxonomy of barriers to flexibility in the DE-ESI

The definition of flexibility in the DE-ESI applied in this study, adheres to the description given by Sneum et al. [25]: DE with thermal storage (TS) can respond flexibly to electricity price or other signals, by shifting between generating technologies. E.g. PtH/C can utilise low prices by consuming electricity; CHP can utilise high prices by producing electricity; and TS and a non-electricity interfaced thermal generator (NEITG – typically a boiler) can fill the gaps in the remaining periods. Barriers are defined as framework conditions that hinder this way of operation. Sneum [9] provides a detailed description of barriers.

As a way to gain insight into the framework conditions for flexibility in the DE-ESI, Sneum [9] developed the taxonomy shown below (*Table 1* – hereafter 'the taxonomy'). The taxonomy is based in a review of literature, while the present study marks the first application of the taxonomy in a concrete context.

With nine categories and 40 barriers (see Sneum [9] for a detailed description), the taxonomy is intended to encompass a broad range of issues in different contexts. The intention with applying the taxonomy in this study is not to identify the full set of 40 barriers, but rather to identify 'hotspots' – areas that in the specific case of U.S. campus DE systems can be addressed to improve flexibility in the DE-ESI.
The column 'Tech. type' describes which technologies that are affected by the barrier. 'Proj. life cycle' describes where in the life cycle of a DE project the barrier has its primary impact (it may additionally have impact in several other parts). 'Level of origin' describes wherefrom the barrier arises. All are described in the caption text of *Table 1*. The term 'electricity grid tariffs' applied here is equivalent to 'rates', which is more frequently applied in U.S. terminology.

Table 1 Sneum's [9] *taxonomy of barriers to flexibility in the DE-ESI. Project life cycle: 1 (Requirements specification), 2 (Scoping), 3 (Feasibility study), 4 (Tendering, construction and permitting), 5 (Operation). Level of origin: 1 (Service and technology providers), 2 (Plant), 3 (Local), 4 (Regional), 5 (National), 6 (International).*

Category	Sub-category	Barrier name	#	Tech. type	Proj. life cycle	Level of origin
Operational signalling	Dispatch signals	Absence of signal-providing scheme	1	cogen + PtH/C	5	4-6
		Electricity market: Absence of flexibility-need (involatile prices)	2	cogen + PtH/C	5	4-6
		Electricity market: Fixed electricity prices	3	cogen	5	4+5
		Physical vs. financial dispatch: Must-run operation	4	cogen + PtH/C	5	3-5
	Operational taxes and subsidies	Operational taxes on flexible DE	5	cogen + PtH/C	5	4+5
		Favourable operational taxes on NEITG	6	NEITG	5	4+5
		Inflexible operational subsidies for flexible DE	7	cogen + PtH/C	5	4+5
		Operational subsidies for NEITG	8	NEITG	5	4+5
	Electricity grid tariffs	Electricity grid tariffs	9	cogen + PtH/C	5	3-5
	Signal related standards and procedures	Barriers for entry into signal-providing schemes	10	cogen + PtH/C	5	4+5
		Barriers for operation in signal-providing schemes	11	cogen + PtH/C	5	4+5
Investment		Investment subsidies for NEITG	12	NEITG	2+3	4+5
		Limitations in capital for flexible DE	13	cogen + PtH/C	2+3	2
		High risk premium for financing flexible DE	14	cogen + PtH/C	2+3	2
		Internal limitations from pay-back time and internal rate of return/discount rate requirements	15	cogen + PtH/C	2+3	2
		Externally imposed limitations from regulated rate of return	16	cogen + PtH/C	2+3	5
Permitting		Technology bans and mandates	17	cogen + PtH/C	2+3	3-5
		Inadequate legal framework for evaluation of DE projects	18	cogen + PtH/C	2+3	3-5
		Friction in the permitting process	19	cogen + PtH/C	4	3-5
Ownership		Tax- and ownership regulation disincentivising grid integration	20	cogen + PtH/C	5	5
DE technology conditions		Limitations in adjustability, ramping and lead time	21	cogen + PtH/C	5	2
		High technological cost	22	cogen + PtH/C	2+3	1

	High business process costs	23	cogen + PtH/C	2+3	2
	Low supply chain maturity	24	cogen + PtH/C	2-5	1
	Limitations in control and visibility	25	cogen + PtH/C	5	1, 4-6
	High-temperature systems	26	PtH/C + TS	5	2
Grid access	High grid-connection cost	27	cogen + PtH/C	2+3	3-5
	Limiting grid codes	28	cogen + PtH/C	5	4-6
	Limiting grid capacity	29	cogen + PtH/C	2+3	3
Physical environment	Limited access to energy sources	30	cogen + PtH/C	2+3	3
	Land availability	31	cogen + PtH/C + TS	2+3	3
Bounded rationality	Limitations from organisational bounded rationality	32	cogen + PtH/C	1, 2, 3+5	2
	Limitations from community bounded rationality	33	cogen + PtH/C	3+4	3
	Limitations from authority bounded rationality	34	cogen + PtH/C	2-5	4+5
	Limitations from individual plant staff's bounded rationality	35	cogen + PtH/C	1, 2, 3+5	2
Acceptance	Limitations from organisational acceptance	36	cogen + PtH/C	2-5	2
	Limitations from community acceptance	37	cogen + PtH/C	3+4	3
	Limitations from authority acceptance	38	cogen + PtH/C	2-5	4+5
	Limitations from incumbent acceptance	39	cogen + PtH/C	2-5	3-5
	Limitations from individual plant staff's acceptance	40	cogen + PtH/C	1, 2, 3+5	2

2.2 Plant manager interviews and verification of results

This study is based in semi-structured interviews, conducted with plant managers of ten different university campus DE systems in the spring of 2018. Nine interviews were conducted in person; one by phone. The simple interview guideline is seen in the appendix (Section 8), based on work by Sneum et al. [26] and Sandberg et al. [27]. As the attentive reader will notice, the guideline has common traits with the taxonomy, but is simpler. The reason is that the interviews were conducted before the taxonomy was finalised. To provide what Creswell [28] calls *member checking*, responses were subsequently filled into the structure of the taxonomy and disseminated to the respondents in December 2019 and January 2020 for verification of the findings. Several plant managers have requested anonymity, which has been granted to all respondents in this working paper. The list of universities in the study is seen in *Table 2*.

Table 2 University profiles, including DE technologies and energy/climate targets. University names have all been anonymised and solely indicate the state in which the university is placed.

#	NAME	Cogeneration (main fuel)	Steam chillers	Electric chillers	Steam boiler	PtH	Energy/climate target
1	U-Connecticut	X (gas)	X	X	X	-	X
2	U-Massachusetts 1	X (gas)	-	X	X	-	X
3	U-Massachusetts 2	X (gas)	X	X	X	-	X
4	U-Massachusetts 3	X (gas)	X	X	X	-	X
5	U-New Hampshire	X (No6 fuel oil)	X	X	-	-	X
6	U-New Jersey	X (gas)	X	X	X	-	X
7	U-New York	-	X	X	X	-	X
8	U-Pennsylvania 1	-	X	X	X	-	X
9	U-Pennsylvania 2	-	X	X	-	-	X
10	U-Vermont		X	X	X	-	X

It is important to note that the findings from these interviews are the interviewees' *perceptions* of the barriers. In other words, the perceived – not necessarily factual – existence of barriers. Whereas determining whether the barrier is actually present (e.g. by techno-economic analyses), perception is initially important since plant managers make decisions on investments and operational procedures, which affects flexibility in the DE-ESI. The issue of perception is discussed by Sovacool et al. [29] and applied in a similar fashion as here by Golove et al. [30]. Numbers in the headlines indicate barrier numbers in the taxonomy.

3. Results

This section presents the findings regarding the campus DE plant managers' perceived barriers to flexibility in the DE-ESI. Identified barriers are briefly described, while broader interpretation is conducted in the discussion, section 4.

3.1 Operational signalling

1 - Absence of signal-providing scheme

Nine of the surveyed plants (Vermont is the exception) are present in real-time power markets. None face signals for CO2-content, but three are looking into that (U-Connecticut, U-New Jersey and U-Massachusetts 1). One (U-New Jersey) is generating into the grid, while five others optimises *behind-the-meter* with no export (U-Massachusetts 1, U-Massachusetts 2, U-Pennsylvania 2, U-Pennsylvania 1, U-Connecticut). Signals are received directly from the system operator or through an intermediary who does optimization of dispatch. Four (U-New Hampshire, U-Massachusetts 1, U-Connecticut, U-Pennsylvania 1) offers or are considering to offer capacity to the electricity market through an aggregator.

2 - Electricity market: Absence of flexibility-need (involatile prices)

U-Pennsylvania 2 (with no CHP capacity) finds that prices are consistently too low to drive shifts in dispatch, while this was the case before deregulation and full customer retail choice was introduced in 2000. Conversely, the U-Connecticut generates most consumed electricity on its natural gas CHP with little incentive to shift. This is explained by natural gas-driven New England power prices and the co-optimisation of thermal and electricity demand against internal energy supply.

3 - Electricity market: Fixed electricity prices
U-New Hampshire faces fixed tariffs, while the U-Vermont faces time of use tariffs. The U-Connecticut faces take-or-pay contracts on electricity, incentivising use of electric chillers and thereby distorting the electricity price signal.

4 - Physical vs. financial dispatch: Must-run operation
Thermal load following is the prevalent form (U-New Hampshire, U-Massachusetts 1, U-Massachusetts 3, U-Pennsylvania 2, U-Pennsylvania 1, U-Vermont). All systems apply a mix of technologies and energy sources, steam and electricity, to provide flexible dispatch according to economic signals and supply-security. Some (U-Massachusetts 3 + U-Massachusetts 2 + U-Connecticut) are growing into their capacities at peak days and thus need to expand existing capacity to have backup and flexibility. University electricity demand is perceived as too sensitive (e.g. supply for laboratories) to perform flexible response. Flexible response must thus be based in the DE plants. Some (U-New Jersey and U-Pennsylvania 2) apply *thermal setback* in buildings, i.e. 'charging' these in periods with excess capacity (typically night) and thereby minimise need for later production, e.g. during peaks. Such thermal inertia enables shifting of load in a few hours, but not for longer durations throughout the day.

6 - Favourable operational taxes on NEITG
Absence of taxation on biomass in all cases. Despite this, no biomass-based capacity is deployed (see 0).

9 - Electricity grid tariffs
Nine (U-New Hampshire, U-Massachusetts 1, U-New Jersey, U-New York, U-Massachusetts 2, U-Massachusetts 3, U-Pennsylvania 2, U-Pennsylvania 1, U-Connecticut) face annually set capacity charge (also called (ratcheted) demand charge or standby charge - $/kW), charged by the system operator. The charge is based on university demand, when the system grid demand peaks. Similarly, the local utility applies capacity charges (U-New Hampshire, U-Massachusetts 1, U-Pennsylvania 2, U-Pennsylvania 1, U-Vermont). As example from U-New Hampshire, the local utility applies capacity charges of 10-$15/kW/month), charged based upon U-New Hampshire's monthly peak demand with an 11 month ratchet clause. The ratchet clause defines the monthly tariff level that the university must pay, based on the highest measured demand within the last year. In both cases, the universities attempt to anticipate the grid peak and adjust consumption and production of electricity behind the meter. In one case (U-Massachusetts 1), the local utility applies a monthly set capacity charge in 15-minute windows in periods from 9 am to 8 pm. This induces a need to spread out the electricity demand – and a hesitance to introduce PtH/C, to avoid increased electricity load.

10 - Barriers for entry into signal-providing schemes
U-Massachusetts 2 stated that current interconnection agreement did not allow for export, but that a later revision will need to, due to deployment of new electric generation capacity. This was more perceived as an administrative necessity, than a barrier.

3.2 Investment

12 - Investment subsidies for NEITG
Several plants are enrolled in capacity payment schemes (as described in 0), remunerating the electric capacity. Additionally, state schemes include Alternative Energy Portfolio and thermal credits, in both cases tradeable certificates in Massachusetts; energy efficiency subsidies and utility subsidies in Vermont; and tradeable thermal renewable energy certificates in in New Hampshire. These can provide a source of

revenue. If these certificates are sold, the university will not be able to claim their contribution to e.g. university renewables-targets.

13 - Limitations in capital for flexible DE

The U-Vermont has limited access to capital for large investments. U-Massachusetts 3 is eligible to low-cost state loans, which do not count as debt on the balance sheet. U-New Hampshire is currently evaluating on/off balance sheet financing of new investments. In U-Massachusetts 1, U-Pennsylvania 2 and U-Connecticut, DE systems are structured as internal retail suppliers. This enables financing on balance sheets through internal rates paid to local campus-utility responsible for the DE system. Access to capital is subject to the approval of the local customers – the individual schools at the university. U-Connecticut points out that the split in access to financing is not necessarily between public and private universities, but rather, between tuition driven versus endowment driven. The former may have less access to cash, and may therefore prefer cash flow-based financing, i.e. letting a third party finance, own and operate utility infrastructure. The model is known as an energy service company (ESCO), and not applied by any of the reviewed universities.

14 - High risk premium for financing flexible DE

U-Massachusetts 3 has some scepticism regarding ESCO models, since the subsequent performance of the contracted services, e.g. regarding savings, could become a dispute among the buyer and supplier. This uncertainty can be factored into the price of new projects, making them expensive. The university prefers the current alternative in Massachusetts: that investments are subject to standardised state agency audit of performance regarding reduced cost of projects. This reduce supplier risk and thereby cost.

15 - Internal limitations from pay-back time and internal rate of return/discount rate requirements

U-Pennsylvania 2 described that projects should usually pay back in less than 10 years, while this requirement be extended to approximately 20 years, if carbon reductions are shown as part of the project.

3.3 Permitting

17 - Technology bans and mandates

U-Pennsylvania 2 noted that approvals for new infrastructure in densely populated areas can be problematic regarding visual- and emissions impacts. U-Vermont noted that electric heat is not allowed.

19 - Friction in the permitting process

U-Connecticut noted that friction can occur with utilities, since these have high experience in the area, have nearly unlimited time and are experts on the field; characteristics that the DE systems do not share. Further, it was noted that streamlined processes are not always present, especially for smaller utilities.

3.4 Ownership

20 - Tax- and ownership regulation disincentivising grid integration

Generating to the grid and subsequently becoming a taxable entity is undesirable for U-Massachusetts 2, U-Massachusetts 3, U-Pennsylvania 1 and U-Connecticut. U-New Hampshire has analysed the option and has decided against it. U-New Jersey is the only exemption.

3.5 DE technology conditions

21 - Limitations in adjustability, ramping and lead time

Optimisation behind the meter is conducted with all available technologies at U-New Hampshire, U-Massachusetts 2, U-New Jersey. U-Pennsylvania 2 and U-Connecticut. This is applied in daily operation, but especially relevant during electricity peak periods, where switching to steam-chillers and, if possible, increased local electricity generation helps reduce electricity demand from the grid. Reliability and resilience of supply is a recurring motivation for the ability to switch between technologies, among all universities. Interruptible gas contracts at U-New Jersey and U-Massachusetts 2 also induces ability to switch between gas and oil combustion. In relation to this, the grid is highly utilised for imports by all, but not necessarily trusted to deliver stable supply. The U-Pennsylvania 1 and U-Vermont are the exceptions, since these are fully reliant on electricity import. The U-Connecticut perceives HPs as impractical due to low efficiency during low temperatures. Regarding CHP, U-Massachusetts 3 notes that gas turbine cycling might be an issue due to wear and tear. At the university in Connecticut, a previous CHP plant was less efficient. This made it more relevant to operate it flexibly than the current CHP, since grid imports more often made economic sense.

22 - High technological cost

U-Pennsylvania 2 is supplied by industrial excess heat at a lower cost than a potential self-owned CHP plant. This makes it the only one which owns the network, but not main generation assets. Conversion from steam to lower temperature systems are generally considered very costly (discussed further in *High-temperature systems* below).

24 - Low supply chain maturity

Regarding dispatch optimisation, experiences range from manual production estimates (U-Vermont) over in-house developed software (U-Massachusetts 3), to external consultants and energy traders (U-Massachusetts 2, U-New Jersey, U-New York). To estimate peak hours setting the rate for standby charges, curtailment service providers are used by U-New Hampshire, U-New Jersey, U-Massachusetts 1, U-New York, U-Massachusetts 2, U-Massachusetts 3, U-Pennsylvania 2, U-Pennsylvania 1 and U-Connecticut. The availability of consultancy services appears to be well-developed. U-Connecticut argues that the American consulting and engineering workforce has a shortage of electrical engineers, making it hard to find qualified staff for utilities and DE systems. This lack of engineers can result in friction in the interconnection process, due to lacking qualifications on both sides.

25 - Limitations in control and visibility

U-New Jersey is the sole DE system, which allows third party control of generation equipment (their energy trader), due to response to short term signals in ancillary services markets. Other types of communication between the DE systems and outside stakeholders such as demand-response schemes or system operators, involve phone calls, e-mail or text messages (U-New York, U-New Hampshire, U-Massachusetts 2 and U-Pennsylvania 1). U-Vermont was enrolled in a demand-response scheme, but found it problematic that signals were given outside business hours where staff was not present to accommodate the requested change in electricity demand. With hundreds of individual electric accounts, city-integrated campuses like the U-Vermont can suffer from limited overview of internal consumption, hindering general visibility and control.

26 - High-temperature systems

All campuses have steam-based systems. All show a general interest in hot water conversion, and a conversion process has been initiated by three (U-New Hampshire, U-New Jersey and U-Massachusetts 3). U-Pennsylvania 1, U-Vermont and U-Connecticut estimates a transition to be too expensive. In the case for Connecticut, because the current system is not at its end of technical life.

3.6 Grid access

29 - Limiting grid capacity

U-New Hampshire and U-Massachusetts 2 mention that systems are not set up for export, but it is not considered a major issue.

3.7 Physical environment

30 - Limited access to energy sources

Natural gas supply is not available at U-New Hampshire, but otherwise this is not considered an issue.

31 - Land availability

Constrained land availability for TS is a recurring issue, noted by U-Massachusetts 1, U-Massachusetts 2, U-Pennsylvania 1, U-Vermont and U-Connecticut. Regarding CHP, U-New Hampshire and U-Pennsylvania 2 describes land constraints. In the former case, there may be opportunity for alternative placement away from the current DE system premises.

3.8 Bounded rationality

32 - Limitations from organisational bounded rationality

U-Connecticut, U-New Jersey and U-Massachusetts 1 explore future options regarding environmental dispatch, thereby broadening their awareness and basis for decision. U-Pennsylvania 2 noted that the everyday logic of operation can be difficult to convey to top-level management. U-Pennsylvania 1 noted that the first priority is to minimise consumption, then perhaps to be flexible. This priority would require an insight into the risks and benefits. U-Connecticut made the point that under current conditions, the internal CHP capacity would already operate on full capacity during grid peaks. Thereby, there is no underutilised capacity at campus energy systems. Further, the economic incentive for exporting electricity has not been analysed, but is assumed to be limited.

35 - Limitations from individual plant staff's bounded rationality

There is a desire to build internal buy-in and knowledge regarding flexible operation responding to larger degree of signals, in U-Massachusetts 3 by developing own dispatch software; in U-Vermont by practising dispatch with fixed rates before entering more advanced operation. At U-Pennsylvania 2, lack of trust in the DE system’s optimization tools has resulted in occasional manual override, at one point resulting in damaged equipment.

3.9 Acceptance

36 - Limitations from organisational acceptance

To maintain credit rating U-New Hampshire has earlier prioritised avoiding own financing of large investments in infrastructure. This lead to priority for external financing and operation. This position has been revised. The U-New York saw PPAs to be preferred in a case, where local gas-based generation was emitting more than the grid. The same is seen for the future at U-Massachusetts 1, opening for PtH/C. Conversely, priority for on-campus actions have resulted in less desire for PPA and similar arrangements at U-Massachusetts 3. At U-New Jersey, environmental dispatch has been proposed to top management, so far without success. At U-Vermont, it is argued that the grid supply already renewables-based (biomass and hydro), leading to little incentive for flexible operation to integrate RE. Generally, among the DE systems structured as local retailers, buy-in for new investments must be ensured from the consumers. Resilience and reliability is a key parameter among U-New Hampshire, U-Pennsylvania 2, U-Massachusetts 3, U-Pennsylvania 1 and U-New Jersey.

37 - Limitations from community acceptance
Barriers to social license to operate has been experienced at U-Massachusetts 3, where local community opposed the construction of new biomass capacity due to opposition against cutting down local trees. A similar opposition to biomass use has been voiced regarding biomass-based generation at U-New Hampshire.

39 - Limitations from incumbent acceptance
While they may previously have been obstructing entities, utilities are now met with understanding (U-Massachusetts 3, U-New Jersey, U-Connecticut). In some cases even as proponents of DE (U-Massachusetts 3). U-New Jersey points out that the utilities may need new incentive structures to enable increased DE participation. U-Connecticut made the point that deregulation in the north-eastern U.S. and phasing out of utility-owned generation helps. That said, there may still be utility staff opposing DE out of old habit.

4. Discussion

Out of a potential 40 barriers, 18 were identified in the study of U.S. campus DE plants (summarised in Appendix, section 8.2). In this section, I discuss the results regarding the identified barriers and their potential solutions.

4.1 Receiving signals

Apart from Vermont, all states have electricity markets, in which the DE systems could potentially be participating. All reviewed DE systems to some degree optimise behind the meter, i.e. manage electricity load and local generation to minimise import from the grid. The main motivation for doing so is to reduce system and local capacity charges, by managing local import of electricity during peak periods. Second, to participate in demand-response schemes, where local load management is rewarded. Third, because own generation is less costly than the rates charged for imports from the grid.

4.2 Flexible electricity export and import

A main finding, is that only one DE system was actively generating into the electricity grid. Under the current conditions, DE CHP is already running at full load when the grid is peaking. This means that there is limited opportunity for peak-period exports in DE systems with electricity generation capacity dimensioned for local electricity demand. University demand may not always peak simultaneously with the grid, which could open for electricity exports. Additionally, there may be value in flexible DE supply to local grids. Such local grids may benefit from DE generation capacity, and may not peak at the same time as the larger electricity system. Furthermore, ancillary services and periods outside peak may be relevant, provided that there is DE electricity capacity in excess of university demand. Since the infrastructure and experience is already in place, it may be relevant to install electric capacity exceeding the university demand, to enable a new revenue stream from the electricity market (as in U-New Jersey). This would have to be analysed on a case-by-case basis. Whereas the Public Utilities Regulatory Policies Act previously required utilities to purchase CHP-based electricity at avoided cost, this was revised in 2005 for market-based electricity systems including ISO-New England, NYISO and PJM [31]. The CHPs are thus solely incentivised by market prices, except in the cases where they earn certificates (e.g. Massachusetts) for generation.
On the demand side, two cases showed lack of incentive for non-peak shifting between respectively demand-sources and CHP and its alternatives. While this can be indicate a flexibility-saturated system, the

local conditions (low-cost industrial excess heat and gas-based plant in gas-based electricity system) are the explanations. In the latter case, having a gas-based CHP in an electricity market dominated by gas-generators results in correlation between gas and electricity prices. In turn, this means that the revenue of the DE CHP selling into the market is always less than cost paid for buying the same amount of electricity to satisfy local demand. This will be the case as long as retail rates are higher than market prices. If retail tariffs are fixed, market prices will sometimes be higher. In those (rare) cases, there is incentive to generate to the grid. Alternately, CHPs could be forced to operate on the market (optimisation behind the meter is prohibited). This would lead to a split into local thermal optimisation and electricity traded on the market, similar to the Nordics. This would increase overall costs for the university, but make the whole market more liquid and the system more efficient.

Overall, electricity markets, if perceived as contestable markets, can be subject to hit and run entry (i.e. where entering and exiting the market is free), as discussed by Baumol [32]. Campus CHP capacity has exactly this characteristic, since this technology in many cases is already built. For that to happen, subsequent studies will need to clarify the details on New Jersey's framework which allows feeding into grid. Such a design may then be expanded other states, to address the issue of becoming subject to utility regulation (and thereby taxation), which is undesirable for the non-profit and tax-exempt universities.

4.3 Tariffs: barrier to PtH or just big post in the budget?

Electricity grid tariffs were a recurring issue among the DE systems. These can make up considerable part of the budget and it is a natural focus, also beyond the scope of flexibility in the DE-ESI. In one case, hesitance to PtH was mentioned as this would add increasing electric local load. While capacity charges may be high and seen as a barrier to PtH/C, they appear not to be a practical problem since several plants already apply PtC in periods where peak capacity charges do not apply. Similar flexible operation of DE has been demonstrated regarding tariffs by elsewhere ([33] and [34]). Demand charges as faced by many DE systems, should acknowledge DE systems' actual cost for the grid by reviewing their past track-record e.g. on outages and reliability [35].

4.4 Money not a problem in steam systems; it is for hot water transition

Whereas only few barriers were identified regarding investment, the issue surfaced regarding a potential conversion to hot water from steam. This indicates that the investment-questions were perceived under the assumption of existing plans and ambitions; not radically different technological setups. Conversion to hot water systems is a common desire among the plant managers. All perceive the significant cost as a barrier, some even dismiss it due to cost. This is thus a significant barrier to enabling use of hot water TS, HP and increased energy efficiency.

Especially at end-of-life of existing steam networks, transition to hot water becomes relevant. To address the large up-front costs, efficiency- or emission-focused public subsidies can be justified [9]. Alternately, a stepwise approach, as applied in one of the universities' hot water conversion, can be justified. Such smaller pilot projects can provide experience for DE systems as well as contractors.

Pagliarini and Rainieri [36] have shown the economic and environmental benefit of campus-based DE system with TS, but further case specific studies would be needed to demonstrate feasibility of hot water conversion. Experience with TS already exists, since some of the DE systems apply thermal setback, which is essentially a thermal building inertia-based TS. So the concept of TS is well-known, whereas TS-deployment is limited.

4.5 Limited in space, not in resources or grid access

Space for a potential TS is an issue brought up among universities in dense urban settings. A few mentioned the opportunity for ice storages, which is feasible through the medium of existing district cooling systems.

Cold storage has also received some media attention, more broadly [37,38]. Space requirement is a known issue regarding storage [39]. Regarding availability of energy sources, a notable absence is the focus on heat sources for HP. This may indicate a lack of focus on HP, since managers otherwise would be aware of the related challenges (Lund and Persson [40] have treated these).
Notable among identified barriers was the almost complete absence of issues regarding grid access. While the interconnection process may include some friction, the only points brought up were the need for changes in local grid infrastructure, to enable export of electricity.
Solutions: Integrate TS into new infrastructure projects. Improved overview of resources for HP can be gained by a mapping [9].

4.6 Local control = Invisible DE system and invisible business process cost?

Whereas no high business process costs were identified as barriers to flexibility, there appear to be considerable costs associated with local management of the DE dispatch. As indicated by a Danish balance responsible party, a single person manages the dispatch of 150 plants [41]. Concluding that the operation of the surveyed DE plants is inefficient would miss an important point: The focus on resilience and the priority for local control is very high among the plants. At the same time, it means that there is limited visibility and possibility for external control: only U-New Jersey allows its aggregator external control due to operation in ancillary services, where humans cannot be in the loop, due to very short timeframes. Other approaches include operators monitoring electricity prices and consultant-provided local servers optimizing operation, but with actual dispatch decided by operators.
This priority for local control is understandable, when considering the high priority for resilience. The question is, if solutions exists that could satisfy both priorities. Techno-economic analyses of the individual cases could shed further light on this question.
There is a fundamental difference between the 150 Danish plants mentioned above, and the U.S. DE systems. In Denmark, the plants optimize solely according to thermal demand, whereas the electricity is traded on the spot market. Conversely, the U.S. DE systems serve a thermal as well as electric load locally, whereby the optimization covers both needs. In complete and efficient markets, buyers and sellers exchange their goods leading to efficient allocation of goods. Since thermal generation and needs are by their physical nature local, these should be served locally. Conversely, electricity can be transported across long distances and could thereby be traded in the larger system. This is thus an argument for removing barriers to export of electricity, while still maintaining the possibility to serve local needs in the least cost (or least emissions) way of operation.

4.7 Bounded rationality and acceptance: Resilience trumps flexibility

There were few overall findings in these categories, except that resilience has high importance. A primary explanation of the absence of focus on flexibility is that it is a measure to achieve a target, rather than a target in itself. This is how it should be, since flexibility of flexibility's sake risks leading to sub-optimisation. A secondary explanation is that any discussion of flexibility in the DE-ESI is likely to start at the plant manager-level, since it relates to subjects on this decision-level: investment and operation. If it is not prioritised at plant manager level, it is unlikely that other parts of university management or the surrounding society will have priorities or knowledge on this subject. This focus on reliability in local supply is also reported by a CHP vendor, motivated by '*cybersecurity, weather related reasons, or even grid congestion*' [42].
As argued by IEA [6] and IEA and NREL [47], flexibility is a subset of – or way to obtain – resilience and low-carbon energy supply. Since both resilience and some variation of a low-carbon energy supply is prioritised at universities and their DE systems, flexibility is a relevant measure. Again, context-specific techno-economic analyses could help expand the bounded rationality. And if relevant, also make it an acceptable solution among the stakeholders.

4.8 Methodology and responses

Answers provided (e.g. regarding financing) may apply to DE projects in general, rather than flexible DE specifically, since this was the frame of reference for the managers. They did not necessarily distinguish between flexible and inflexible technologies. Similarly, barriers may not have been identified due to lack of awareness of these among plant managers (e.g. due to lack of experience with flexible DE-projects). This appears to be the case regarding the general perception of 'unproblematic funding, except for a hot water conversion'. Despite bounded rationality being a part of the taxonomy and the interview, the meta-problem arises that interviewees are themselves subject to bounded rationality.

This indicates a shortcoming in the methodology of a semi-structured interview. Instead, a more inquisitive 'what if-approach' could have defined concrete technological setups of flexible DE-ESI systems, including specific regulatory conditions, and asked plant managers to reflect specifically on these. Alternately, to approach the question from other angles through other stakeholders with different perspectives.

5. Conclusion

In this working paper, I have treated two questions through case studies of U.S. DE systems. First, whether a taxonomy on barriers to flexibility in the DE-ESI is applicable in real-world cases: Out of the taxonomy's 40 barriers, 18 were identified among U.S. DE systems. Methodologically, the taxonomy was applied almost unchanged to survey responses from interviewees. This approach has two major shortcomings. First, the frame of reference among interviewees was DE, not flexible DE. Since flexible DE had not necessarily been explored by interviewees, and barriers therefore not experienced or thought about, this bounded rationality may potentially have omitted identification of barriers. Bounded rationality is one of the categories of the taxonomy. To mitigate this, additional stakeholders (consultants, policy-makers, industry experts) could be relevant supplements. Techno-economic analyses could further help identify discrepancies between perceived barriers and actual barriers. In summary, Sneum's taxonomy is applicable, and will benefit from methods beyond surveying plant manager perceptions.

The second research question addressed the concrete barriers and implications of these in U.S. DE systems. Access to a signal providing scheme in form of a market does generally not appear to be a hindrance. Even in Vermont without an electricity market, demand response schemes are present. The motivation for participating in a market is, on the other hand, limited to U-New Jersey. DE electric generation capacity is generally not dimensioned to allow export. On the consumption-side, there is broad experience with shifting according to prices, especially electricity grid tariffs. Regarding tariffs, these have considerable attention across the surveyed DE systems. Provided that these tariffs accommodate for the flexibility of DE systems, these are not necessarily a hindrance for especially PtH. Capital for investments is generally perceived to be available. The perception on availability of capital became more conservative, when conversion from steam to hot water was discussed. Such an investment was perceived to be in the scale of hundreds of millions USD with expected long payback. The findings indicate that DE systems are an underutilised flexibility-asset in the US energy system.

A common solution is to bring perceptions from being estimates to informed choice. In practice by conducting techno-economic analyses of alternative scenarios in a manner, which take into account the benefits and costs of increased flexibility. Either for generic, but representative DE systems, or for an array of representative real DE systems.

6. Acknowledgements

I wish to thank the university DE plant managers who generously shared their knowledge and time with me. Furthermore, I wish to thank Professor Elizabeth Wilson, Dartmouth College, who kindly hosted me during the research stay where this research was conducted.

7. References

[1] Pompeo M. On the U.S. Withdrawal from the Paris Agreement. US Dep State Website 2019. https://www.state.gov/on-the-u-s-withdrawal-from-the-paris-agreement/ (accessed April 3, 2020).
[2] Pyper J. Tracking Progress on 100% Clean Energy Targets. Greentech Media Website 2019. https://www.greentechmedia.com/articles/read/tracking-progress-on-100-clean-energy-targets (accessed April 3, 2020).
[3] Bird L, Clevenger T. 2019 Was a Watershed Year for Clean Energy Commitments from U.S. States and Utilities. World Resour Inst Website 2019. https://www.wri.org/blog/2019/12/2019-was-watershed-year-clean-energy-commitments-us-states-and-utilities (accessed April 3, 2020).
[4] Münster M, Iliceto A, Berger M, Bramstoft R, Bühler F, Elmegaard B, et al. Sector Coupling: Defitions, state-of-the-art and perspectives 2020.
[5] IEA. The power of transformation. Paris: IEA; 2014. doi:10.1007/BF01532548.
[6] Lund H, Østergaard PA, Connolly D, Mathiesen BV. Smart energy and smart energy systems. Energy 2017;137:556–65. doi:10.1016/j.energy.2017.05.123.
[7] Østergaard PA, Lund H, Mathiesen BV. Smart energy systems and 4th generation district heating. Int J Sustain Energy Plan Manag 2016;10:1–2. doi:dx.doi.org/10.5278/ijsepm.2016.10.1.
[8] Lund H. Renewable Energy Systems. 2nd ed. Academic Press, Incorporated; 2014.
[9] Sneum DM. Barriers to flexibility in the district energy-electricity system interface – the (in)complete overview [Under peer review]. [Submitted to] Renew Sustain Energy Rev 2020.
[10] U.S. Department of Energy. U.S. DOE Combined Heat and Power Installation Database. US Dep Energy Website 2020. https://doe.icfwebservices.com/chpdb/ (accessed March 14, 2020).
[11] Gadd H, Werner S. Thermal energy storage systems for district heating and cooling. Adv. Therm. Energy Storage Syst. Methods Appl., Halmstad: Woodhead Publishing Limited; 2014, p. 467–78. doi:10.1533/9781782420965.4.467.
[12] US Energy Information Administration. U.S. District Energy Services Market Characterization. Washington: 2018.
[13] IEA. Renewable Heat Policies 2018.
[14] Billimoria S, Guccione L, Henchen M, Louis-Prescott L. The Economics of Electrifying Buildings. 2018.
[15] Shipley J, Lazar J, Farnsworth D, Kadoch C. Beneficial Electrification of Space Heating. Montpelier, VT: 2018.
[16] Pensini A, Rasmussen CN, Kempton W. Economic analysis of using excess renewable electricity to displace heating fuels. Appl Energy 2014;131:530–43. doi:10.1016/j.apenergy.2014.04.111.
[17] Konidena R, Sun B, Bhandari V. Missing discourse on microgrids – The importance of transmission and distribution infrastructure. Electr J 2020;33:106727. doi:10.1016/j.tej.2020.106727.
[18] Dragoon K, Papaefthymiou G. Power System Flexibility Strategic Roadmap - Preparing power systems to supply reliable power from variable energy resources. Berlin: 2015.
[19] Malskær NF. US district energy in the age of Trump. HOT|COOL 2017:8–9.
[20] Seel J, Mills A, Wiser R, Deb S, Asokkumar A, Hassanzadeh M, et al. Impacts of High Variable Renewable Energy Futures on Wholesale Electricity Prices, and on Electric-Sector Decision Making. 2018.
[21] Bade G. Updated: ISO-NE seeks to keep 1,600 MW of gas generation from retirement. Util Dive 2018. https://www.utilitydive.com/news/updated-iso-ne-seeks-to-keep-1600-mw-of-gas-generation-from-retirement/520567/ (accessed March 15, 2020).

[22] Lambert F. Tesla Powerwall is chosen for a virtual power plant in Lebanon, but Sunrun wants in. Electrek 2018. https://electrek.co/2018/04/07/tesla-powerwall-virtual-power-plant-lebanon-surun/ (accessed March 15, 2020).
[23] Berkeley Lab. Capacity and Generation by State | Electricity Markets and Policy Group. 2018 Wind Technol Mark Rep 2019. https://emp.lbl.gov/capacity-and-generation-state (accessed March 15, 2020).
[24] Berkeley Lab. Wind Energy Growth, 2010 to 2018 | Electricity Markets and Policy Group. Util Sol 2019 Ed 2019. https://emp.lbl.gov/wind-energy-growth-2010-2018 (accessed March 15, 2020).
[25] Møller Sneum D, Sandberg E, Emilie Rosenlund S, Klaus S, Ole Jess O. Framework conditions for flexibility in the district heating- electricity interface. Lyngby: 2016.
[26] Sneum DM, Sandberg E, Soysal ER, Skytte K, Olsen OJ. Framework conditions for flexibility in the district heating-electricity interface. Lyngby: 2016.
[27] Sandberg E, Sneum DM, Trømborg E. Framework conditions for Nordic district heating - Similarities and differences, and why Norway sticks out. Energy 2018;149:105–19. doi:10.1016/j.energy.2018.01.148.
[28] Creswell JW. Research design : qualitative, quantitative, and mixed methods approaches. 4th ed. Thousand Oaks: SAGE Publications; 2014.
[29] Sovacool BK, Axsen J, Sorrell S. Promoting novelty, rigor, and style in energy social science: Towards codes of practice for appropriate methods and research design. Energy Res Soc Sci 2018;45:12–42. doi:10.1016/j.erss.2018.07.007.
[30] Golove WH, Eto JH. Market Barriers to Energy Efficiency : A Critical Reappraisal of the Rationale for Public Policies to Promote Energy Efficiency. Energy Environ 1996;26:66. doi:10.1177/0042098011427189.
[31] Chittum A, Farley K. Utilities and the CHP Value Proposition. Washington, DC: 2013.
[32] Baumol WJ. Contestable Markets: An Uprising in the Theory of Industry Structure. Am. Econ. Rev., vol. 72, 1982, p. 1–15.
[33] Sandberg E, Kirkerud JG, Trømborg E, Bolkesjø TF. Energy system impacts of grid tariff structures for flexible power-to-district heat. Energy 2018. doi:10.1016/j.energy.2018.11.035.
[34] Sneum DM, Sandberg E. Economic incentives for flexible district heating in the Nordic countries. Int J Sustain Energy Plan Manag 2018;16:27–44. doi:10.5278/ijsepm.2018.16.3.
[35] Selecky J, Iverson K, Al-Jabir A. Standby Rates for Combined Heat and Power Systems. Montpelier: 2014.
[36] Pagliarini G, Rainieri S. Modeling of a thermal energy storage system coupled with combined heat and power generation for the heating requirements of a University Campus. Appl Therm Eng 2010;30:1255–61. doi:10.1016/j.applthermaleng.2010.02.008.
[37] Walton R. Thermal energy storage drops refrigerated warehouse's peak demand by 29%. Util Dive 2018. https://www.utilitydive.com/news/thermal-energy-storage-drops-refrigerated-warehouses-peak-demand-by-29/530718/ (accessed March 15, 2020).
[38] Walton R. Ice Energy, NRG installing new energy storage solutions for SoCal Edison. Util Dive 2018. https://www.utilitydive.com/news/ice-energy-nrg-installing-new-energy-storage-solutions-for-socal-edison/440436/ (accessed March 15, 2020).
[39] The Danish Energy Agency, Energinet. Technology Data - Energy storage v0007 2020.
[40] Lund R, Persson U. Mapping of potential heat sources for heat pumps for district heating in Denmark. Energy 2016;110:129–38. doi:10.1016/j.energy.2015.12.127.
[41] Rasmussen L, Rygaard S. Personal communication with Lotte Rasmussen and Søren Rygaard of Centrica Energy Trading A/S 2020.
[42] Energy Solutions Center Inc. CHP, DG, and microgrids energize universities. Gas Technol Mag 2018:A3–5.
[43] EMD International A/S. Svendborg District Heating. EMD Website 2020. http://www.energyweb.dk/svendborg/?english&history (accessed March 28, 2020).

8. Appendix

8.1 Interview template

Name		*Institution*		
Other	**Planning**	**Financing**	**Construction**	**Operation**
	Technical limitations	Stability of investment climate	Contractor's competence	Marginal production costs (taxes, tariffs, subsidies)
	Management competence		Grid connection	Operator's competences
	Advisor's competences	Advisor's competences		Grid codes
	Communication with decision-makers	Investment incentives		Market rules
	Clear goals to invest from			Technological (heat storage, limits in tech)
				Commodity prices

8.2 Identified barriers

Category	Sub-category	Barrier name	#	Barrier found
Operational signalling	Dispatch signals	Absence of signal-providing scheme	1	**U-Vermont**
		Electricity market: Absence of flexibility-need (involatile prices)	2	**U-Pennsylvania 2 U-Connecticut**
		Electricity market: Fixed electricity prices	3	**U-New Hampshire U-Vermont U-Connecticut**
		Physical vs. financial dispatch: Must-run operation	4	**U-New Hampshire U-Massachusetts 2 U-Massachusetts 3 U-Pennsylvania 1 U-Pennsylvania 2 U-Vermont**
	Operational taxes and subsidies	Operational taxes on flexible DE	5	**-**
		Favourable operational taxes on NEITG	6	**All**

		Inflexible operational subsidies for flexible DE	7	**-**
		Operational subsidies for NEITG	8	**-**
	Electricity grid tariffs	Electricity grid tariffs	9	**U-Massachusetts 1**
	Signal-related standards and procedures	Barriers for entry into signal-providing schemes	10	**-**
		Barriers for operation in signal-providing schemes	11	**-**
Investment		Investment subsidies for NEITG	12	**U-Massachusetts 1** **U-Massachusetts 2** **U-Massachusetts 3** **U-Vermont**
		Limitations in capital for flexible DE	13	**-**
		High risk premium for financing flexible DE	14	**-**
		Internal limitations from pay-back time and internal rate of return/discount rate requirements	15	**-**
		Externally imposed limitations from regulated rate of return	16	**-**
Permitting		Technology bans and mandates	17	**U-Pennsylvania 2**
		Inadequate legal framework for evaluation of DE projects	18	**-**
		Friction in the permitting process	19	**-**
Ownership		Tax- and ownership regulation disincentivising grid integration	20	**U-Massachusetts 2** **U-Massachusetts 3** **U-Pennsylvania 1** **U-Connecticut**
DE technology conditions		Limitations in adjustability, ramping and lead time	21	**-**
		High technological cost	22	**U-Pennsylvania 2**
		High business process costs	23	**-**
		Low supply chain maturity	24	**-**
		Limitations in control and visibility	25	**All**
		High-temperature systems	26	**All**
Grid access		High grid-connection cost	27	**-**
		Limiting grid codes	28	**-**
		Limiting grid capacity	29	**-**
Physical environment		Limited access to energy sources	30	**U-New Hampshire**
		Land availability	31	**U-Connecticut** **U-Massachusetts 2** **U-Massachusetts 3** **U-Pennsylvania 1** **U-Vermont** **U-Pennsylvania 2**
Bounded rationality		Limitations from organisational bounded rationality	32	**U-Pennsylvania 2**
		Limitations from community bounded rationality	33	**-**
		Limitations from authority bounded rationality	34	**-**
		Limitations from individual plant staff's bounded rationality	35	**U-Pennsylvania 2**
Acceptance		Limitations from organisational acceptance	36	**U-New Jersey** **U-Vermont**
		Limitations from community acceptance	37	**U-Massachusetts 3**
		Limitations from authority acceptance	38	**-**
		Limitations from incumbent acceptance	39	**-**
		Limitations from individual plant staff's acceptance	40	**-**

Journal of Energy Markets **10**(2), 1–19
DOI: 10.21314/JEM.2017.161

Research Paper

Barriers for district heating as a source of flexibility for the electricity system

Klaus Skytte, Ole Jess Olsen, Emilie Rosenlund Soysal and Daniel Møller Sneum

Department of Management Engineering, Energy Economics and Regulation, Technical University of Denmark (DTU), Produktionstorvet, Bldn 426, DK-2800 Lyngby, Denmark; emails: klsk@dtu.dk, oleo@dtu.dk, emso@dtu.dk, dasn@dtu.dk

(Received February 8, 2017; revised April 20, 2017; accepted April 24, 2017)

ABSTRACT

The Scandinavian countries Denmark, Norway and Sweden currently deploy large amounts of variable renewable energy (VRE) sources, especially wind power. This calls for additional flexibility in the power market. The right coupling to the underlying national and local district heating (DH) markets can generate large amounts of flexibility. However, regulatory barriers and different energy market designs may hinder the potential benefits from system integration, and lower the potential that can be realized. The Scandinavian countries have a large extension of DH with a good potential for providing flexibility services to the electricity market. We survey and discuss regulatory barriers and drivers for exploiting this potential for flexibility. Combined heat and power (CHP) is widely integrated in the power market, but it is threatened by low electricity prices due to the increasing amounts of wind power. Power-to-heat technologies, electric boilers and heat pumps are blocked by high tariffs and taxes. A calculation of the heat costs of different DH technologies demonstrates that, under the present price and tax conditions in Denmark and Sweden, CHP and power-to-heat are unable to compete with heat-only boilers that use tax-free biomass.

Keywords: variable renewable energy; regulation; combined heat and power (CHP); power-to-heat; energy taxes.

Corresponding author: K. Skytte

Print ISSN 1756-3607 | Online ISSN 1756-3615

1 INTRODUCTION

To reach the ambitious energy and climate goals of carbon-neutral energy systems, the three Scandinavian countries deploy a large proportion of variable renewable energy (VRE) sources, especially wind power, in addition to storable renewable energy sources, such as biomass and hydropower. By nature, the temporal supply of VRE is highly variable because

- it is determined by weather conditions,
- it is uncertain due to forecasting errors (Ravn and Skytte 2000), and
- it is location specific, as the primary energy carrier cannot be stored or transported like coal or biomass (Borenstein 2012; Hirth *et al* 2015).

Such properties imply major integration and interfacing challenges for VRE with the energy system. At high VRE penetration rates, the overall integration costs could be substantial (International Energy Agency 2014; Ueckerdt 2013); consequently, cost-effective integration of VRE has become a pressing challenge. The energy system requires much additional flexibility to minimize integration costs while ensuring balance in supply and consumption, security of supply and capacity adequacy and an increase in the economic value of domestic VRE (International Energy Agency 2013, 2014).

Integrating markets may expand the potential for flexibility at a low cost and thus contribute to an increase in the economic value of VRE. Thus far, the creation of the Nordic and internal European Union (EU) electricity markets has concentrated on central generation and harmonization of support schemes. Less has been done to create common regulatory frameworks for a supply of flexibility from other energy sectors, although flexibility is needed for further VRE deployment (Ropenus and Skytte 2007; Skytte 1999a). Until now, the Nordic power market has been able to handle the fluctuations of VRE (Skytte and Grohnheit 2017); however, when the amount of VRE surpasses a certain level, it can no longer be ignored in the planning and operation of the electricity supply system (Skytte and Ropenus 2006, 2007).

Hydropower from dams in Norway and Sweden accounts for a large percentage of the electricity supply, which today provides flexibility in the Nordic electricity market. However, hydropower resources are limited and strongly depend on variations in precipitation.

A flexible resource of considerable magnitude is district heating (DH), which is widely used in Scandinavian countries. With the right coupling of the Nordic power market to the underlying national and local DH markets, a considerable potential for flexibility can be generated cost effectively, and thus a larger amount of VRE can be embraced (Lund *et al* 2015).

Unlike the electricity market, DH has not been oriented toward liberalization (Sneum *et al* 2016). It is not economically feasible to transport hot water over longer distances and thus integrate the supply nationally or internationally. Therefore, DH is organized by local monopolies and regulated within a national framework, which can differ greatly even between historically and politically similar countries such as those in Scandinavia. However, as there are large interdependencies between electricity and DH, changed conditions or barriers on one side create new conditions on the other (Skytte 1999a; Sneum *et al* 2016). Therefore, improvements in the regulatory frameworks of the DH sector that can supply flexibility must occur alongside growth in VRE in the electricity supply in order to develop coherent energy markets. This strategy will require well-thought-out market designs and framework conditions, implemented in a timely fashion. Otherwise, the diverging framework conditions (eg, heat versus electricity) may prevent the transition to integrated energy systems and increased flexibility. Without additional flexibility, even the well-functioning Nordic power market mechanism could come under pressure.

In this paper, we investigate the barriers to including DH as a flexible resource for the electricity market in the Scandinavian countries Denmark, Norway and Sweden. Denmark has the largest share of wind energy in the world and thus has the most immediate need for flexible resources. Denmark is also already deploying DH as an important source of flexibility. The problem today is smaller for the two other countries, but it will increase with the present and future rapid growth of wind power. However, there are several barriers to continuing and extending the use of DH for this purpose. Market development threatens the extended utilization of combined heat and power (CHP) as a flexible resource, and important barriers to the introduction of large-scale electric heating exist.

This paper starts with a short presentation of the Nordic power market and its present solutions for balancing the system. Then, DH in our three selected countries is introduced, and the barriers to supplying flexibility to their electricity systems are identified and discussed. Of particular interest are those barriers within the framework conditions for CHP and power-to-heat technologies, such as electric boilers and large heat pumps. The use of flexible DH technologies to balance markets is analyzed with a numerical example. Our findings are discussed in the concluding section of the paper.

2 THE NORDIC POWER MARKET

The common Nordic power market, Nord Pool, has a long tradition of coordinating supply and exchanging flexibility services (Olsen and Skytte 2003). The market dates to 1971 and was originally designed to balance variations in precipitation and water inflow to hydropower stations. Later, the market was further developed to exploit

beneficial interaction among and within the Nordic countries between hydropower and large thermal plants (conventional coal power and nuclear power plants). This development was very effective. In wet precipitation years, production in flexible conventional power plants in Denmark and Finland decreased, and excess generation by Norwegian and Swedish hydropower plants was exported to Denmark and Finland (and later to other countries in Northern Europe). In dry precipitation years, Norway and Sweden imported electricity from conventional power plants in other countries (Førsund 2011).

This beneficial exchange between the countries is facilitated by the considerable capacity of the interconnectors that connect the national transmission grids. New interconnector lines are being constructed to neighboring countries, such as Germany and the Netherlands, which are expected to contribute positively to balancing Nordic power systems.

In line with the transition to a fossil-free energy system in the Nordic countries, flexible conventional fossil fuel power plants are being phased out, and VRE (especially wind energy) is being deployed instead. This development is challenging the stability of the Nordic power market. It was first seen in Denmark, which has made a dramatic change from centralized coal-fired power plants to a large percentage of wind energy.

In 1990, Denmark's wind turbines contributed 2% of its total power generation, while large coal-fired plants contributed 94%. In 2014, the share of these two technologies was of a similar magnitude (41% and 45%, respectively), and this trend is expected to continue in future. By 2020, the political goal is for 50% of the annual electricity generation to come from wind energy.

The power supply in Norway is entirely dominated by hydropower; in Sweden, hydropower and nuclear power each account for about 40% of the supply. Both countries now have ambitious plans to extend new, renewable energy. Sweden created a market for green certificates in 2003 that Norway has now joined. During the last ten years, the deployment of wind energy has increased rapidly in Sweden and now accounts for about 10% of the total supply.

The increasing need for flexibility in the energy system also comes from neighboring countries such as Germany, which is deploying a significant amount of wind energy just south of Denmark. This restricts the possibility of using the transmission lines to send Danish surplus electricity to Germany. In fact, bottlenecks in the German transmission lines may even increase the need for additional flexibility in Denmark.

3 DISTRICT HEATING AS A SOURCE OF FLEXIBILITY

Flexibility can be defined as a measure to maintain a balance between the generation and consumption of electricity, since the variability in generation and consumption

is to be balanced in flexible supply and flexible demand. The term "variable" can be defined as fluctuating variations that cannot be controlled, whereas the term "flexible" is used when it is possible to regulate the increase or decrease of generation or consumption. These definitions are not only technical (a gas turbine can follow the load, whereas a wind turbine cannot), but also behavioral (does the gas turbine have an incentive?) and regulatory (do public rules, taxes, etc, create barriers to acting flexibly?). Similar considerations can be applied to the demand side. A DH plant coupled with the electricity system is usually dispatchable; the question is whether there are incentives for or barriers to exploiting this potential.

DH is coupled to the electricity system either by CHP, which sells the electricity at the power market, or by power-to-heat plants (eg, electric boilers and heat pumps), which convert electricity bought at the power market to heat. Such plants can be dispatched and therefore are potential providers of flexibility services.

Today, flexibility in the Scandinavian system is mainly provided by CHP combined with heat storage (water tanks) that can shift the generation to hours when electricity prices are high. Water tanks are widely installed and used in Denmark and Sweden. This flexibility potential is very important in Denmark due to its large share of wind energy and lack of hydropower.

CHP plants prefer to operate when power prices are high. If this happens at times with low heat demand, the surplus heat is stored in the water tank. When electricity prices are low, the plant is closed, and heat is extracted from storage. Smaller CHP plants apply back-pressure technology with a fixed proportion between power and heat. Large condensing-extraction CHP plants offer additional flexibility by varying the steam outlet for heat (some even have the option to let all steam bypass the turbine), and because very fast ramping rates have been developed, especially in the Danish CHP plants that use this technology.

Power-to-heat technologies, such as electric boilers and large heat pumps, can provide additional flexibility and are being tested in some DH systems. Power-to-heat will provide the option of using surplus electricity for heat generation when electricity prices are low, which occurs more often with large capacities of wind power (Ravn and Skytte 1999). At present, hydropower is used as a flexible resource when there is surplus electricity. Thus, the pressure on hydropower from the increasing flexibility demand can be eased by power-to-heat. However, there are several barriers to exploiting these technologies in an optimal way, such as taxation and the design of the grid tariffs. In contrast, the design of the different markets (spot, intraday and ancillary services) does not provide obstacles to the use of power-to-heat as a flexible resource.

In the following, we investigate the economics and framework conditions for electric boilers and large heat pumps in the DH system.

TABLE 1 Descriptive statistics regarding district heating in the three Scandinavian countries (Sneum *et al* 2016).

	District heating			
	Percentage of heat supply	**CHP percentage of DH**	**CHP percentage of electricity supply**	**Power-to-heat percentage of DH**
Denmark	50%	69%	65%	<1%
Norway	<5%	<1%	<1%	22%
Sweden	32%	50%	9%	9%

4 DISTRICT HEATING IN THE SCANDINAVIAN COUNTRIES

The Scandinavian countries have a long heating season, which makes DH an economic option. DH networks were constructed a long time ago and now account for 50% and 32% of the total heat supply in Denmark and Sweden, respectively. However, they account for less than 5% in Norway, where individual electric heating has long dominated the heat supply (see Table 1). The share of DH in the heat supply is even higher for residential homes (63% in Denmark), where heat is used not only for space heating but also for domestic hot water.

In Denmark, DH is supplied by central power plants (extraction-condensing, 40%), local DH plants (back-pressure, 40%), waste incineration plants and surplus heat from the manufacturing industry (20%). A total of 69% of the DH supply is produced by CHP plants. These plants contributed a significant percentage of electricity generation (65%). A very small but increasing share of DH in Denmark is from electric boilers, large heat pumps and large solar panels.

In Sweden, DH is supplied by CHP (50%), heat-only boilers (41%) and heat pumps and boilers (9%). The percentage of electricity generation is much lower than in Denmark (9%). In Norway, DH is marginal for the heat and electricity markets (<1%). Waste is an important fuel in Sweden as well as the other two countries.

Denmark has a long tradition of regulating the heat supply (Münster *et al* 2012). Thermal energy planning in Denmark was implemented in the early 1980s and focused on developing least-cost zones for a collective natural gas supply, DH based on heat-only boilers and CHP, and individual heat supply (mostly oil boilers). In areas dedicated to DH, connections to the DH grid were mandatory, which ensured the fast and dense penetration of DH.

Traditionally, Denmark has given preferential status to CHP. Central power plants were transformed into CHP, and, in the 1990s, DH plants with heat-only boilers were forced to substitute them with gas-fired CHP. Landfills were banned and substituted

with waste incineration, which were later forced to transform into CHP. As most CHP plants have thermal storage (water tanks), they provide a very flexible electricity supply.

The authorities in the other two Scandinavian countries also favored DH and CHP, but less so than in Denmark. No heat plans dedicate certain areas to DH to protect the local DH monopoly from competition from other heat sources. This means that utility companies developed DH according to private economic incentives. Tax exemptions favor CHP when biomass is used as a fuel. In Norway and Sweden, CHP plants that use biomass (including waste) are subsidized by green certificates.

Today, the flexibility provided by CHP is threatened from several directions. Gas-fired CHP in Denmark receives a small subsidy; however, the prolongation of this support scheme beyond 2018 is an object of political discussion and therefore uncertain. In addition, the high share of VRE in the power market has decreased the price of electricity, which has resulted in fewer and fewer hours of economic generation by the CHP plants. This lack of economic operating hours threatens large central CHP plants in particular. In Sweden, many biomass-fired CHP plants were constructed after green certificates were introduced in 2003. Recently, the percentage of this technology in the power-generation mix has decreased significantly, as the right to obtain green certificates has expired for many older plants. Low electricity prices that are expected to continue, in combination with high investment costs for small CHP plants that use biomass, make it more economical for DH utility companies to invest in heat-only boilers that use tax-free biomass.

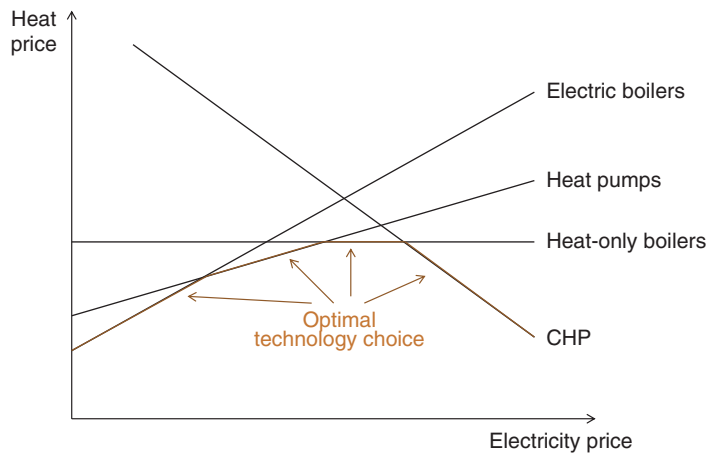
In Denmark, a counter-tendency is represented by municipalities in large cities taking control of central power plants to secure the future heat supply. The remaining CHP, waste incineration, is not very flexible, as the primary task of a waste incineration plant is to manage waste. Therefore, these plants have to run all day and are mainly used as the base load.

5 OPTIMAL USE OF TECHNOLOGIES FOR DH

In a DH system with several heat-generation technologies, heat should be generated according to a merit order, with the technologies ranked according to (short-term) marginal heat-generation cost. The merit order for the technologies considered here depends on the price of electricity, but in different ways. The impact of the price of electricity on different DH technologies is illustrated in Figure 1.

CHP plants generate heat and electricity. As CHP plants sell electricity at market prices, the heat cost of CHP has a negative dependency on electricity prices: the higher the price for the electricity produced, the lower the price for the heat produced. This is illustrated by the negative slope of the CHP line in Figure 1.

FIGURE 1 Choice of heat supply technologies with different electricity prices.

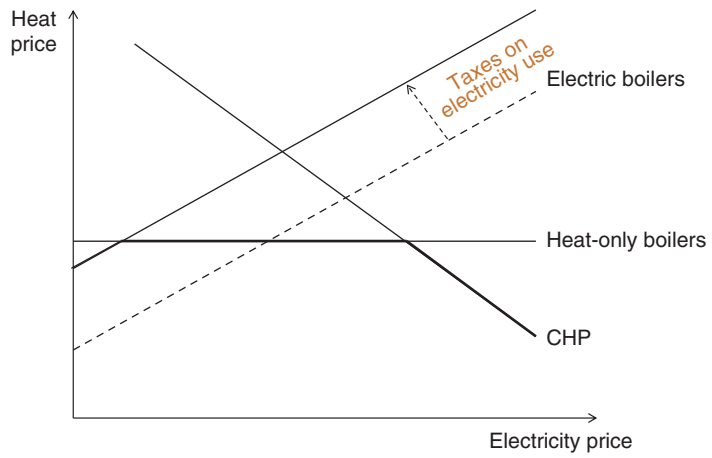


Electric boilers convert electricity to heat with an efficiency close to 100%, which means that an increase in electricity price of €1 increases the heat cost by €1. Thus, the line in Figure 1 representing electric boilers has a slope of 1.

Heat pumps also use electricity to generate heat, but with much higher efficiency than electric boilers. Depending on the temperature of the heat source, heat pumps' coefficient of performance (COP) values vary between 2.5 and 6. Therefore, the relationship between electricity and heat prices is positive but less than 1; this is represented in Figure 1 by the line for heat pumps having a less steep slope than that for electric boilers. Finally, heat-only (HO) boilers (ie, natural gas or biomass combustion) do not use or produce electricity and therefore generate heat independently of the electricity price.

The level of the lines in Figure 1 depends on the fuel choice and prices, grid tariffs and energy taxes. Figure 2 shows how an energy tax on electricity used to generate heat increases the marginal cost of electric boilers, leading to these technologies being the optimal dispatch choice only at very low electricity prices. As a result, heat-only boilers will be used more. The problem derives from the present system of energy taxation, in which electricity is taxed at the consumer. For heat production, the fuel consumed is taxed. Furthermore, the structure of the grid cost plays an important role in the competitiveness of power-to-heat technologies. Grid costs usually consist of a capacity charge (euros per MW) and an energy charge (euros per MWh), and while the former does not affect short-term marginal costs, the latter does. Shifting the weight of the tariff from capacity to energy increases the short-term marginal

FIGURE 2 Effect of taxes on heat costs with different electricity prices.



cost and reduces the possibility that power-to-heat technologies will be the optimal dispatch choice.

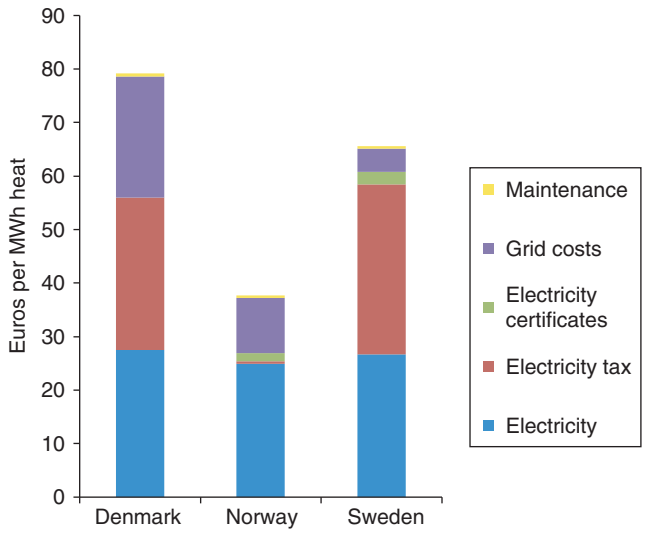
6 CAN POWER-TO-HEAT COMPETE?

Power-to-heat technologies, such as electric boilers and large heat pumps, are interesting options for future integration between DH and the electricity system. In this section, we compare the framework conditions for these technologies and the resulting production costs in our three Scandinavian countries. Electric boilers are an interesting provider of flexibility for the power system, as they have low investment costs and therefore require relatively few hours of operation to cover these costs. Heat pumps have larger investments costs, which require more hours of operation to cover, and higher start-up costs, which make the pumps less flexible.

Large heat pumps and electric boilers in DH have to a larger extent than in Denmark been deployed in Norway and Sweden. However, DH is marginal in Norway, and the introduction of new capacity has stagnated for a long time in Sweden. In Denmark, there has been much discussion about these technologies, but thus far, little has been realized. There are cases of such plants being installed and operated by Danish DH utilities for peak loads or balancing power to Germany (see below), but they are very few.

The high costs of power-to-heat technologies create an important barrier to their increased deployment in the DH system. The short-term marginal cost (from here on,

FIGURE 3 Marginal cost of DH from electric boilers in Denmark, Norway and Sweden.

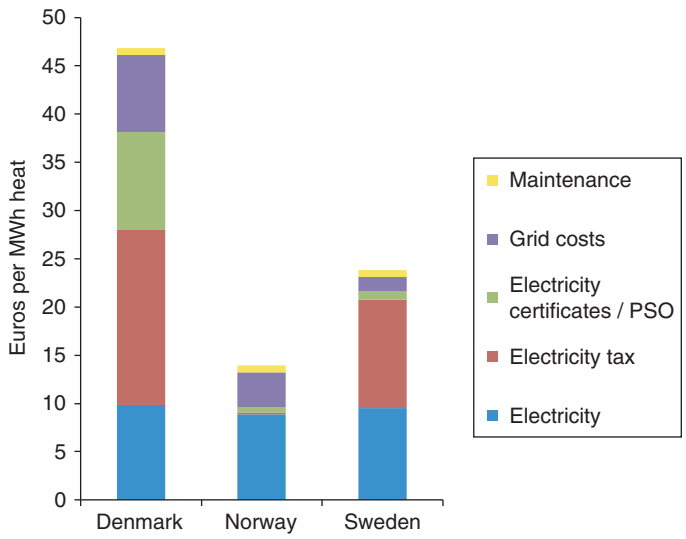


marginal costs) of heat is determined not only by the electricity prices but also by other variable costs, such as grid tariffs and taxes. In Figures 3 and 4, the different components of the marginal costs of electric boilers and large heat pumps (with COP 2.8) in Denmark, Norway and Sweden are presented. The figures demonstrate how differences in national taxation policy and variable grid tariffs lead to significant differences in the marginal cost of heat among the three countries. The present tariffs and taxes on the use of electricity for heat generation increase the marginal heat costs in Denmark and Sweden for electric boilers and large heat pumps by more than 100%, under the assumption of the average spot electricity price in 2014–15 for each country.

Electric boilers and heat pumps are usually installed in a DH system in which other generation technologies exist. The marginal costs determine the optimal dispatch of the technologies, and therefore the competitiveness of each technology. As demonstrated in the figures, the marginal costs of power-to-heat installations in the Scandinavian countries depend heavily on the taxes and tariffs on electricity consumption. They change the merit order between the heat-generating technologies completely. In Figures 5–7, the marginal heat costs of electric boilers and large heat pumps are compared with those of the competing technologies for a range of electricity prices in Denmark, Norway and Sweden.

The alternatives considered are wood chip-fired or natural gas CHP and heat-only boilers. The technical data, including efficiencies and emissions, is taken from the

FIGURE 4 Marginal cost of heat from heat pumps with COP 2.8 in Denmark, Sweden and Norway.



Danish Energy Agency's (2016) technology catalog. Together with national taxation laws and grid cost statistics, the technical data provides the foundation for calculating the marginal cost. Rosenlund Soysal *et al* (2016) provide a detailed account of the calculation.

Natural gas boilers and CHP are not available in Norway. The COP for heat pumps in Figure 4 is assumed to be 2.8. When the marginal costs of electric boilers and heat pumps are compared with those of competing technologies, the lack of competitiveness in Denmark and Sweden becomes evident.

The dark blue line in Figure 5 indicates the cost of electric boilers, while the light blue line represents the cost of heat pumps. The electricity prices at which the marginal heat cost of electric boilers is equal to that of natural gas HO and CHP are marked by the intercept between the dark blue line and the orange and red lines, respectively. As can be seen in Figure 5, under the present cost structure, biomass is always cheaper than electric boilers and heat pumps. Electric boilers can compete with natural gas boilers for prices lower than €10.1 per MWh, and with natural gas CHP at prices lower than €22.5 per MWh. Heat pumps can compete with natural gas CHP and HO at electricity prices below €44.2 per MWh and €69.3 per MWh, respectively.

In Norway (Figure 6), it is possible for electric boilers to compete with biomass HO at electricity prices below €10.5 per MWh, and with biomass CHP at prices lower

FIGURE 5 Denmark: marginal cost of heat as a function of the price of electricity (NG = natural gas).

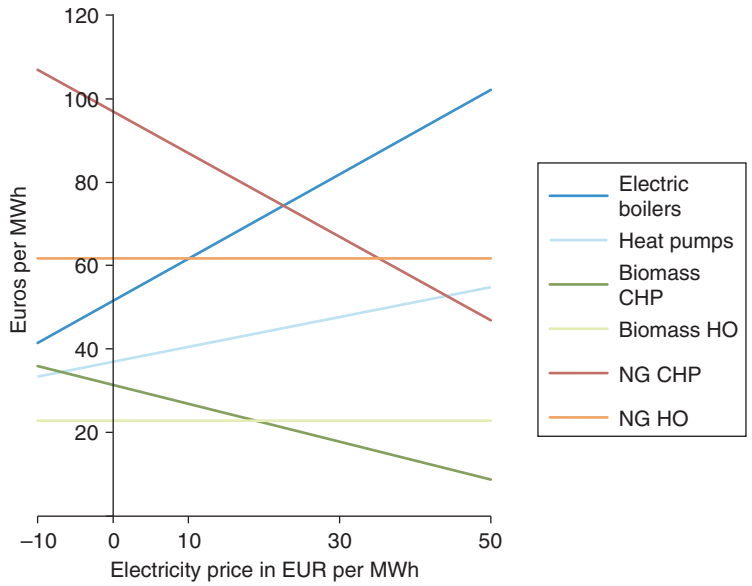


FIGURE 6 Norway: marginal cost of heat as a function of the price of electricity.

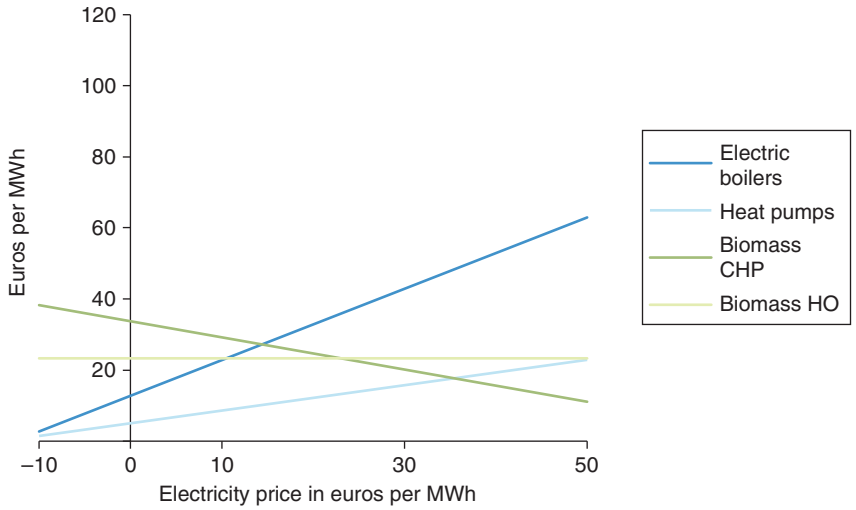
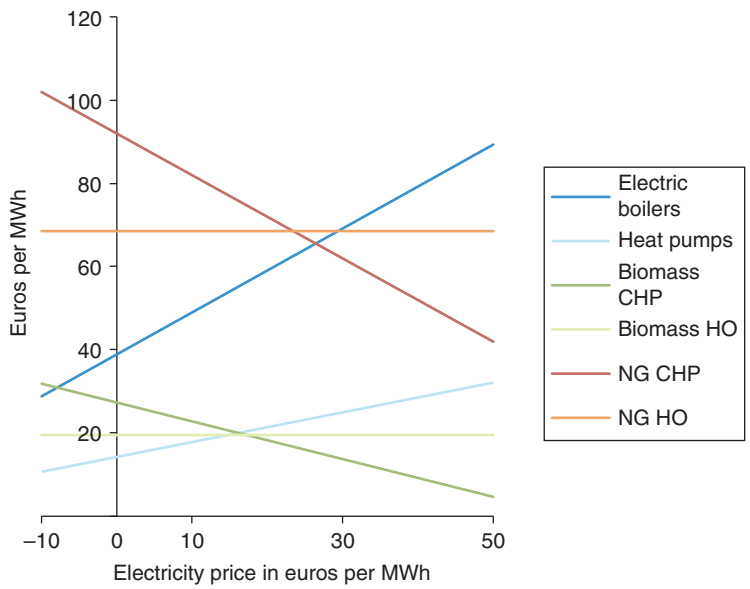


FIGURE 7 Sweden: marginal cost of heat as a function of the price of electricity (NG = natural gas).



than €14.4 per MWh. Heat pumps are a very competitive alternative to biomass CHP and HO, and they are the optimal dispatch options for prices below €35.5 per MWh and €51.2 per MWh, respectively.

The situation in Sweden (Figure 7) is similar to that in Denmark. Electric boilers cannot compete with biomass but they can compete with natural gas HO up to an electricity price of €26.4 per MWh, and with natural gas CHP up to a price of €29.4 per MWh. Heat pumps have lower marginal costs than biomass CHP and HO at electricity prices below €35.5 per MWh and €14.7 per MWh, respectively. Furthermore, heat pumps are always cheaper to run than natural gas plants. However, in Sweden, natural gas is available only in a limited area in the southeastern region.

6.1 Hours of operation

This numerical analysis gives rise to an additional question: how often will the spot market price make it possible for electric boilers and heat pumps to compete with the other technologies? We calculated the number of hours the spot prices in 2014–15 were below break-even prices, given by the intercept between the lines representing electric boilers, heat pumps and the competing technologies. The numbers of hours

TABLE 2 The percentage of hours in which electric boilers are the optimal dispatch choice compared with the competing technologies.

	Electric boilers (% hours of operation)			
	Biomass CHP	**Biomass HO**	**Natural gas CHP**	**Natural gas HO**
Denmark	0.1%	0.0%	25.8%	6.6%
Norway	14.4%	7.1%	—	—
Sweden	0.0%	0.0%	46.0%	61.4%

The percentages are calculated as a country average based on historical hourly price observations at Nord Pool in 2014 and 2015.

of feasible operation are presented in Tables 2 and 3 as a percentage of the total hours in these two years.

As can be seen in Table 2, the number of hours of electric boilers is close to zero when competing with biomass technologies in Denmark and Sweden; however, in Norway, for 7–14% of the hours the prices are low enough for electric boilers to compete. The number of hours is significant when electric boilers compete with natural gas technologies in Sweden, but the availability of natural gas is very limited in Sweden. In Denmark, with a significant share of natural gas CHP, the number of hours is about one-fourth. To pay the investment costs of a boiler, the price should be significantly lower than the break-even price in a considerable number of hours. In a similar fashion, Table 3 presents the number of hours in which heat pumps have lower marginal costs than competing technologies. The numbers indicate that heat pumps have far lower marginal costs than natural gas CHP plants; however, only in Norway are heat pumps competitive with biomass plants the majority of the time. However, these figures depend on the assumption of the COP: a higher COP value can increase the competitiveness of the heat pump significantly.

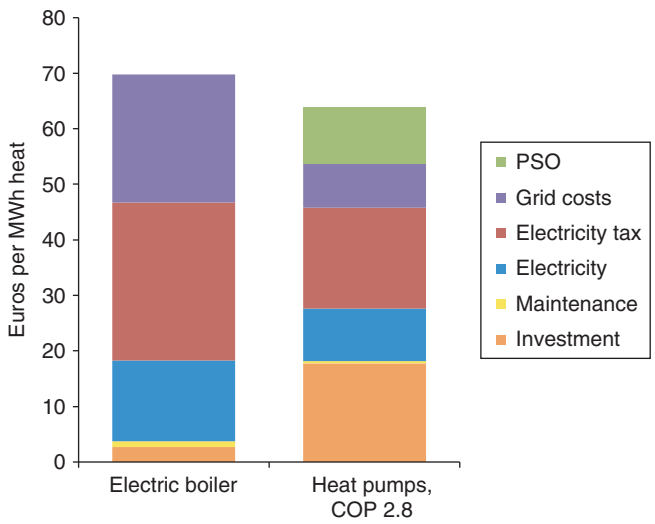
Based on the number of hours in which electric boilers and heat pumps are the optimal dispatch choice, the total cost of heat produced by the two technologies can be calculated. To give an example of this calculation, we consider a DH plant in eastern Denmark with an existing natural gas CHP plant. Electric boilers would be the optimal dispatch choice in 23% of the hours of the year, while a heat pump would be optimal 94% of the time. If investing in either a heat pump or an electric boiler, the resulting levelized cost of heat (LCOH) of the respective technologies is €69.74 per MWh and €63.92 per MWh. For heat pumps, the investment cost contributes significantly to the LCOH, while the LCOH of electric boilers is mainly driven by taxation and grid costs. Figure 8 shows the cost distribution of the two technologies.

TABLE 3 The percentage of hours in which heat pumps are the optimal dispatch choice compared with the competing technologies.

	Heat pumps (% hours of operation)			
	Biomass CHP	**Biomass HO**	**Natural gas CHP**	**Natural gas HO**
Denmark	0.2%	0.0%	93.3%	99.8%
Norway	95.8%	99.6%	—	—
Sweden	14.2%	12.5%	99.6%	100.0%

The percentages are calculated as a country average based on historical hourly price observations in 2014 and 2015.

FIGURE 8 Levelized cost of heat (LCOH) for electric boilers and heat pumps in eastern Denmark, when competing with natural gas CHP.



The calculations are based on operations 23% and 94% of the time, respectively. Despite the increased hours of operation, the investment cost of heat pumps significantly affects the LCOH.

6.2 Can the balancing market be an alternative?

Are there other opportunities for power-to-heat technologies in the present circumstances? As well as in the spot market, electricity can be bought as down-regulation services in balancing markets, which are operated by the transmission system operators. In Denmark, there are two such markets: the regulating power market and a market for special regulation. The former is a balancing market close to real time,

with marginal cost pricing. It was organized cooperatively by Denmark, Sweden, Norway and Finland (Skytte 1999b; Skytte 2000). The market for special regulation is a pay-as-bid market, used in situations when transmission grid constraints limit the applicability of the common regulating power market. That is, the system operator Energinet.dk can handpick the bids with respect to bottlenecks in the transmission grid and without disturbing the marginal price setting in the regulating power market. The special regulating market is mostly used to handle surplus electricity from German wind farms where grid constraints exist in Germany.

In western Denmark, a total of 157 GWh of down-regulation were traded in 2015 in the common regulating power market. At the same time, 401 GWh of special down-regulation were supplied. In December 2015 alone, more than 160 GWh were traded as special regulation, which is more than the total annual down-regulation demanded in the regulating power market.

The prices in these markets are lower than those in the spot market (Skytte 1999b; Skytte 2000), and even negative in hours with large electricity surplus; this provides a good business case for power-to-heat technologies. In particular, electric boilers, which are very flexible, can improve profitability by supplying down-regulation services. Electric boilers also have a low investment cost (see Figure 8), which means they do not need as many hours of operation to pay this cost. The balancing market therefore has the potential as a driver to introduce more electricity boilers into the system.

Large heat pumps are not very active in the balancing markets. Due to the large investment costs associated with large heat pumps, they are mainly used as the base load. In addition, they have a lead time from cold start until the optimal efficiency is reached. This implies that it is not cost-effective to use heat pumps for short-term flexibility in the balancing markets between hours with short start–stop intervals.

7 DISCUSSION AND MAIN FINDINGS

The rapid increase in electricity generated by intermittent renewable energy technologies, such as wind power, will either increase balancing costs dramatically or require an increased use of flexible resources that can help to balance the system. In cold countries such as those in Scandinavia, extended use of DH integrated with the electricity system can provide an important flexible resource. CHP plants with water storage already provide such services. Power-to-heat technologies, such as heat pumps and electric boilers, can serve as an important flexible resource through demand response, especially when there is an electricity surplus with very low or even negative electricity prices.

This paper reveals that the choice of technologies for generating heat is mainly driven by outdated policies and regulatory framework conditions that raise barriers

to additional flexibility in the overall energy system. Although, unlike the electricity market, DH has not been oriented toward liberalization, the heavy interdependencies between the two sides implies that changed framework conditions on one side create new conditions on the other.

Denmark, Norway and Sweden have very different electricity supply systems, which is also reflected in their respective heat supplies. Denmark and Sweden have a large share of DH, but this is marginal in Norway, which has long relied on individual electric heating. Norway and Sweden have large amounts of hydropower that provide abundant resources for balancing the electricity system. Denmark boasts the largest wind energy contribution to electricity generation. Thus far, (coal- and gas-fired) CHP has provided the electricity system with important flexible services. On a smaller scale, Sweden has developed a certain amount of biomass-fired CHP. However, CHP technologies are being threatened by the development of the market and, in some cases, are being substituted by tax-free heat-only boilers; this implies an increase in decoupling of DH from the electricity system. While some developments are unavoidable (eg, thermal power plants becoming less economically feasible due to increasing wind production causing many hours with low spot market prices), some can be avoided by political action that adapts the energy tax system to present-day realities.

The barriers created to increasing the integration of DH with the electricity system by current energy taxes become even more evident when we switch our focus to power-to-heat technologies, such as large heat pumps and electric boilers. They should benefit from many hours with low spot market prices for electricity. However, heavy taxation of electricity combined with tax exemption for biomass makes it almost impossible for these technologies to compete, even when electricity prices are very low. Grid tariffs also constitute a significant barrier, as they are not adapted to market conditions. Adapting the system of energy taxes to the current conditions and political priorities is mandatory to enhance the flexibility potential offered by DH, but, politically, it is very hard to achieve.

DECLARATION OF INTEREST

The authors report no conflicts of interest. The authors alone are responsible for the content and writing of the paper.

ACKNOWLEDGEMENTS

This paper was prepared as part of the research project Flex4RES, supported by Nordic Energy Research, for which we are grateful. We thank the two reviewers of this journal for their suggestions, which have greatly improved the paper. We are

also thankful for comments received at the International Conference on the European Energy Market 2016, where the content of this paper was first presented.

REFERENCES

Borenstein, S. (2012). The private and public economics of renewable electricity generation. *Journal of Economic Perspectives* **26**, 67–92 (http://doi.org/b62x).

Danish Energy Agency (2016). Technology data for energy plant. Report, Ministry of Energy, Utilities and Climate. URL: http://bit.ly/2qzJqgk.

Førsund, F. R. (2011). Energy in a bathtub: electricity trade between countries with different generation technologies. In *Modern Cost–Benefit Analysis of Hydropower Conflicts*, Johansson, P.-O., and Kriström, B. (eds), pp. 76–96. Edward Elgar, Cheltenham.

Hirth, L., Ueckerdt, F., and Edenhofer, O. (2015). Integration costs revisited: an economic framework for wind and solar variability. *Renewable Energy* **74**, 925–939 (http://doi.org/b62z).

International Energy Agency (2013). Nordic energy technology perspectives. Report, IEA.

International Energy Agency (2014). The power of transformation: wind, sun and the economics of flexible power systems. Report, IEA.

Lund, P. D., Lindgren, J., Mikkola, J., and Salpakari, J. (2015). Review of energy system flexibility measures to enable high levels of variable renewable electricity. *Renewable and Sustainable Energy Reviews* **45**, 785–807 (http://doi.org/f67bg8).

Münster, M., Morthorst, P. E., Larsen, H. V., Bregnbæk, L., Werling, J., Lindboe, H. H., and Ravn, H. (2012). The role of district heating in the future Danish energy system. *Energy* **48**(1), 47–55 (http://doi.org/f4m9nr).

Olsen, O. J., and Skytte, K. (2003). Competition and market power in Northern Europe. In *Competition in European Electricity Markets*, Glachant, J.-M., and Finon, D. (eds), pp. 169–192. Edward Elgar, Cheltenham.

Ravn, H. F., and Skytte, K. (1999). Optimal use of heat pumps at the power exchange. In *Proceedings*, Frederiksen, S. (ed). Nordic Energy Research Programme, Lund.

Ravn, H. F., and Skytte, K. (2000). Uncertainty in energy-economic modelling of the electrical power sector. *Annals of Software Engineering* **97**(1–4), 213–229.

Ropenus, S., and Skytte, K. (2007). Regulatory review and barriers for the electricity supply system for distributed generation in the EU-15. *International Journal of Distributed Energy Resources* **3**, 243–257.

Rosenlund Soysal, E., Sneum, D. M., Skytte, K., and Olsen, O. J. (2016). Electric boilers in district heating systems: a comparative study of the Scandinavian market conditions. In *Proceedings of Swedish Association for Energy Economics (SAEE) Conference 2016*. SAEE.

Skytte, K. (1999a). Market imperfections on the power markets in northern Europe: a survey paper. *Energy Policy* **27**, 25–32 (http://doi.org/fvxgpm).

Skytte, K. (1999b). The regulating power market on the Nordic power exchange Nord Pool: an econometric analysis. *Energy Economics* **21**(4), 295–308 (http://doi.org/dnvkh4).

Skytte, K. (2000). Fluctuating renewable energy on the power exchange. In *The International Energy Experience: Markets, Regulation and the Environment*, MacKerron, G., and Pearson, P. (eds), pp. 219–231. Imperial College Press, London.

Skytte, K., and Grohnheit, P. E. (2017). Market prices in a power market with more than 50% wind power. In *Electricity Markets, Renewable Generation and Software Agents: Traditional and Emerging Market Designs*, Lopes, F., and Coelho, H. (eds), Chapter 4, pp. 79–92. Springer (forthcoming).

Skytte, K., and Ropenus, S. (2006). Assessment and recommendations: overcoming in short-term grid system regulatory and other barriers to distributed generation. Report D2, DG-GRID Project.

Skytte, K., and Ropenus, S. (2007). Economic, policy and regulatory barriers and solutions for integrating more DER in electricity supply. Report, SOLID-DER Project.

Sneum, D. M., Sandberg, E., Rosenlund Soysal, E., Skytte, K., and Olsen, O. J. (2016). Flexibility in the district heating-electricity interface. Report, Nordic Energy Research.

Ueckerdt, F., Hirth, L., Luderer, G., and Edenhofer, O. (2013). System LCOE: what are the costs of variable renewables? *Energy* **63**, 61–75 (http://doi.org/bjq2).

Utilities Policy 51 (2018) 61–72

Contents lists available at ScienceDirect

Utilities Policy

journal homepage: www.elsevier.com/locate/jup

Policy incentives for flexible district heating in the Baltic countries

Daniel Møller Sneum[a,*], Eli Sandberg[b], Hardi Koduvere[c], Ole Jess Olsen[d], Dagnija Blumberga[e]

[a] DTU Management Engineering, Systems Analysis Division, Produktionstorvet, Building 426, DK-2800 Lyngby, Denmark
[b] Faculty of Environmental Sciences and Natural Resource Management, Norwegian University of Life Sciences, PO Box 5003, N-1432 Ås, Norway
[c] Tallinn University of Technology, School of Engineering, Department of Electrical Power Engineering and Mechatronics, Estonia
[d] DTU Management Engineering, System Analysis Division, Denmark
[e] Riga Technical University, Institute of Energy Systems and Environment, Faculty of Power and Electrical Engineering, Latvia

ARTICLE INFO

Keywords:
District heating
Flexibility
Energy policy

ABSTRACT

This study analyzes the impacts of taxes, subsidies, and electricity transmission and distribution tariffs and heat storage on the operation and economic feasibility of district heating plants with different flexibility potentials in the Baltic countries. Under 2016 conditions, the lowest levelized cost of heat is achieved by a combination of wood chip boilers, electric boilers, and heat storage. Heat storage enables a higher utilization of least-cost technologies, resulting in greater cost efficiency for all considered scenarios. Current taxes and subsidies are found to have limited impact on the operation of combined heat and power plants and electric boilers.

1. Introduction

The renewable shares of 2014 total final energy consumption in Estonia, Latvia, and Lithuania were 25, 40 and 28%, respectively. These shares have increased steadily since the dissolution of the Soviet Union in 1991, when they were 3, 18, and 3% (The World Bank, 2017). The renewable share in Baltic district heating (DH[1]) systems is already significant: In 2015, biofuels represented 43, 37, and 59% of DH in Estonia, Latvia, and Lithuania, respectively, most of which was solid biomass (IEA, 2017). Heat-only boilers and combined heat and power (CHP) options, which use biomass as their only fuel source, are, therefore, currently common in the Baltic countries. In addition to biomass, the main fuels used in DH are natural gas and waste (Sneum et al., 2016). In 2015, the three Baltic countries managed a combined net export of more than four million tons of fuelwood (Eurostat, 2017), indicating strong potential for regional biomass development. The renewable share in the Baltic energy systems is expected to increase further, as energy and climate policy indicate a general future increase in renewable energy across the EU member states to achieve compliance with national action plans for the 20-20-20 targets (e.g., the Latvian Guidelines of Energy Development for 2016–2020 (Likumi, 2016)), and the proposed EU 2030 targets (European Commission, 2014). Assuming that a proportion of this increased share of renewable energy will stem from variable renewable energy (VRE) sources, such as wind power and solar photovoltaics, there may arise an increased need for a well-integrated and flexible energy system. The matter of security of supply and energy imports adds to this picture. The Baltic countries are largely dependent on imported fossil fuels (Roos et al., 2012). The Ignalina nuclear power plant in Lithuania accounted for 70% of the country's electricity production before it was shut down in 2009 (IEA, 2014a), and Lithuania's dependence on imported energy resources has increased remarkably since the closure, growing from 50 to 62% to approximately 80–82%, exceeding the EU average of 53–54% (Gaigalis et al., 2016). To decrease its dependency on imports, Lithuania has been prioritizing an increase in the renewable energy share (Lund et al., 2005).

Due to the increase in renewables and the possible following need for an integrated, flexible energy system, this study asks the following research question:

> How do policies, in the form of taxes and subsidies, incentivize investment in technologies which flexibly couple the DH and the electricity systems in the Baltic countries?

DH facilitates the interaction between electricity and heat production. In the Baltic context, this has been illustrated by Kuhi-Thalfeldt and Valtin (2009), who describe how VRE can be balanced by local small-scale CHP plants in Estonia. In Latvia, Bazbauers and Cimdina (2011) shows that it is possible to increase the share of renewable

* Corresponding author.
E-mail addresses: dasn@dtu.dk (D. Møller Sneum), elisand@nmbu.no (E. Sandberg), hardi.koduvere@ttu.ee (H. Koduvere), oleo@dtu.dk (O.J. Olsen), Dagnija.blumberga@rtu.lv (D. Blumberga).

[1] Abbreviations: CHP: combined heat and power, DH: district heating, DSO: distribution system operator, EB: electric boiler, EE: Estonia, LCOH: levelized cost of heat, similar to the more commonly used term *levelized cost of electricity*, LV: Latvia, LT: Lithuania, NETP: Nordic Energy Technology Perspectives, O&M: operation and maintenance, P2H: power-to-heat, PSO: public service obligations, T&D: transmission and distribution, TSO: transmission system operator, VRE: variable renewable energy.

https://doi.org/10.1016/j.jup.2018.02.001
Received 14 June 2017; Received in revised form 31 January 2018; Accepted 1 February 2018
Available online 10 March 2018
0957-1787/

energy sources by combining the surplus electricity produced by wind power in heat pumps with heat storage. Mathiesen et al. (2015) termed such flexible coupling in the energy system *smart energy systems*. Other studies demonstrate that CHP and power-to-heat (P2H) technologies, such as electric boilers (EB), may support flexibility in smart energy systems (Blarke, 2012; IEA, 2014b; Lund, 2003; Lund et al., 2015). An important enabler of such system integration is heat storage, which allows a partial decoupling of heat production and heat demand; e.g., by allowing a CHP to generate electricity whenever the electricity price is high and store the excess produced heat (Colmenar-Santos et al., 2016). This coupling of heat generation and electricity is already practiced in CHPs in the Baltic countries. Storage capacity and P2H technologies, however, are currently virtually nonexistent in Baltic DH (Sneum et al., 2016).

DH constitutes more than 50% of households' energy demand for heating, and the CHP share is above 50% of the DH production in Latvia and Lithuania, as seen in Figs. 1 and 2. The potential to deploy DH as a flexibility provider in the Baltics is, thus, considerable.

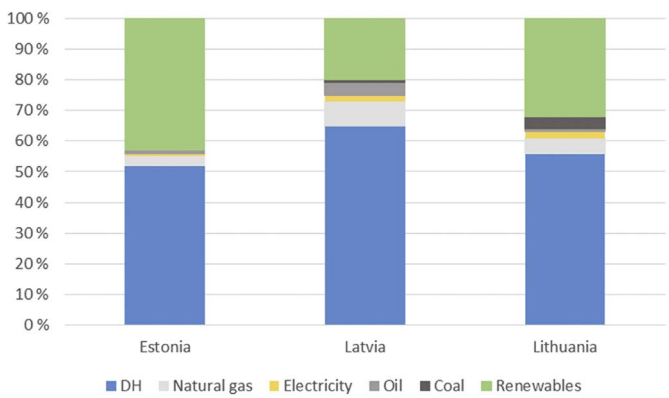


Fig. 1. Share of residential energy consumption for heating in the Baltic countries in 2013 (Euroheat and Power, 2015).

The present energy policies of the Baltic countries in terms of taxes and subsidies are not favorable for exploiting this potential. Feed-in-premiums promote CHP for the sake of security of supply and the use of domestic fuels. The electricity used for DH production is subject to the same tax rates as any other electricity consumption, reducing incentives for P2H deployment. The decision to invest in heat storage is entirely determined by market incentives (Sneum et al., 2016).

The objective of this paper is to investigate the feasibility of flexible DH technologies in a future electricity system comprised of a large share of VRE in the three Baltic countries, which assumes a greater need for flexibility options. We accomplish this by modelling different compositions of a DH system under current policies in terms of taxes and subsidies to find the resulting heat production costs. Furthermore, the impacts of electricity T&D tariffs and heat storage are explored. This approach shows if combinations of DH technologies and current policies produce both low heat costs and an opportunity for coupling DH with the electricity system.

Section 2 describes the methodology of the study, and Section 3 presents the results of the analyses. Section 4 concludes the study.

2. Methodology

This study analyzes the impacts of taxes and subsidies on investment incentives. Using the analysis tool energyPRO (EMD International A/S, 2018), we developed a model for DH plants with different degrees of coupling to the electricity system and, thus, different potentials for providing flexibility. The inputs and policies for the model plants are derived from the policy schemes for the different Baltic countries. By applying current economic conditions to the model plants, we test whether it is economically feasible to invest in flexible technologies in the Baltic countries. Earlier studies have addressed and modelled alternative policies for the operation of (Skytte et al., 2017) and investment in DH plants by taxation (Olsen and Munksgaard, 1998), using the capacity factor as a measure (Athawale and Felder, 2014). This study extends these methods by including storage, hourly variations, and long-term changes in fuel and electricity prices. The focus is on heat production costs, measured as the levelized cost of heat (LCOH).

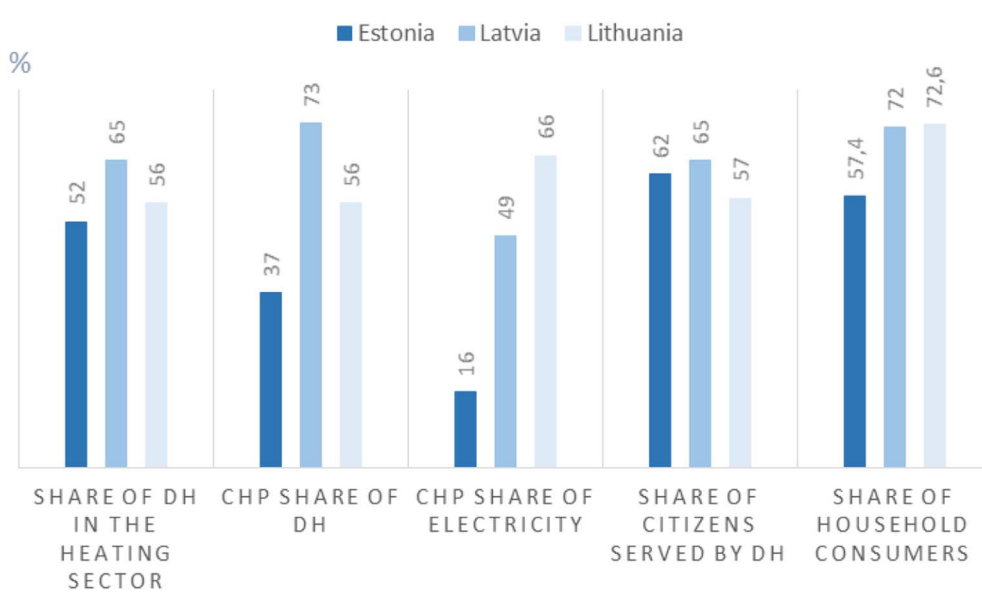


Fig. 2. Key figures in Baltic district heating shares in 2013 (Euroheat and Power, 2015).

2.1. Definition of flexibility

The operation of DH technologies facilitated by policies is an important part of this study, whereas an analysis of flexible operation falls outside the study's scope. Nonetheless, flexibility is a key element of the study, since it is a characteristic assigned to some of the analyzed technologies.

This study defines flexibility as the ability of a DH technology to frequently and quickly increase or decrease its consumption or production of electricity in response to system signals and needs. Conversely, an inflexible DH technology is one that does not possess these attributes. This definition is in line with the more electricity-oriented definition applied by Lannoye et al. (2015), the grid interface-oriented definition proposed by Salpakari et al. (2016), and the energy system-oriented definitions applied by Lund et al. (2005) and Mathiesen et al. (2015). One proxy for flexibility need is the forecast price of electricity on the spot market. Low spot prices indicate an oversupply, which can be mitigated by a decrease in electricity production or an increase in electricity consumption (and vice versa for high electricity prices).

The ability of DH to respond to the needs of the electricity system depends on the technology of the installed plant and on the incentives for operating it. Investment incentives for flexibility should favor technologies capable of interacting with the electricity system, and operational incentives should not blur the signals created by the electricity spot market. This study addresses both the investment and operational incentives affecting the economic feasibility of flexible technologies.

2.2. What does the literature say about Baltic DH and flexibility?

A review of the literature on policy alternatives for Baltic DH reveals that extant research has focused primarily on increasing the share of renewables. From the Soviet era, Baltic DH inherited old, over-capacitated, and inefficient DH plants dependent on imported fuels (Lauka et al., 2015; Lund et al., 1999; Roos et al., 2012). Researchers have discussed ways for the Baltic energy sector to adapt to a market economy. CHP is frequently mentioned, as it is considered a means to utilize domestic fuels (Lund et al., 2005) and increase energy efficiency (Ziemele et al., 2016) and the renewable share in Baltic DH (Konstantinaviciute et al., 2013; Perednis et al., 2012). EBs are not mentioned. A few studies mention heat pumps in combination with heat storage (Bazbauers and Cimdina, 2011; Colmenar-Santos et al., 2016; Lauka et al., 2015). With respect to the Baltic energy sectors, the focus is on energy efficiency and increasing the share of domestic fuels in order to decrease DH prices (Kveselis et al., 2017; Ziemele et al., 2016) and reduce import dependency (Lund et al., 1999; Miskinis et al., 2006). The choice of renewable fuels for domestic fuels stems from environmental concerns. Within this body of work, flexibility is rarely mentioned, though it could be considered in the planning of long-term energy investments, concerns related to climate gas emissions and the adoption of fourth-generation DH (Ziemele et al., 2016). Flexibility is given greater attention in more recent work (Bergaentzle et al., 2017; Kuhi-Thalfeldt and Valtin, 2009).

2.3. Operation and investment analysis

The adoption of DH technologies may be affected by taxation and subsidization. Energy taxes within DH can be used to address negative externalities associated with production as well as for fiscal purposes (Olsen and Munksgaard, 1998). Subsidies can be used to address policy priorities, such as promoting the use of certain fuels.

In the Baltic countries, transmission and distribution system operators charge for services provided by the grid infrastructure according to electricity tariffs. Like taxes, tariff structures differ in design and levels. Larger or smaller cost-shares of electricity consumption can be allocated to fixed and variable (marginal) costs, respectively (Soysal et al., 2016), and tariffs can be levied on the utilization of either capacity (EUR/MW) or energy (EUR/MWh).

Heat storage has been shown to have a significant impact on the operation and feasibility of DH plants, both in academic research (Streckiene et al., 2009) and in practice in Denmark (EMD International A/S, 2017). Through heat storage, operations can be optimized to utilize least-cost technologies, such as P2H during periods with low electricity prices and CHP during periods with high electricity prices. Research by Sneum et al. (2016) indicated a limited use of heat storage in the Baltic countries. The present study examines this technology to determine its potential impact.

Public policies can impact investment in and operation of flexible technologies and thus their economic feasibility. This study analyzes all existing (2016) taxes, subsidies, and electricity T&D tariffs in the Baltic region in order to determine their collective impact on plant operation and, subsequently, to measure their effect on the economic feasibility for the given DH technologies.

2.3.1. Operation analyses in the energyPRO simulation software

EnergyPRO is an industry operation optimization software used for techno-economic studies of DH plants (Connolly et al., 2010). The software has been used in earlier research on CHP plants with heat storage (Streckiene et al., 2009; Trømborg et al., 2017) and P2H in DH (Østergaard and Andersen, 2015). Energy demands, costs, temperatures, technologies, and other factors are incorporated as input data, and operational optimization is performed on an hourly basis, considering such constraints as storage content. Heat demand can be covered by different technologies, depending on marginal production costs defined by inputs such as fuel costs, taxes, and so on. Fig. 3 illustrates the marginal heat production cost as a dependent of the electricity cost: For P2H, low electricity prices mean low heat production costs (and vice versa for CHP). Exceptions are the marginal costs of fuel-based heat-only boilers (e.g., wood chip boilers), which are unaffected by electricity costs. Each technology serves as the preferred unit for dispatch depending on the price of electricity and subject to heat demand and the availability of heat storage capacity. Finally, the P2H technology case illustrates the implementation of levies, with the dotted line indicating an increase in marginal cost associated with, for example, the introduction of an electricity tax.

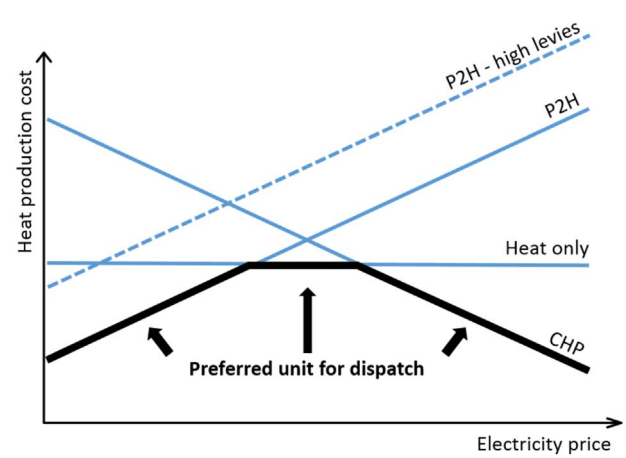


Fig. 3. Marginal heat production cost and preferred unit for dispatch in a district heating plant with a heat-only boiler, P2H, and CHP.

The energyPRO software optimizes operation under perfect foresight, minimizing heat production costs based on day-ahead electricity spot prices. Perfect foresight describes that the model includes future energy prices and heat demand in its optimization. In the real-world, operators would have a similar foresight due to weather- and price forecasts, but with some added uncertainty. This is how DH plants are commonly operated in the Nordic and Baltic countries. In this study, operational optimization is conducted hourly across a 20-year timescale (2016–2035). The perfect foresight utilized in the optimization could potentially lead to too-perfect operation. To address this issue, the P2H and CHP units are only allowed to operate in a full-load manner (i.e., no partial load), which is a typical bidding strategy for the decentralized back-pressure DH plant operating on the electricity spot market.

Dispatch optimization in energyPRO is conducted by assigning priorities to the heat-producing technologies each hour based on the variables that affect the marginal heat production cost (e.g., electricity prices). The units with the highest priority (i.e., least marginal heat production cost) are committed first, and the dispatch calculation is subsequently repeated for the remaining technologies until the heat demand is fully served (EMD International A/S, 2016). Operational optimization in energyPRO has been described in further detail by Lund and Andersen (2005).

Like other types of energy storage, heat storage enables an optimized use of resources. In this study, as is the case for similar-size plants in Denmark, Finland, and Sweden, heat storage is water-based and dimensioned according to one to three days of heat demand, corresponding to 2000 m^3.

2.3.2. Feasibility study of investment incentives

A fundamental prerequisite for the flexible operation of DH technologies is that flexible technologies are present. This, in turn, requires investment in such technologies. As noted by Olsen and Munksgaard (1998), in the case of DH, a *profit-maximizing investor will select the production technology having the lowest long run production costs taking into consideration the present tax regime including subsidies*. In this study, this long-run production cost, and its subsequent role as an indicator for investment incentives, is termed LCOH. LCOH is similar to the more commonly applied *levelized cost of energy* and represents the economic lifetime cost of heat generated. The LCOH calculation follows the standard approach of calculating the levelized cost of energy, as seen below.

$$LCOH = \frac{\sum_{t=0}^{n} \frac{TC_t}{(1+r)^t}}{\sum_{t=0}^{n} \frac{q_t}{(1+r)^t}}$$

Where.

- $LCOH$ is the levelized cost of heat
- n is the number of years
- t is the given period
- r is the discount rate
- TC_t is the total cost in period t
- q_t is the heat production in period t

TC_t is further specified below, since the variable costs are a significant part of this study.

$$TC_t = I_t + FOM_t + VOM_t + F_t + E_t + T_t + TF_t + TV_t - E_t - S_t$$

Where.

- I_t is the investment cost in period t
- FOM_t is the fixed operation and maintenance cost in period t
- VOM_t is the variable operation and maintenance cost in period t
- F_t is the fuel cost in period t
- E_t is the spot electricity cost in period t
- T_t is the tax (CO_2, energy, and public service obligations) in period t
- TF_t is the fixed charge under the electricity tariff in period t
- TV_t is the variable charge under the electricity tariff in period t
- E_t is the revenue from electricity sales in period t
- S_t is the subsidy in period t

Revenue from heat production is not part of the equation, while electricity spot market sales are, because the purpose of calculating the LCOH is to determine the level at which heat must be priced for the project to be feasible at the break-even point.

While a plant's owner, developer, and operator might, in practice, be different companies, we treat them as a single aggregate entity. Athawale and Felder (2014) take a similar approach in their study of CHP plants.

2.4. Technologies, policies, and their variations

Table 1 details four different analyzed technological combinations for DH plants. These represent DH technologies with characteristics that range from flexible production and consumption (CHP and EB) to no flexibility at all (wood chip boiler). For each combination, an oil boiler is present for back-up and peak load. While DH can be produced by a multitude of technologies, we chose those that represent potential future setups in which CHP capacity is fossil-free and P2H is capable of utilizing the increased amounts of VRE in the energy system. This approach is in line with the general Baltic policy of increasing the share of domestic fuels and the efficiency of DH plants (Ziemele et al., 2016), the Latvian policy of increasing energy efficiency by increasing the CHP share and the share of renewable energy (ABB, 2012; Klavs and Kudrenickis, 2016), and the Lithuanian policy of enhancing energy efficiency and increase the renewable share, particularly by replacing natural gas with biomass in DH (Macevičius, 2015; Sekmokas, 2012).

Table 1
Technological combinations considered. The model plant load compositions are based on Norsk Energi and Thema Consulting Group (2014).

Technological combination	Base load	Mid-load	Peak load	Potential flexibility: Production	Potential flexibility: Consumption
	5.4 MW_{TH} 45% of peak load, low fuel price	6.6 MW_{TH} 55% of peak load	12 MW_{TH} 100% of peak load, low investment cost		
A	Wood chip CHP	Wood chip boiler	Oil boiler	X	
B	Wood chip CHP	EB	Oil boiler	X	X
C	Wood chip boiler (12 MW_{TH})	–	Oil boiler		
D	Wood chip boiler	EB	Oil boiler		X

Table 2
Policy conditions considered. *Condition 4 is included for discussion purposes only, due to the limited impact found for electricity capacity tariffs. It is addressed in Section 3.5.

Policy condition #	Policy condition	Purpose
1	With taxes and subsidies, no heat storage	Together with 2, determines the impact of having storage.
2	With taxes and subsidies, with heat storage	Together with 1, determines the impact of having storage. Together with 3, determines the impact of taxes and subsidies.
3	No taxes and subsidies, with heat storage	Together with 2, determines the impact of taxes and subsidies.
4	With taxes and subsidies, with heat storage, no electricity capacity tariffs*	Compared against 2, determines whether investment incentives are impacted by capacity tariffs.

All four technological combinations are subject to four policy conditions that affect DH investment incentives, as explained in Table 2. Our approach to policy follows the work of Hvelplund and Lund (1998), who describe how regulations can make economically rational, profit-maximizing actors in the energy system act in accordance with societal goals. For this study, societal goals are assumed to be some version of flexible, low-carbon DH supply. Policy conditions 1 and 2 enable an analysis of the impact of heat storage. To explore whether the policies force the DH plant to act in accordance with societal priorities, we include Policy condition 3, which enables analyses of how taxation impacts operation. The load demand tariff/capacity tariff is a charge on the maximum load demand for 1 h over the course of a year. Depending on their design, such grid tariffs can be either barriers to or drivers for P2H. Thus, we include Policy condition 4 to determine the degree of impact of capacity tariffs on LCOH.

In summary, the technological combinations have been ordered using letters A through D, the policy conditions have been ordered using numbers 1 through 4, and the scenarios have been named using a combination of the letters and numbers. This scheme produces a total of 16 scenarios for each country and 48 in total, as summarized in Table 3.

Table 3
Overview of technological combinations and policy conditions applied in the analyzed scenarios. *Variations in the electricity capacity tariffs is reviewed in the discussion section.

Technology	Storage	Taxes and subsidies	Electricity capacity tariffs	Scenario
Wood chip CHP + EB	–	Yes	Yes	A1
	Yes	Yes	Yes	A2
		–	Yes	A3
		Yes	*	A4
Wood chip CHP + wood chip boiler	–	Yes	Yes	B1
	Yes	Yes	Yes	B2
		–	Yes	B3
		Yes	*	B4
Wood chip boiler + EB	–	Yes	Yes	C1
	Yes	Yes	Yes	C2
		–	Yes	C3
		Yes	*	C4
Wood chip boiler	–	Yes	Yes	D1
	Yes	Yes	Yes	D2
		–	Yes	D3
		Yes	*	D4

2.5. Data and assumptions

To ensure that the results reflect differences in policy, not in fuel prices, we assumed the prices of oil and wood chips to be uniform for all countries. The wood chip price is an average of 2015 and 2016 prices, and the oil price is an average of 2016 prices. For each country, we used hourly Nord Pool Spot prices for electricity, since Nord Pool serves the Baltic countries and the Northern European countries due to physical trade, based on interconnections. Table 4 presents the 2016 fuel prices. Fuel and electricity prices were adjusted according to annual averages in the Nordic Energy Technology Perspectives (NETP) 2016 (IEA, 2016). This approach reflects that electricity is traded based on hourly values, while fuel is purchased in bulk via long-term contracts. The NETP 2016 analyzes transition to a carbon-neutral energy system by 2050 and, thus, provide a macro-economic framework that is thematically aligned with our study's micro-economic perspective of local transitions to renewable energy. System-scale impacts on, for example, the electricity and fuel prices of transitions to certain DH fuels or technologies are assumed to be factored in through the values drawn from the NETP 2016.

Table 4
Fuel prices applied in the modelling. Based on the European Commission (2017) and Baltpool (2017).

Fuel	2016 PRICE – EUR/MWh
Oil	28.1
Wood chips	11.5

Hourly values (heat demand, electricity spot prices) and annual values (fuel prices) are adjusted annually according to indices drawn from the NETP 2016. This accommodates expected development over time of e.g. reduction in heat demand due to gradually increased energy efficiency.

Table 5 displays the taxes, subsidies, and electricity T&D tariffs applied in the present study. Electricity grid tariffs normally reflect a fixed customer charge, a capacity (or power) charge, and an energy charge; the annual or monthly capacity charge is based on the maximum electric capacity drawn from the grid and the energy charge is based on the amount of MWh consumed.

Table 5
2016 levels of taxes, subsidies, and electricity T&D tariffs in each of the Baltic countries. All numbers in EUR/MWh unless otherwise stated.

Country	Electricity tax	PSO tariff	CO2 tax	Energy tax - oil	Subsidy on bio CHP elec. prod.	DSO energy charge [Time and seasonal variation]	DSO capacity charge [EUR/MW/month based on yearly max.]	TSO energy charge	TSO capacity charge [EUR/MW /month based on yearly max.]
EE	–	9.6	0.57	5.22	53.70	2.9–5.1	3600	Time and seasonal variation 8.2–16.4	–
LV	–	26.79	1.00	6.08	–	17.7–31.2	1630	4.2	792.8
LT	0.52	16.42	–	1.36	70.00	15–24	580	1.1	–

Current CHP subsidies in Estonia were introduced in 2007 to incentivize increased CHP efficiency, to displace boiler-based DH production, and to increase the use of renewable fuels in CHP (Euroheat and Power, 2015). Estonia's 12-year subsidy is provided as a feed-in premium that supplements the electricity spot price (Riigi Teataja, 2014). For Lithuania, the subsidy is a 12-year feed-in tariff (National Commission for Energy Control and Prices, 2016). Here, additional aspects of energy security play an important role in incentivizing the use of biomass in the heat sector (Kveselis et al., 2017). While Latvia also subsidizes CHP plants, this support is directed toward existing plants (Likumi, 2017) and, thus, is not included in this study.

Table 6 displays capital costs, which are divided into labor and hardware costs. This division is necessary to adjust for the differences in labor costs from the reference used (Norwegian Water Resources and Energy Directorate (2015)). Thus, hardware costs are assumed to be fixed, while labor costs are adjusted according to Baltic GDP levels using World Bank data (The World Bank, 2017). Later capital investments and all operation and maintenance (O&M) costs are subject to inflation. The annual inflation rate (1.5–2.3%) is based on the Danish Energy Agency (2016a). The capital cost does not include any financing. A 4% nominal discount rate is applied to the combined capital and O&M costs for the economic life of the plant.

Table 6
Capital costs divided into labor and hardware costs. The CHP capital cost is based on electricity output capacity, while the capital costs for the remaining technologies are based on heat output capacity.

Technology	Labor costs	Hardware costs	Total capital costs
	EUR per MW	EUR per MW	EUR per MW
Wood chip boiler	866	602 151	603 017
Oil boiler	2143	55 645	57 788
EB	2273	62 903	65 176
Wood chip CHP	352 907	3 239 785	3592 692
	EUR for a 2000 m^3 heat storage		
Heat storage[a]	88 768	–	88 768

[a] Capital cost is allocated on labor, since split between labor and hardware cost is unknown. Cost data are from The Norwegian Water Resources and Energy Directorate (2015) and the Danish Energy Agency (2016b). Danish and Norwegian labor costs have been adjusted to Baltic labor costs.

Table 7 presents the technological assumptions. Reinvestment is necessary for the wood chip boiler, since its technical lifetime is lower than the plant's 20-year economic lifetime in our analysis. The remaining lifetimes of the technologies are included in the analysis as linear scrap values.

Table 7
Efficiencies and minimum loads for DH technologies (Danish Energy Agency, 2015; Norsk Energi and Thema Consulting Group, 2014). Lifetimes from The Norwegian Water Resources and Energy Directorate (2015).

Technology	Heat efficiency	Electric efficiency	Minimum load	Technical lifetime (years)
Wood chip CHP	77%	28%	100%	25
EB	98%	–	100%	20
Wood chip boiler	89%	–	25%	15
Oil boiler	92%	–	0%	20

3. Results

This section presents the results for each technological combination and its scenarios based on the policy conditions affecting incentives for investment in DH technologies. The LCOH for each scenario indicates the investment incentive, detailed by the individual cost components. Insight into the operational incentives underlying the given framework conditions is drawn from the distribution of heat production. Slight deviations from the 40 GWh heat demand occur when the model adjusts in response to local temperatures. The contents in each section refer to that section's respective figure(s).

3.1. Combination A: wood chip CHP and wood chip boiler

In all scenarios, heat storage enables a significantly better utilization of the biomass CHP capacity and, thereby, a lower LCOH than scenarios without storage. While cost parameters are similar, income varies. CHP production deviates only slightly among the countries, and the differences are attributable to the Estonian and Lithuanian subsidies on electricity production. In all cases, taxes and subsidies have almost no operational impact. Furthermore, in all scenarios, the wood chip CHP and EB can only operate at full capacity, meaning that periods with a lower heat demand than heat output must be supplied either by the fuel-based boilers or through a simultaneous loading or unloading of the heat storage (if present). This explains the differences in production for scenarios with and without heat storage. The same effect applies to combinations A through D (see Figs. 4 and 5).

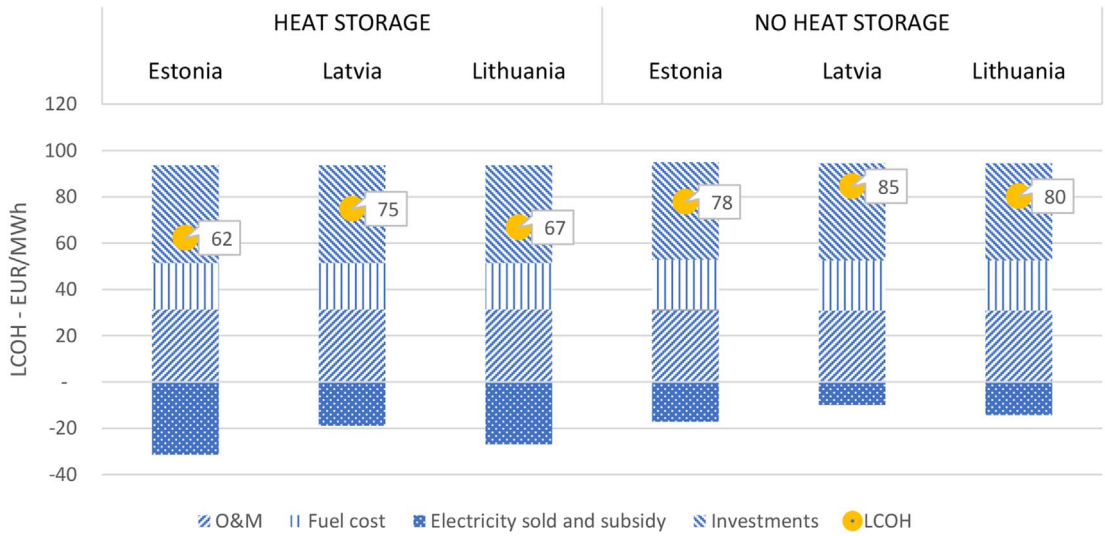


Fig. 4. Levelized cost of heat for Combination A (CHP + wood chip boiler) divided into main cost components.

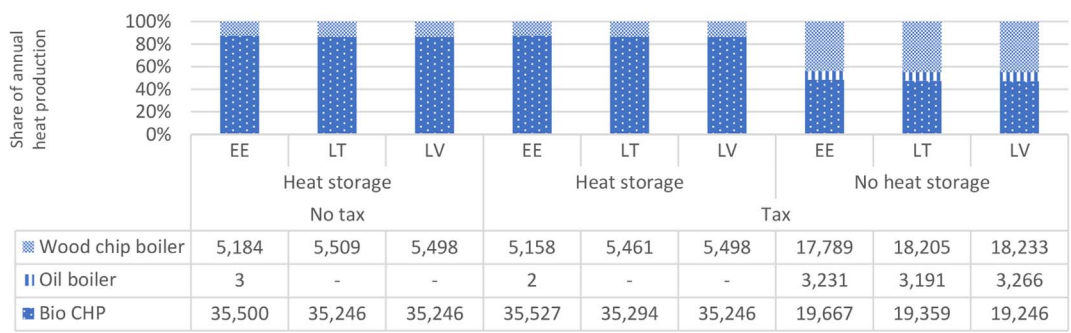


Fig. 5. Fuel distribution for Combination A (CHP + wood chip boiler).

3.2. Combination B: wood chip CHP and EB

As seen in 3.1, the heat storage induces a higher cost efficiency in the operation of the CHP unit. However, the heat storage has little or no effect on the operation of the EB, due to the competitiveness of the oil boiler. This competitiveness is present even in the no-tax scenario, indicating that electricity prices and grid tariffs, particularly in Latvia and Lithuania, are at such a level that EB operation is economically infeasible. Taxes and subsidies have an impact in Estonia due to its relatively lower electricity price, making the EB feasible to operate in a no-tax scenario (see Figs. 6 and 7).

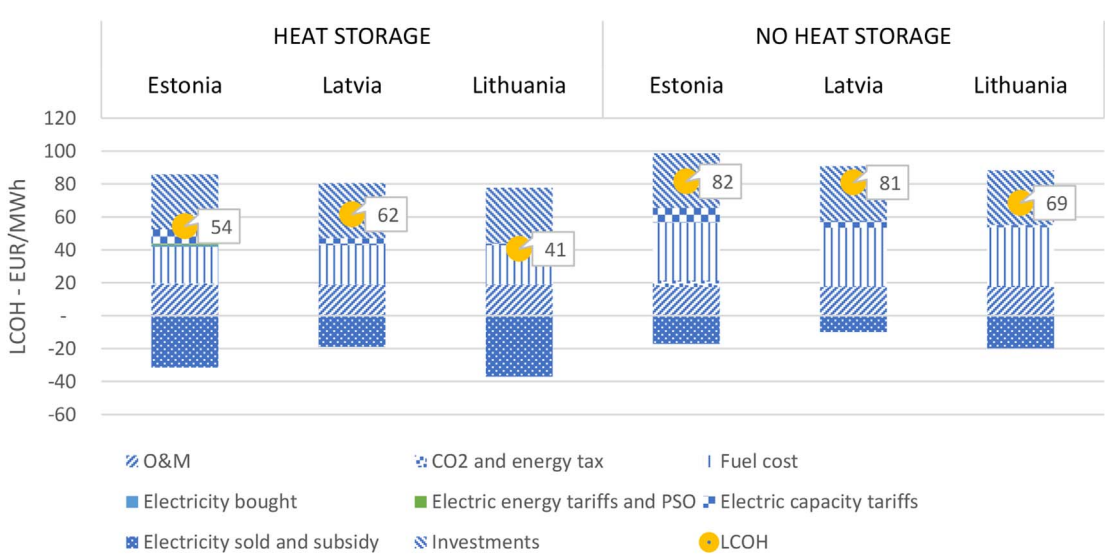
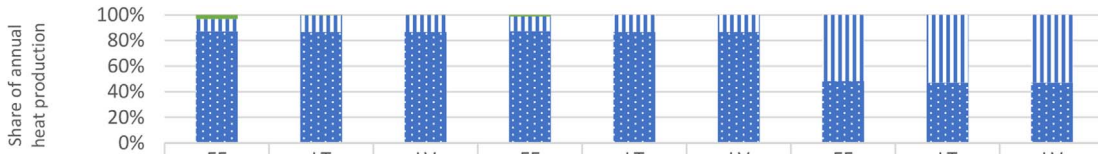


Fig. 6. Levelized cost of heat for Combination B (CHP + EB) divided into main cost components.



	EE	LT	LV	EE	LT	LV	EE	LT	LV
	Heat storage, No tax			Heat storage, Tax			No heat storage, Tax		
Electric boiler	1,300	99	26	495	-	-	-	-	-
Oil boiler	3,887	5,383	5,451	4,665	5,472	5,477	21,020	21,499	21,499
Bio CHP	35,500	35,273	35,267	35,527	35,273	35,267	19,667	19,246	19,246

Fig. 7. Fuel distribution of Combination B (CHP + EB).

3.3. Combination C: wood chip boiler

The heat storage enables a nearly full utilization of the wood chip boiler, but the LCOHs for the different scenarios are the same regardless of storage. The increased O&M costs induced by the increased operation of the wood chip boiler in the heat storage variations displace the higher costs of using oil in the no-storage scenarios. Changes in taxation have no impact on operation, indicating that biomass is competitive with oil regardless of taxes. Although the costs are roughly the same, heat storage offers small environmental and national economic benefits by facilitating a reduction in CO_2, a reduction in imported fuels, and increased use of domestic fuels (see Figs. 8 and 9).

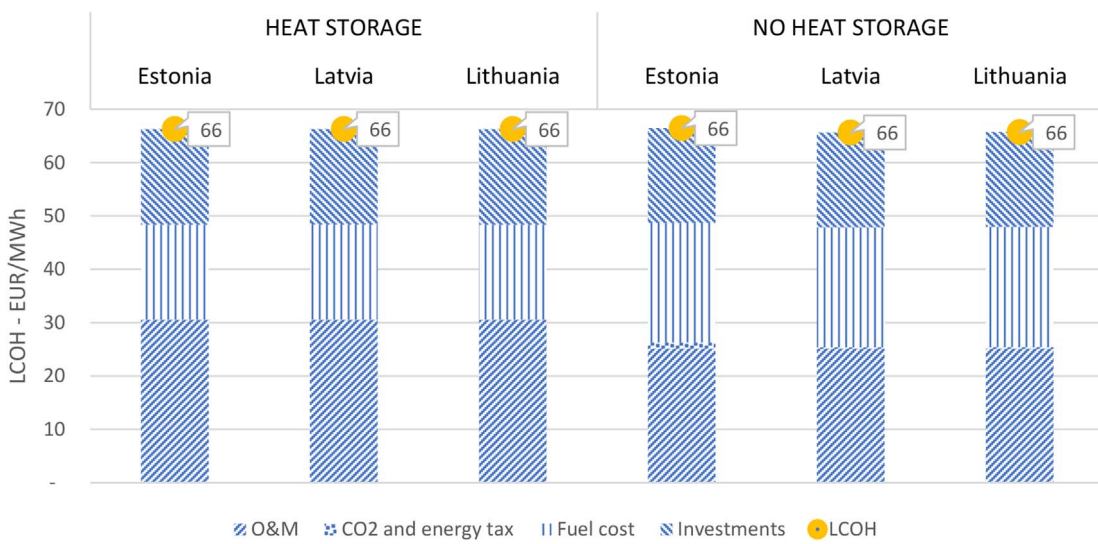
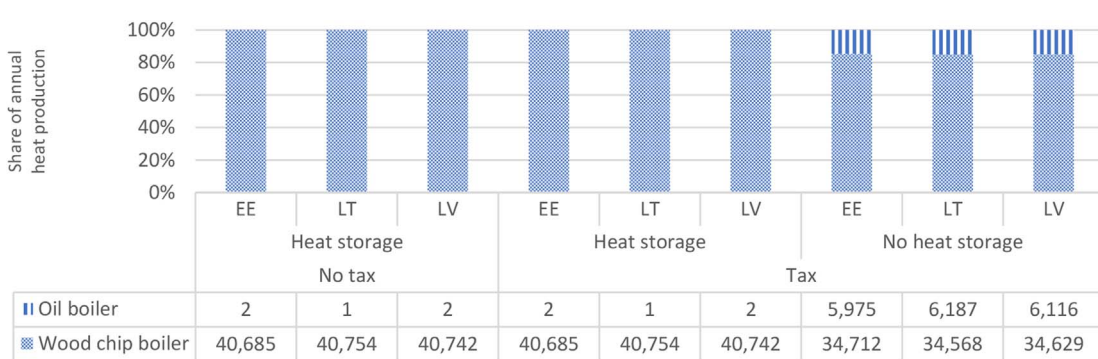


Fig. 8. Levelized cost of heat for Combination C (wood chip boiler) divided into main cost components.



	EE	LT	LV	EE	LT	LV	EE	LT	LV
	Heat storage, No tax			Heat storage, Tax			No heat storage, Tax		
Oil boiler	2	1	2	2	1	2	5,975	6,187	6,116
Wood chip boiler	40,685	40,754	40,742	40,685	40,754	40,742	34,712	34,568	34,629

Fig. 9. Fuel distribution in Combination C (wood chip boiler).

3.4. Combination D: wood chip boiler + EB

Unlike CHP, the wood chip boiler is allowed to produce at a partial load. Thus, the impact of storage is not as significant as in the previous scenarios. This is also reflected in the LCOH, which is almost unchanged between the cases with and without storage. As in the scenario reported in section 3.2, an absence of taxes leads to increased production on EBs in Estonia (see Figs. 10 and 11).

and heat storage yields the lowest LCOH. By a small margin, Lithuania deviates towards CHP with an EB. It can be argued that since the investment costs are significantly higher for the combination of CHP and EB (19.9 MEUR vs. 3.8 MEUR), and since this combination is solely dependent on electricity prices, the small margin to the wood chip boiler and EB combination might incentivize an investor to prefer this solution. In this case, the inflexible supply/flexible demand solution appears attractive, which might contrast with the Baltic priorities for

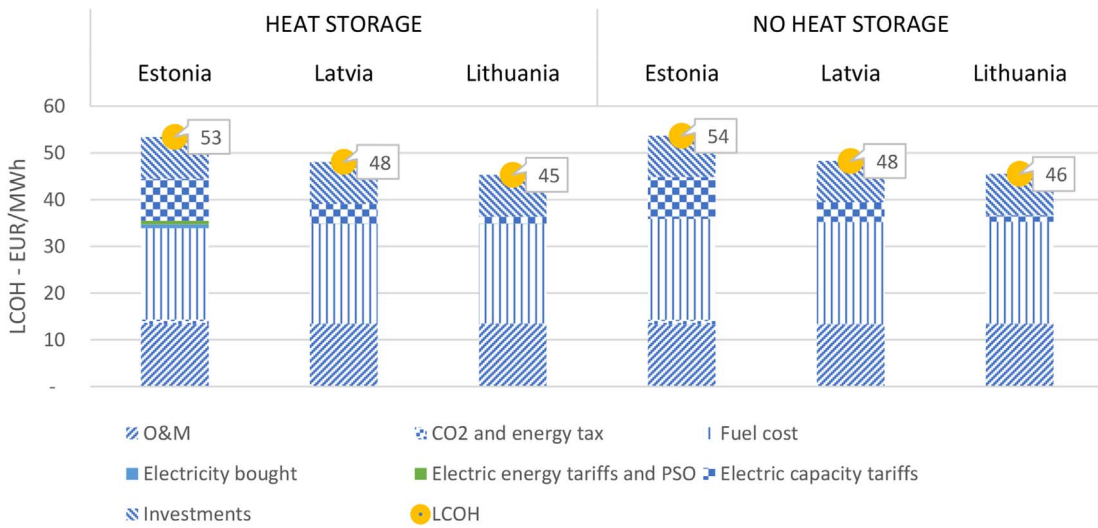


Fig. 10. Levelized cost of heat for Combination D (wood chip boiler + EB) divided into main cost components.

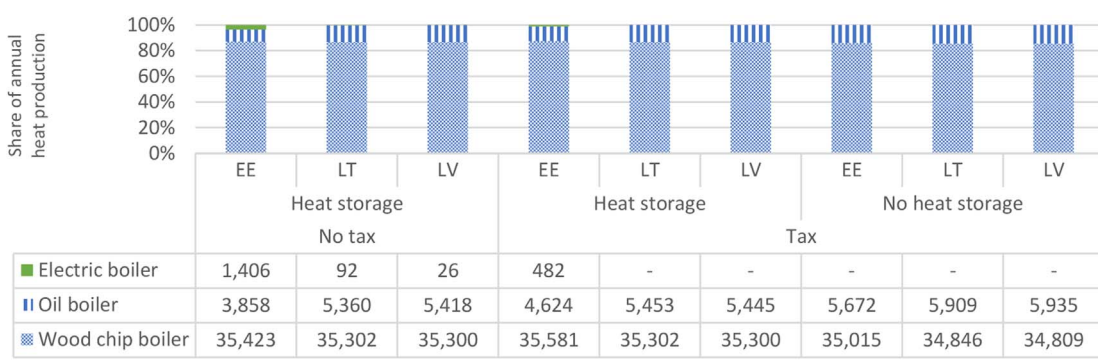


Fig. 11. Fuel distribution in Combination D (biomass boiler + EB).

3.5. Discussion of results

Table 8 indicates incentives to invest in flexible technologies, represented by LCOH. Here, the LCOHs of the scenarios with and without heat storage show that the combination of the wood chip boiler, the EB,

Table 8
Levelised costs of heat for all scenarios with tax. The color scale is read vertically and indicates the LCOH for each country, where green is low and red is high.

Technological combination	Heat storage	EE	LV	LT
A - CHP + wood chip boiler	Storage	-62	-75	-67
A - CHP + wood chip boiler	No storage	-78	-85	-80
B - CHP + EB	Storage	-54	-62	-41
B - CHP + EB	No storage	-82	-81	-69
C - large wood chip boiler	Storage	-66	-66	-66
C - large wood chip boiler	No storage	-66	-66	-66
D - wood chip boiler + EB	Storage	-53	-48	-45
D - wood chip boiler + EB	No storage	-54	-48	-46

CHP-based DH. The large differences in economy and operation between scenarios with and without storage indicate that, internally, plants can utilize their technologies flexibly in the presence of heat storage. This internal flexibility supports a better utilization of least-cost production technologies, which is reflected in the lower LCOH of these scenarios.

The power charge components in the grid tariffs paid for utilizing the EB have disproportionally high costs compared to the amount of heat produced by the EB. For example, in the case of Estonia, this cost is 600 EUR/MWh heat, in addition to variable costs. This issue is not new in the context of DH. An earlier study showed how such charges *could result in higher payments for longer durations, even when utility services are used only for a limited period of time* (Athawale and Felder, 2014). A normal capacity tariff is similar to an investment cost, meaning that the more it is used, the smaller the cost per unit. Whereas removing capacity grid tariffs reduces the LCOH, it does not shift the relative LCOH sufficiently to incentivize a different technology choice, as seen in Table 9.

Table 9
Levelised costs of heat for all scenarios with tax and without capacity grid tariffs.

Technological combination	Heat storage	EE	LV	LT
A - CHP + wood chip boiler	Storage	-62	-75	-67
A - CHP + wood chip boiler	No storage	-78	-85	-80
B - CHP + EB	Storage	-45	-57	-39
B - CHP + EB	No storage	-73	-77	-67
C - large wood chip boiler	Storage	-66	-66	-66
C - large wood chip boiler	No storage	-66	-66	-66
D - wood chip boiler + EB	Storage	-44	-44	-44
D - wood chip boiler + EB	No storage	-45	-44	-44

The results also illustrate the large share of heat production covered by the CHP. The CHP has a lower marginal heat production cost, resulting in the electricity production being close to baseload (ranging from 6527 to 6569 full-load hours in 2016) in all CHP scenarios with storage and only slightly less without taxes and subsidies. In this technology setup, the subsidies Estonia and Lithuania provide for CHP have a negligible impact on operations, though they do serve as significant investment incentives. Whereas the operational impact of subsidies and taxes is small, the CHP subsidies dampen market-based signals for flexibility because they provide out-of-market incentives for operation. Blumberga et al. (2014) shows that a similar phenomenon occurs in Latvia (see Fig. 11).

Regarding the EB, the limited or non-existent operation (75 full-load hours in Combination B with tax in Estonia and less or none in Latvia and Lithuania and in other scenarios) illustrates the absent need for EB operation under current conditions. EB operation improves to varying degrees in the absence of taxes in all countries. An excerpt from the operation in scenario A1 (CHP + EB with tax and storage) in Estonia shows that the EB can operate flexibly, as seen in Fig. 12. Low DSO and TSO electricity tariffs during the night, combined with low electricity spot prices, allow the EB to operate across two periods. This result corresponds to the findings of Kirkerud et al. (2016). Fig. 12 shows the baseload-like operation of the CHP plant.

Though this operational pattern of CHP and EB is the best solution in private economic terms, it contradicts the initial assumption for the system scale, that is, an increased need for flexible production and consumption to integrate VRE. The Baltic and Nordic power systems already handle significant shares of VRE, and these shares are expected to increase in Europe according to 2030 targets (European Commission, 2014). In combinations A and B (with storage and CHP), CHP runs as a baseload that is almost unchanged until 2035, even in variations without taxes and subsidies. Without storage, CHP operation is limited and displaced by other technologies. This, together with the low EB operation, indicates that the electricity market requires flexibility, not in the form of electricity consumption or reduced CHP production, but, rather, in the form of increased CHP production under the given conditions.

3.6. Sensitivity to O&M and investment costs

The similarity of the LCOH for combinations B (CHP + EB) and D (wood chip boiler + EB) brings into question whether the results would be significantly different in the event of small changes in costs. The investment cost of CHP is explored because investment is a more significant share (24–29%) of the LCOH in the CHP scenarios with storage than it is in the wood chip boiler scenarios (9–14%). Likewise, O&M costs are significant in the scenarios with the wood chip boiler. O&M is sub-divided into variable (EUR/MWh) as well as fixed (EUR/year) costs, where the fixed part is analyzed here. Fig. 13 displays the results of the sensitivity analyses, in which the two combinations (B and D with storage) are compared, such that the values represented by each line describe the differences between the combinations. This illustrates whether each combination is robust against its closest alternative. The figure shows that the Estonian combinations are sensitive to changes in both categories, while Lithuania experiences only a minor shift in response to an increased CHP investment cost.

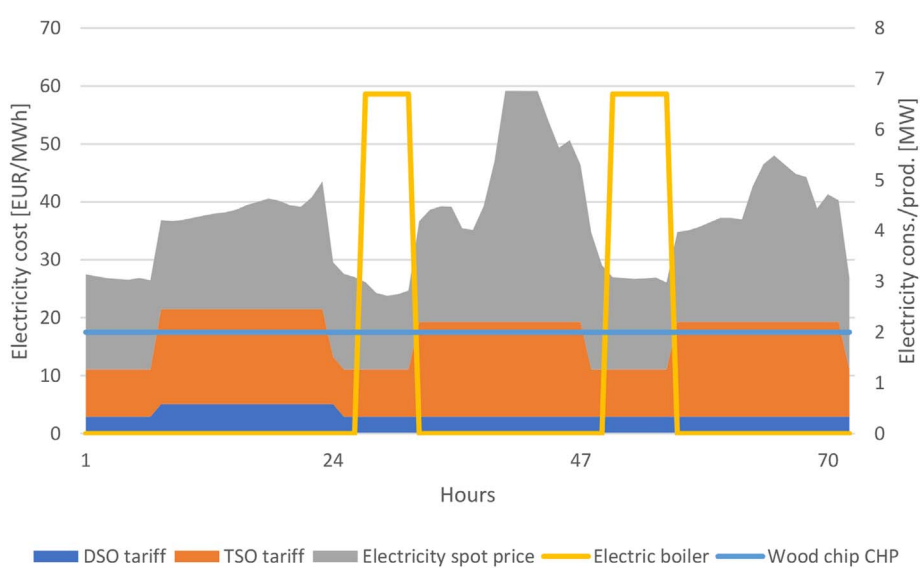


Fig. 12. Optimized operation for the first three days of January 2016 in Estonia.

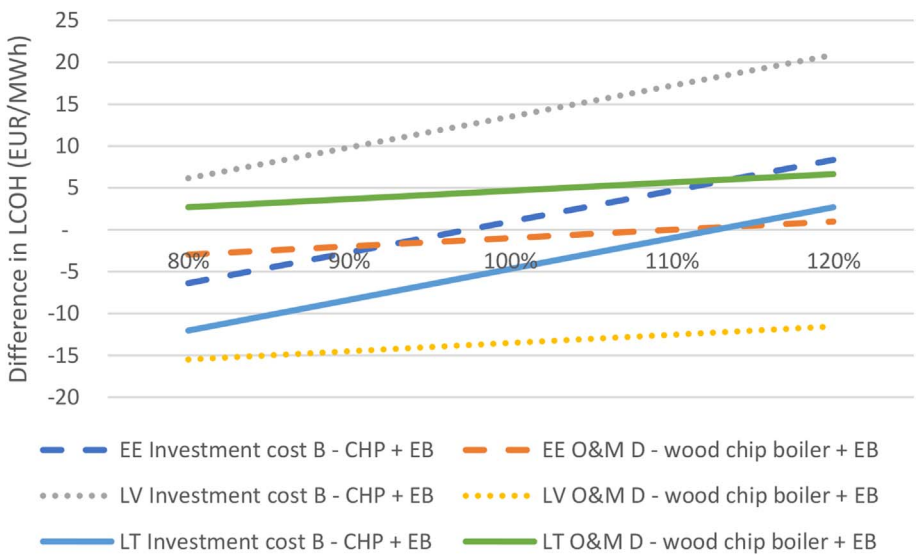


Fig. 13. Sensitivity analyses for the fixed O&M costs for the wood chip boiler and the investment costs for the CHP. Vertical scale depicts the difference of alternatives from the base case (at 100%). For example, the solid green line depicts the difference between Combination D and the base value of Combination B. Negative values indicate a lower LCOH than the other scenario. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

4. Conclusion

By analyzing scenarios based on technological combinations and policy conditions, this study explored how current policies on taxes and subsidies affect incentives for investment in flexible technologies, focusing on the coupling of the DH and electricity systems the Baltic countries. Additionally, impacts of electricity T&D tariffs and heat storages were explored.

Investment incentives were evaluated using the proxy of the LCOH, integrating investment and O&M costs over the economic life of the DH plant. Operations were analyzed in terms of the share of heat production from flexible and non-flexible technologies.

On investment can be concluded.

- Current policies in Estonia, Latvia, and Lithuania are not directed at increased flexibility from the coupling of DH and electricity systems. While investment incentives are offered for CHP, direct flexibility incentives beyond electricity market signals are absent for CHP and P2H.
- Current policies incentivize investment in technology combinations with inflexible production and flexible consumption. The combination of the wood chip boiler, the EB, and heat storage has the lowest LCOH and, thus, the highest investment incentive in Estonia and Latvia. In Lithuania, the CHP–EB combination has a marginally better LCOH. Despite this lower cost, the preferred technology combination in Lithuania is likely to be the second-most attractive alternative (the wood chip boiler and the EB) due to CHP being capital-intensive and sensitive to power prices.
- Heat storage is a no-regrets technology in that heat storage generally improves LCOH for all technological setups and enables plants to respond flexibly to external signals, such as electricity spot market prices.
- Charges under tariffs based on the maximum yearly capacity drawn from the grid are not prohibitive to the use of EBs, but represent a considerable additional cost, particularly when compared to the very low or absent cost of EB production.

On operation can be concluded.

- Current taxes and subsidies only marginally impact the operation of EB and CHP. Instead, energy prices and electricity T&D tariffs impact operation of these technologies.
- Operation of EB is marginal compared to the CHP and wood chip boiler. The relatively low biomass prices encourage near-baseload generation on CHP and wood chip boiler, while the electricity price combined with electricity T&D tariffs make EB operation uncompetitive. Under these conditions, the importance of EB as a flexible DH technology is likely to be for shorter peaks, and possibly on the ancillary services markets instead of the electricity spot market.

4.1. Future work

The extant research has not yet divided O&M costs into labor and other components. However, O&M is a significant reason for the electric- and wood chip boiler combination being the least costly. Thus, an increased focus on O&M is necessary to determine whether this factor could prompt a shift toward other technologies.

Though the impact of taxes on operations has been analyzed, the specific impact of electricity tariffs has not yet been examined. Future studies could reveal whether changes to tariffs impact the operation of electric boilers.

The Latvian exemption of EB from the electricity tax ended January 1, 2017. Further analyses could examine the changes brought by this shift in policy.

Estonia's electricity tariffs changed significantly in July 2017 and might lead to different results.

While the present study prioritized the running of a large array of scenarios, we did not conduct sensitivity analyses on electricity and wood chip prices.

The plant-scale analysis pursued by the present study provides insight into local consequences. This perspective could be broadened in scale by using a system model. Extending the analysis in this manner would provide additional insight into the roles and benefits of both flexible and inflexible technologies in the energy system.

Acknowledgements

This paper was prepared as part of the Flex4RES (www.flex4RES.org) research project, which is supported by Nordic Energy Research. Furthermore, EMD International A/S provided a software license for the academic use of energyPRO. The authors are grateful to both organizations for their support for the study. Neither organization was in any other way involved in or responsible for the study. Additionally, we wish to extend our gratitude to the reviewers of this article, whose feedback has provided input for valuable discussions among the authors and relevant revisions of the study.

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jup.2018.02.001.

References

ABB, 2012. Latvia Energy Efficiency Report.

Athawale, R., Felder, F.A., 2014. Incentives for combined heat and power plants: how to increase societal benefits? Util. Pol. 31, 121–132. http://dx.doi.org/10.1016/j.jup.2014.10.005.

Baltpool, 2017. Supply price | Energy Exchange | BALTPOOL [WWW Document]. Biomass Exch. - Supply Price. URL. http://www.baltpool.eu/en/supply-price/?mwh, Accessed date: 6 June 2017.

Bazbauers, G., Cimdina, G., 2011. The role of the Latvian district heating system in the development of sustainable energy supply. Sci. J. Riga Tech. Univ. Environ. Clim. Technol. 7. http://dx.doi.org/10.2478/v10145-011-0024-0.

Bergaentzle, C., Skytte, K., Soysal, E.R., Boscan, L., Olsen, O.J., 2017. Regulatory barriers for activating flexibility in the Nordic-Baltic electricity market. Int. Conf. Eur. Energy Mark. EEM. http://dx.doi.org/10.1109/EEM.2017.7981948.

Blarke, M.B., 2012. Towards an intermittency-friendly energy system: comparing electric boilers and heat pumps in distributed cogeneration. Appl. Energy 91, 349–365. http://dx.doi.org/10.1016/j.apenergy.2011.09.038.

Blumberga, D., Barisa, A., Veidenbergs, I., Blumberga, A., Kuhi-Thalfeldt, R., 2014. Evaluation of RES-e support policies in the baltic states. In: The 9th International Conference "Environmental Engineering 2014." Vilnius Gediminas Technical University Press "Technika" 2014, Vilnius, Lithuania, http://dx.doi.org/10.3846/enviro.2014.255.

Colmenar-Santos, A., Rosales-Asensio, E., Borge-Diez, D., Blanes-Peir, J.J., 2016. District heating and cogeneration in the EU-28: current situation, potential and proposed energy strategy for its generalisation. Renew. Sustain. Energy Rev. 62, 621–639. http://dx.doi.org/10.1016/j.rser.2016.05.004.

Connolly, D., Lund, H., Mathiesen, B.V., Leahy, M., 2010. A review of computer tools for analysing the integration of renewable energy into various energy systems. Appl. Energy 87, 1059–1082. http://dx.doi.org/10.1016/j.apenergy.2009.09.026.

Danish Energy Agency, 2015. Technology Data for Energy Plants. Copenhagen.

Danish Energy Agency, 2016a. Regneark Med Tabeller - Samfundsøkonomiske Beregningsforudsætninger.

Danish Energy Agency, 2016b. Technology Data for Energy Plants. Copenhagen.

EMD International A/S, 2016. User's Guide EnergyPRO.

EMD International A/S, 2017. Production on Hvide Sande District Heating Plant [WWW Document]. Web Page. URL. http://www.emd.dk/desire/hvidesande/, Accessed date: 30 March 2017.

EMD International A/S, 2018. energyPRO.

Euroheat, Power, 2015. District Heating and Cooling - Country by Country 2015 Survey. Euroheat & Power, Brussels.

European Commission, 2014. A Policy Framework for Climate and Energy in the Period from 2020 to 2030. EUR-lex - 52014DC0015-EN.

European Commission, 2017. Weekly Oil Bulletin - European Commission [WWW Document]. Wkly. Oil Bull URL. https://ec.europa.eu/energy/en/data-analysis/weekly-oil-bulletin, Accessed date: 6 June 2017.

Eurostat, 2017. Eurostat - Data Explorer [WWW Document]. EU Trade since 1988 by HS2,4,6 CN8. URL. http://appsso.eurostat.ec.europa.eu/nui/submitViewTableAction.do, Accessed date: 9 October 2017.

Gaigalis, V., Skema, R., Marcinauskas, K., Korsakiene, I., 2016. A review on heat pumps implementation in Lithuania in compliance with the national energy strategy and EU policy. Renew. Sustain. Energy Rev. 53, 841–858. http://dx.doi.org/10.1016/j.rser.2015.09.029.

Hvelplund, F., Lund, H., 1998. Feasibility Studies and Public Regulation in a Market Economy, ISP Skriftserie nr. 218. Institute for Development and Planning. Aalborg University, Aalborg.

IEA, 2014a. Lithuania: Electricity and Heat [WWW Document]. Stat. Search URL. https://www.iea.org/statistics/statisticssearch/report/?country=Lithuania&product=electricityandheat, Accessed date: 6 July 2017.

IEA, 2014b. The Power of Transformation. IEA, Paris. http://dx.doi.org/10.1007/BF01532548.

IEA, 2016. Nordic energy technology perspectives 2016–nordic energy research [WWW document]. Nord. Energy Technol. Perspect 2016 URL. http://www.nordicenergy.org/project/nordic-energy-technology-perspectives/, Accessed date: 10 January 2017.

IEA, 2017. IEA - Statistics Search [WWW Document]. IEA Stat. Search URL. https://www.iea.org/statistics/statisticssearch/, Accessed date: 10 August 2017.

Kirkerud, J.G., Trømborg, E., Bolkesjø, T.F., 2016. Impacts of electricity grid tariffs on flexible use of electricity to heat generation. Energy 1–9. http://dx.doi.org/10.1016/j.energy.2016.06.147.

Klavs, G., Kudrenickis, I., 2016. Energy Efficiency Trends and Policies in LATVIA. Riga.

Konstantinaviciute, I., Bobinaite, V., Tarvydas, D., Gatautis, R., 2013. Renewable energy in the Lithuanian heating sector. Energy Pol. 59, 32–43. http://dx.doi.org/10.1016/j.enpol.2013.04.016.

Kuhi-Thalfeldt, R., Valtin, J., 2009. Combined heat and power plants balancing wind power. Oil Shale 26, 294. http://dx.doi.org/10.3176/oil.2009.3S.11.

Kveselis, V., Dzenajavičienė, E.F., Masaitis, S., 2017. Analysis of energy development sustainability: the example of the Lithuanian district heating sector. Energy Pol. 100, 227–236. http://dx.doi.org/10.1016/j.enpol.2016.10.019.

Lannoye, E., Flynn, D., O'Malley, M., 2015. Transmission, variable generation, and power system flexibility. IEEE Trans. Power Syst. 30, 57–66. http://dx.doi.org/10.1109/TPWRS.2014.2321793.

Lauka, D., Gusca, J., Blumberga, D., 2015. Heat pumps integration trends in district heating networks of the Baltic States. Procedia Comput. Sci. 52, 835–842. http://dx.doi.org/10.1016/j.procs.2015.05.140.

Likumi, 2016. Guidelines of Energy Development for 2016-2020 [WWW Document]. URL. https://m.likumi.lv/doc.php?id=280236, Accessed date: 6 August 2017.

Likumi, 2017. Noteikumi Par Elektroenerģijas Ražošanu Un Cenu noteikšanu, Ražojot Elektroenerģiju Koģenerācijā [WWW Document]. URL. https://m.likumi.lv/doc.php?id=189260, Accessed date: 6 July 2017.

Lund, H., 2003. Technical Design of Flexible Sustainable Energy Systems, in: 2nd Dubrovnik Conference on Sustanaible Development Og Energy, Water and Environment Systems. Balkema Publishers, A.A, Taylor & Francis The Netherlands,, Dubrovnik, pp. 1–10.

Lund, H., Andersen, a. N., 2005. Optimal designs of small CHP plants in a market with fluctuating electricity prices. Energy Convers. Manag. 46, 893–904. http://dx.doi.org/10.1016/j.enconman.2004.06.007.

Lund, H., Hvelplund, F., Kass, I., Dukalskis, E., Blumberga, D., 1999. District heating and market economy in Latvia. Energy 24, 549–559. http://dx.doi.org/10.1016/S0360-5442(99)00017-1.

Lund, H., Šiupšinskas, G., Martinaitis, V., 2005. Implementation strategy for small CHP-plants in a competitive market: the case of Lithuania. Appl. Energy 82, 214–227. http://dx.doi.org/10.1016/j.apenergy.2004.10.013.

Lund, P.D., Lindgren, J., Mikkola, J., Salpakari, J., 2015. Review of energy system flexibility measures to enable high levels of variable renewable electricity. Renew. Sustain. Energy Rev. 45, 785–807. http://dx.doi.org/10.1016/j.rser.2015.01.057.

Macevičius, V., 2015. Lithuanian district Heating Sector: Present Situation and Future of the Lithuanian Energy Market.

Mathiesen, B.V., Lund, H., Connolly, D., Wenzel, H., Ostergaard, P.A., Möller, B., Nielsen, S., Ridjan, I., KarnOe, P., Sperling, K., Hvelplund, F.K., 2015. Smart Energy Systems for coherent 100% renewable energy and transport solutions. Appl. Energy 145, 139–154. http://dx.doi.org/10.1016/j.apenergy.2015.01.075.

Miskinis, V., Slihta, G., Rudi, Y., 2006. Bio-energy in the baltic states: current policy and future development. Energy Pol. 34, 3953–3964. http://dx.doi.org/10.1016/j.enpol.2005.09.021.

National Commission for Energy Control and Prices, 2016. Tariffs for Electricity from RES 2015 year [WWW Document]. URL. http://www.regula.lt/en/Pages/tariffs-for-electricity-from-res-2015-year.aspx, Accessed date: 7 June 2017.

Norsk Energi and Thema Consulting Group, 2014. Fjernvarmens Rolle I Energisystemet. Oslo.

Olsen, O.J., Munksgaard, J., 1998. Cogeneration and taxation in a liberalized Nordic power market. Util. Pol. 7, 23–33. http://dx.doi.org/10.1016/S0957-1787(98)00002-2.

Østergaard, P.A., Andersen, A.N., 2015. Booster heat pumps and central heat pumps in district heating. Appl. Energy. http://dx.doi.org/10.1016/j.apenergy.2016.02.144.

Perednis, E., Katinas, V., Markevičius, A., 2012. Assessment of wood fuel use for energy generation in Lithuania. Renew. Sustain. Energy Rev. 16, 5391–5398. http://dx.doi.org/10.1016/j.rser.2012.05.044.

Roos, I., Soosaar, S., Volkova, A., Streimikene, D., 2012. Greenhouse gas emission reduction perspectives in the Baltic States in frames of EU energy and climate policy. Renew. Sustain. Energy Rev. 16, 2133–2146. http://dx.doi.org/10.1016/j.rser.2012.01.013.

Salpakari, J., Mikkola, J., Lund, P.D., 2016. Improved flexibility with large-scale variable renewable power in cities through optimal demand side management and power-to-heat conversion. Energy Convers. Manag. 126, 649–661. http://dx.doi.org/10.1016/j.enconman.2016.08.041.

Sekmokas, A., 2012. The National Energy Independence Strategy Presented to the Seimas [WWW Document]. Press Releases. URL. http://www.lrs.lt/sip/portal.show?p_r=9252&p_k=2&p_t=124673, Accessed date: 6 August 2017.

Skytte, K., Olsen, O.J., Rosenlund Soysal, E., Møller Sneum, D., 2017. Barriers for district heating as a source of flexibility for the electricity system. J. Energy Mark 10, 1–19. http://dx.doi.org/10.21314/JEM.2017.161.

Sneum, D.M., Sandberg, E., Soysal, E.R., Skytte, K., Olsen, O.J., 2016. Framework Conditions for Flexibility in the District Heating-electricity Interface, Flex4RES Project. Lyngby.

Soysal, E.R., Møller Sneum, D., Skytte, K., Olsen, O.J., Sandberg, E., 2016. Electric boilers in district heating systems: A comparative study of the Scandinavian market conditions - DTU orbit. In: Swedish Association for Energy Economics (Ed.), Swedish Association for Energy Economics Conference 2016. Swedish Association for Energy Economics, Luleå.

Streckiene, G., Martinaitis, V., Andersen, A.N., Katz, J., 2009. Feasibility of CHP-plants with thermal stores in the German spot market. Appl. Energy 86, 2308–2316. http://dx.doi.org/10.1016/j.apenergy.2009.03.023.

Riigi Teataja, 2014. Electricity Market Act [WWW Document]. URL. https://www.riigiteataja.ee/en/eli/528082014005/consolide, Accessed date: 6 July 2017.

The Norwegian Water Resources and Energy Directorate, 2015. Kostnader i energisektoren. Oslo.

The World Bank, 2017. World Development Indicators | Data [WWW Document]. World Dev. Indic Dataset. URL. http://data.worldbank.org/data-catalog/world-development-indicators, Accessed date: 6 July 2017.

Trømborg, E., Havskjold, M., Bolkesjø, T.F., Kirkerud, J.G., Tveten, Å.G., 2017. Flexible use of electricity in heat-only district heating plants. Int. J. Sustain. Energy Plan. Manag 12, 29–46. http://dx.doi.org/10.5278/ijsepm.2017.12.4.

Ziemele, J., Pakere, I., Blumberga, D., 2016. The future competitiveness of the non-Emissions Trading Scheme district heating systems in the Baltic States. Appl. Energy 162, 1579–1585. http://dx.doi.org/10.1016/j.apenergy.2015.05.043.

International Journal of
Sustainable Energy Planning and Management

Economic incentives for flexible district heating in the Nordic countries

Daniel Møller Sneum[1a], Eli Sandberg[b]

[a]*Systems Analysis Division, DTU Management Engineering, Produktionstorvet, Building 426, DK-2800 Lyngby, Denmark.*
[b]*Faculty of Environmental Sciences and Natural Resource Management, Norwegian University of Life Sciences, PO 5003, NO-1432 Ås, Norway.*

ABSTRACT

By analysing four types of district heating plants, ranging from fully integrated with an electricity system (combined heat and power and electric boiler) to no integration with an electricity system (wood chip boiler), operation and investment incentives for flexible district heating plants under current Danish, Finnish, Norwegian and Swedish framework conditions have been investigated. Hourly-based operation optimisation over 20 years using the modelling software energyPRO showed that the largest investment incentive in Finland, Norway and Sweden was for combined heat and power with an electric boiler. This is largely driven by subsidies. Conversely, the less-subsidised Danish case incentivised investment in wood chip boilers. Untaxed biomass is the major energy source in all scenarios, while electricity use is limited. Capacity component-based tariffs can eliminate operation of electric boilers, while less costly energy component-based tariffs can increase the operation of electric boilers. Heat storage was found to be a no-regrets solution for optimising operation and lowering costs in all cases.

Keywords:

District heating;
Flexibility;
Thermal storage;
Energy taxation;
Electricity grid tariffs;

URL:
dx.doi.org/10.5278/ijsepm.2018.16.3

1. Introduction

The energy share from renewable sources of the total primary energy supply in the Nordic countries Denmark, Finland, Norway and Sweden was 27–43% in 2014. Present EU-wide policy targets include an increase in the EU 2014 15% gross share of renewable energy in energy consumption to at least 27% by 2030 [1], and decarbonisation goals for 2050 [2] are likely to further increase the share of renewable energy in the Nordic region. If a significant portion of this additional renewable energy stems from variable renewable electricity (VRE) production, such as solar photovoltaics and wind power, there could be an increased future need for flexibility in energy systems (*flexibility* is defined in Section 2.1). As of 2015, Denmark had the largest penetration of VRE among the Nordic countries, where wind power corresponded to 50% of Danish net electricity generation.

Increased coupling among the energy sectors is emphasised as a pertinent challenge for policy makers by IEA [3] and can lead to energy systems that are flexible and able to integrate VRE [4], summarized under the term *smart energy systems* [5]. Smart energy systems by definition span several sectors and flexibility can thus be offered by a multitude of technological options. A comprehensive overview of such flexibility options has been provided by Lund et al. [6], where examples include hydropower capacity, electric vehicles,

[1] Corresponding author e-mail: dasn@dtu.dk

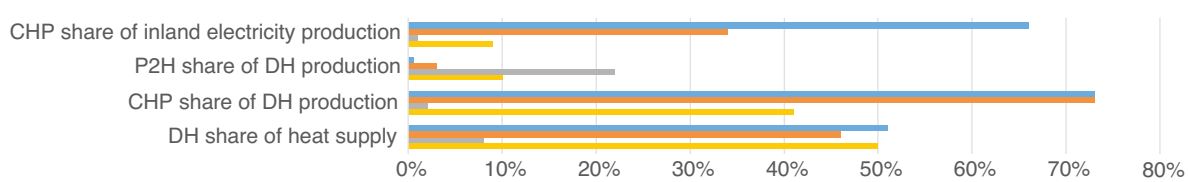
Abbreviations

CHP: Combined heat and power
CT: Capacity component-based electricity transmission and distribution grid tariff
DH: District heating
DK: Denmark
DSO: Distribution system operator
EB: Electric boiler
ET: Energy component-based electricity transmission and distribution grid tariff
FI: Finland
HS: Heat storage
LCOH: Levelised cost of heat
NETP: Nordic Energy Technology Perspectives 2016
NO: Norway
O&M: Operation and maintenance
OB: Oil boiler
P2H: Power-to-heat
PUD: Preferred unit for dispatch
SE: Sweden
T&D: transmission and distribution
VRE: Variable renewable energy
WCB: wood chip boiler

individual consumers, hydrogen and synthetic fuels production, and heating and cooling. Coupling and smart energy systems are therefore considered enablers for renewable-based, less expensive and resource-efficient energy systems [7,8].

Several studies have indicated that the interface between the electricity system and the district heating (DH) system is an important aspect of energy system integration [7–9]. Furthermore, the potential of flexible DH technologies for sector coupling has been demonstrated in both real-world deployment in the Nordic countries and in the literature [4,6,10]. Combined heat and power (CHP) and power-to-heat technologies (P2H), i.e. heat pumps and electric boilers (EB), are relevant flexibility providers for DH systems [4,6,10–13]. As an example of the impact of introducing increased electricity demand flexibility (e.g. from P2H), Tveten et al. [14] have demonstrated a 7.2 TWh/year increased integration of VRE in Northern Europe by 2030. Connolly and Mathiesen define such introduction of CHP and P2H as two of the key stages in a transition to a 100% renewable energy system [15]. In addition, studies have shown that the deployment and use of heat storage (HS) is an important enabler of the flexible operation of both CHP and P2H [16–19]. Increased flexible coupling of heat to an electricity system would thus be one step towards a smart energy system, where the integration of VRE can be facilitated by the flexible operation of DH plants.

Energy consumption in Nordic countries in 2013 amounted to 115 TWh DH and 345 TWh electricity [20]. Figure 1 presents the share of CHP for national electricity production, of P2H for DH-production, of CHP for DH-production and of DH for total heat demand in each of the Nordic countries [21]. Norway is an exception because



	DH share of heat supply	CHP share of DH production	P2H share of DH production	CHP share of inland electricity production
Denmark	51%	73%	1%	66%
Finland	46%	73%	3%	34%
Norway	8%	2%	22%	1%
Sweden	50%	41%	10%	9%

Figure 1: Characteristics of district heating for Nordic energy systems in 2014. Data based on Euroheat & Power [21] and national statistics.

the DH sector is relatively small, compared to the other Nordic countries. The share of heat production from heat pumps and EB for DH is insignificant in all countries except Norway and Sweden, where heat pumps comprise the largest share of P2H production. HS are generally applied in all countries except Norway, where the operational practice is that generation follows heat demand rather than utilising HS [22].

While earlier framework conditions have generally accommodated a large deployment of DH in Denmark, Finland and Sweden, incentives for further investment in flexible DH technologies are less clear for the Nordic countries. As indicated by Difs [23] and Jacobsen and Zvingilaite [24], national regulation can be unconducive for flexible Nordic energy systems. Therefore, national regulation in Nordic countries encompassing taxes, subsidies and electricity tariffs was explored during this study. Specifically, investment incentives in flexible DH technologies were identified and investigated for new DH plants. Sandberg et al. compared framework conditions for DH in the Nordic countries in general [25]. Skytte et al. [26] explored the impact of DH technologies on marginal operation costs in Denmark, Norway and Sweden; Sneum et al. examined policy impacts on operation and investment incentives of DH in the Baltics [27]; and Trømborg et al. [28] analysed the impact of framework conditions for generic heat-only DH plants on operation and profitability. Munksgaard and Olsen [29] evaluated the impact of taxation on investment, and Kirkerud et al. [30] investigated the impact of electricity tariffs in Nordic countries. The novelty of this study is to extend existing knowledge by providing a holistic picture of the investment and operational conditions for new DH capacity in the Nordic countries. We do so by analysing how current policy and regulation align with assumed societal needs for increased flexible DH capacity in the energy system. In summary, the study answers the question:

How do HS, current electricity transmission and distribution grid tariffs, taxes and subsidies incentivise investment in and operation of flexible DH technologies in the Nordic countries?

The methodology is described in Section 2, followed by the results of the analyses in Section 3. Results are discussed in Section 4. The conclusions are presented in Section 5. The acknowledgement is given in Section 6, the references are listed in Section 7 and the appendix is provided in Section 8.

2. Methodology

Taxes, subsidies and electricity transmission and distribution (T&D) grid tariffs were analysed in aggregate along with HS to determine their impacts on operation and investment incentives. Models for four types of DH plants were developed using the analysis tool energyPRO. Each type of plant had a different degree of coupling to the electricity system, representing different options for potentially flexible interactions in the DH-electricity interface. Furthermore, for each country, the model was subjected to the current (2016) levies and subsidies applicable for each Nordic country. The outcomes of these feasibility studies indicate whether the current economic framework conditions incentivise investment in flexible DH plants of the chosen type and to what degree HS impacts economic feasibility.

2.1. Definition of flexibility

During this study, incentives for investment in potentially flexible DH technologies were analysed. While an analysis of flexibility in itself is outside the scope of this study, it is important to define flexibility because it is a characteristic assigned to the technologies addressed in this study.

In recent years, flexibility in energy systems has received comprehensive coverage in both grey literature and academic literature, such as IEA [4], Denholm and Hand [31], Holttinen et al. [32] and Lund et al. [6]. In this study, flexibility is characterised by the ability of a DH-technology to provide frequent increases or decreases in its consumption or production of electricity according to signals from the electricity system, such as the use of P2H during hours when electricity prices are low, CHP electricity production during hours when electricity prices are high and the use of HS to supply heat when demanded. This electricity-oriented definition is in line with the DH-electricity focus applied by Salpakari et al. [33] as well as with the definitions applied by Lund [6] and Mathiesen [5] from a broader energy system perspective.

Thus, to accommodate flexibility in the energy system, investment incentives for DH technologies should favour those technologies which enable interactions in the DH-electricity interface. Furthermore, the flexibility of these technologies should not be impeded by operational barriers. The operational focus in this study is thus not to determine the flexibility of a

given plant but rather to clarify the impact of operation on the economic feasibility of flexible DH technologies.

2.2. Operation and investment analysis

By analysing the economic framework conditions and the presence of HS, the operational patterns, and subsequently the investment incentives, were explored for flexible and inflexible configurations of DH plants in Nordic countries. This section introduces each of the three concepts.

Electricity T&D grid tariffs are set by grid companies—transmission and distribution system operators—to cover the cost of using the grid. Electricity T&D grid tariffs vary in terms of design and magnitude among countries and regions but are typically constructed as *grid tariff = fixed component + energy component + capacity component*. Variations in structure and volume can be explained by factors such as customer types and connection level and can induce different operational patterns in P2H technologies because they impact the marginal cost of operation. In turn, operational patterns can be decisive for the economic feasibility of the technology or plant. This study focused on local distribution grid tariffs for business customers with an installed capacity of 10 MW and a high voltage connection of 10-20 kV (DH plants), and the costs embedded in those. For the electricity T&D grid tariffs included in this study, Finland, Norway and Sweden all apply capacity components, which are set by the highest electricity consumption in MW per month and a reduced energy component per MWh electricity consumed. Denmark applies only energy components. In Norway and Sweden, some grid companies allow so-called non-prioritised tariffs for devices interruptible on short notice such as P2H. Non-prioritised tariffs can be structured as a reduced or removed capacity component and an energy component, which is the same or higher than under the capacity component-based tariff scheme. To explore the impact of capacity component-based electricity grid tariffs (CT) as well as energy component-based electricity grid tariffs (ET), it was assumed that all countries provide both tariff options.

In contrast to electricity T&D grid tariffs, taxes and subsidies do not necessarily reflect the costs of using a product but can be applied to address externalities or for fiscal purposes [29]. Like electricity T&D grid tariffs, taxes and subsidies impact the marginal operation costs and thereby the operation. This impact was explored by subjecting the scenarios to a removal of all taxes and subsidies, whereby it was determined how taxes and subsidies impacted the operation of the DH plants analysed.

HS can allow improved utilisation of least-cost technologies by enabling a decoupling between heat demand and electricity prices. For CHP and P2H technologies, this means that they can operate when electricity prices are respectively high or low regardless of the correlation with heat demand.

2.2.1. Operation analyses using energyPRO simulation software

The quantitative analyses were conducted as techno-economic studies of four different types of DH plants for each of the Nordic countries. This allowed for a comparison of the impacts of taxes and subsidies and the use of HS. Operation optimisation was conducted using the DH simulation software energyPRO because this is a proven tool that has been applied in industries and academia (e.g. [34,35]) for performing techno-economic feasibility studies, scenario analyses and simulations of operations for DH plants [28,36]. energyPRO optimises operation on an hourly level with deterministic results to obtain the lowest heat production cost, and it also considers the availability of HS capacity.

Inputs for the model include temperatures, energy demands, technologies and costs, some of which impact the marginal heat production cost. As illustrated in Figure 2, operation depends on the marginal heat production cost in relation to the electricity price, here termed *preferred unit for dispatch* (PUD). In the example provided in Figure 2, the inclining lines represent P2H, which is PUD in periods with low

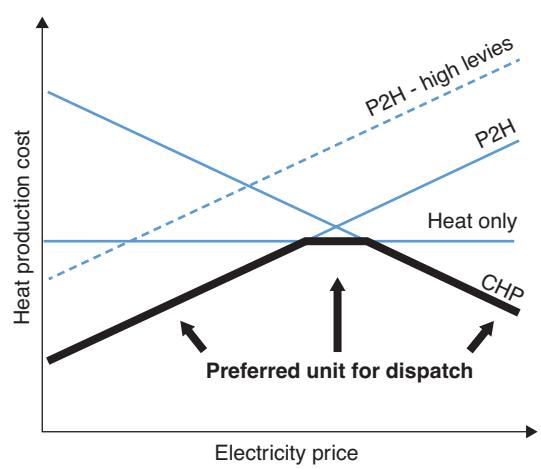


Figure 2: PUD and marginal heat production costs in a DH plant with heat-only boilers, P2H and CHP

electricity prices. Whereas electricity spot prices define the general tendency of an inclination/declination in costs, electricity T&D grid tariffs, taxes and subsidies determine the internal relations between each unit. This is exemplified by the dotted line, where due to high levies, P2H has relatively higher marginal heat production costs than P2H without levies (solid line), and therefore it is only PUD in periods with very low electricity prices.

The analyses conducted using energyPRO were based on a perfect foresight regarding electricity prices, which means that the models were optimised using known future electricity prices. This could potentially lead to unrealistically perfect hour-by-hour load-following in the DH production of CHP and EB. To address this issue, CHP and EB were only allowed to operate in full load. This operation, which is based on power market bids for full loads, is seen in real Danish CHP plants. The day-ahead electricity spot market prices are applied in the modelling. For further details on additional power markets, Sorknæs et. al [37] have provided insights on the ability of CHP to integrate VRE through the ancillary services markets. Further details on the optimisation using energyPRO can be found in [38].

2.2.2. Feasibility study of investment incentives

For a DH plant to offer flexibility, it must exist in an energy system. To exist, there must be an investment. Thus, in addition to operational aspects, investments in flexible DH technologies are important for securing the availability of flexible technology options.

Combining the operational costs and revenues from the energyPRO simulations with investments allows for microeconomic feasibility studies of the technologies applied in the scenarios. In turn, this provides a means of comparison between scenarios, indicating the most profitable/least costly projects. In practice, comparisons were done on the levelised cost of heat (LCOH), i.e. the discounted sum of expenses, income and energy calculated over the lifetime of the project. Discounting was performed at a nominal rate of 4%, reflecting the current low cost of capital and low risk for such long-term projects in the Nordic countries. All income and expenditures were subject to inflation (1.5 to 2.3% varying over years) based on projections by the Danish Energy Agency [39]. Investment costs were based on The Norwegian Water Resources and Energy Directorate [40]. The project period spans from 2015 (investment year) and 2016 (first year of operation) to 2035 (final year of operation), where components with a remaining lifetime were decommissioned at a linear scrap value for hardware costs. Revenue from sales of heat was not included in the study because this is represented by the LCOH. LCOH thus indicates the cost of supplying heat, where lower is better because it is assumed that the economically rational *profit-maximizing investor will select the production technology having the lowest long run production costs taking into consideration the present tax regime including subsidies* [29]. LCOH calculation followed the normal approach for the levelised cost of energy, as seen in Eq. (1).

$$LCOH = \frac{\sum_{t=0}^{n} \frac{TC_t}{(1+r)^t}}{\sum_{t=0}^{n} \frac{q_t}{(1+r)^t}} \tag{1}$$

Where

- *LCOH*: levelised cost of heat
- *n*: number of years
- *t*: given period
- *r*: discount rate
- TC_t: total cost in period *t*
- q_t: heat production in period *t*

TC_t is specified in Eq. (2) because taxes and other variable costs were a significant part of this study. The energyPRO operational optimisation included the parameters marked in *italics*.

$$TC_t = \mathrm{I_t}\ \mathrm{IS_t} + \mathrm{FOM_t} + VOM_t + F_t + E_t + T_t + TF_t + TV_t - E_t - S_t \tag{2}$$

Where

- I_t: investment cost in period *t*
- IS_t: investment subsidy in period *t*
- FOM_t: fixed operation and maintenance cost in period *t*
- VOM_t: variable operation and maintenance cost in period *t*
- F_t: fuel cost in period *t*
- E_t: spot electricity cost in period *t*
- T_t: tax (CO_2, energy and public service obligations) in period *t*
- TF_t: capacity component-based electricity T&D grid tariff in period *t*
- TV_t: energy component-based electricity T&D grid tariff in period *t*
- E_t: revenue from electricity sales in period *t*
- S_t: energy dependent subsidy in period *t*

2.3. Technologies, framework conditions and their combined variations

For this study, four different combinations of DH technologies were chosen to reflect potential investment options under policies for the increased use of renewable energy in the DH system. Each of these technology combinations described DH plants in varying degrees of potential flexibility in the DH-electricity interface. Thus, the combinations ranged from inflexible (large wood chip boiler [WCB]) to flexible production and consumption (backpressure wood chip CHP and EB). All technology combinations were required to satisfy the same heat demand of 40 GWh (2016) and were supplemented with an oil boiler (OB) as a fall-back option, providing capacity for backup and peak load. Each technology combination, ordered from A through D, is detailed in Table 1. The terms *baseload, mid-load* and *peak load* indicate a level of operation (load) according to the design assumption for a typical plant. A water-based 2000 m^3 storage was included in scenarios with HS. This volume corresponds to one to three days of heat demand in similar sized DH plants in Denmark.

The technological combinations were subjected to three overall conditions to determine impacts on investment incentive and operation. Specifically, we evaluated the operational impact of taxes and subsidies, and the impact on investment incentive and operation of HS and electricity T&D grid tariffs.

Together, the technological combinations and conditions provided a set of scenarios, which are shown in Figure 3. Analysing each scenario for each of the four countries under study yielded 96 different operation analyses, whereof the economic feasibility (LCOH) was analysed for the 48 studies with tax.

2.4. Data and assumptions

The impact of electricity T&D grid tariffs, taxes, subsidies and HS on incentives for operation and investment were the focal points of this study. To analyse taxes, subsidies and electricity T&D grid tariffs, it was necessary to conduct extensive reviews of their levels and designs for each country. The regulations for heat and electricity production vary among the countries, e.g. depending on the categorisation under the European Emissions Trading System or to which customers the DH is supplied. This review combined desk research, dialogue with national authorities and dialogue with national partners in energy academia (Technical University of Denmark, Aalto University in Finland, Norwegian University of Life Science and the Swedish Royal Institute of Technology) to ensure validation. To the best of the authors' knowledge, the data are thus comprehensive for electricity T&D grid tariffs, taxes and subsidies as of 2016.

Changes in heat demand and price levels of wood chips, electricity and oil followed the projections from the dataset of the Carbon Neutral Scenario in the Nordic Energy Technology Perspectives (NETP) [42], which for this purpose was considered the most comprehensive and valid source of data considering the geographical region and time period. The projected increases in wind power (2014: 7%, 2040: 24%) and electricity prices are illustrated in Figure 4.

Heat demand (40 GWh) is dependent on outdoor temperatures, which have been adjusted to the area of the capital of each of the four countries.

Levies on NO_x and SO_2 emissions are not included, as these are negligible in all countries in comparison to the levies included in this review. Electricity T&D grid tariff design and magnitude can vary greatly within countries and was thus selected from the capital areas of each country. Financial regulations (e.g. corporate tax regulation, depreciation rules), reactive power charge and trade on the ancillary services markets are outside the scope of this study.

Table 2 presents the wood chip and oil prices. The oil price is set at an average common price. Electricity prices

Table 1: Technological combinations considered. Capacities and load shares are based on Norsk Energi and Thema Consulting Group [41]

	Baseload	Mid-load	Peak load		
Technological combination	**5.4 MW_{TH} 45% of peak load, low fuel price**	**6.6 MW_{TH} 55% of peak load**	**12 MW_{TH} 100% of peak load, low investment cost**	**Flexible technology: Production**	**Flexible technology: Consumption**
A	Wood chip CHP	EB	OB	X	X
B	Wood chip CHP	WCB	OB	X	
C	WCB (12 MW_{TH})	—	OB		
D	WCB	EB	OB		X

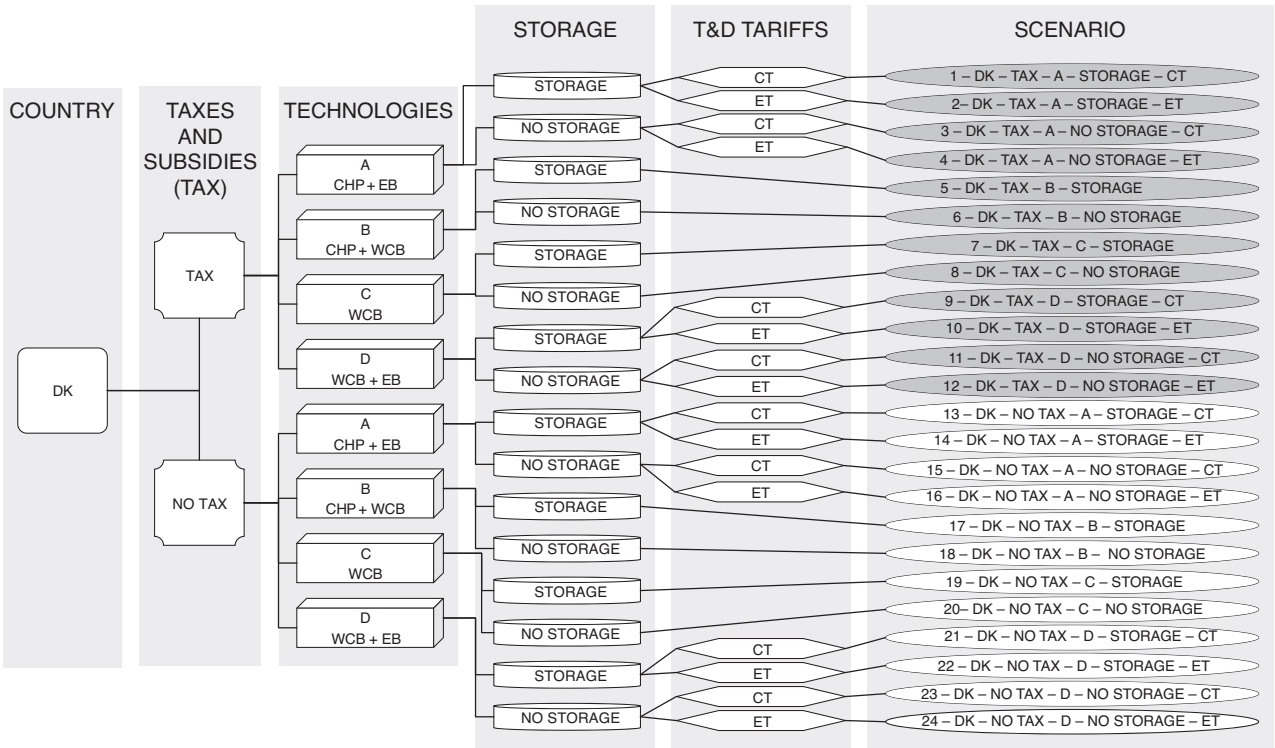
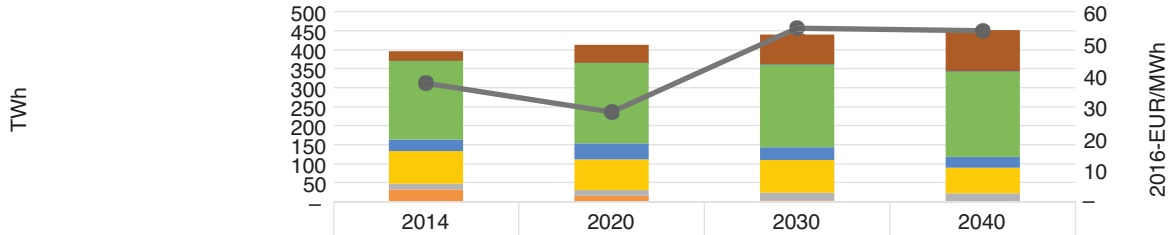


Figure 3: Structure of scenarios with Denmark as example. Analyses were conducted respectively with and without tax and subsidies, and storage, on the technological combinations. Furthermore, the technological combinations with EB were subjected to electricity T&D grid tariffs, leading to a total of 24 scenarios for each country. Shaded scenarios include taxes and subsidies, and formed the economic analysis resulting in values on LCOH. 'TAX' defines both taxes and subsidies in the figure



	2014	2020	2030	2040
Wind	26	47	78	108
Solar	1	1	1	1
Hydro	206	213	217	225
Biofuels and Waste	31	42	33	28
Nuclear	86	81	87	68
Natural gas	16	15	20	20
Coal and other fossils	31	15	4	0
Oil	0	0	–	–
Electricity price - Nordics	37	28	55	54

Figure 4: Projected development in the Nordic countries: electricity generation mix (left axis), electricity prices (right axis) [42]

are based on hourly variations for each country from the Nordic electricity exchange Nord Pool Spot. All prices are from 2016 and were projected for the future using the annual averages of the NETP 2016 [43]. NETP is exploring a transition to a carbon neutral energy system in 2050. Thus, the NETP energy prices were assumed to provide a framework suitable for the micro-economic perspective of the present study, especially due to the assumption that a Nordic energy system will become increasingly reliant on renewable energy.

Table 3 displays the taxes, subsidies and electricity T&D grid tariffs applied in this study. The origins of the taxes and subsidies that dictate taxation have been reviewed by Sneum et al. [22]: Tax exemption for biomass is motivated by its characteristic as a locally available and secure fuel, a renewable and CO_2-neutral fuel and—perhaps most importantly—a fuel that is difficult to tax due to its availability in many forms. Subsidies for CHP are not directly motivated by increasing a flexible operation but rather by security of supply and priority for energy efficiency. All countries are applying levies for EB operation. In countries where electricity production traditionally has been based on fossil fuel and thermal technology, these levies tend to be higher because taxation has been applied to prevent the use of electricity for heating.

Table 2: Fuel prices in 2016 based on national statistics and the European Commission [44]

Fuel price – EUR/MWh	DK	FI	NO	SE
Oil	28.1	28.1	28.1	28.1
Wood chips	22.8	21.3	19.0	19.9

Capacity components in electricity T&D grid tariffs vary in design and volume among and within countries. For this study, we applied capacity components with the following characteristics: Denmark has none, Finland a constant, Norway a seasonal and Sweden a seasonal component, which is also dependent on time of day. The seasonal variations shown in Figure 5 indicate high prices during cold periods.

Investment costs, which are subdivided into hardware components and labour costs, are displayed in Table 4. The labour cost shares of investments have been adjusted according to the relative labour costs in each country, while the hardware costs remain fixed for all countries. Financing was not included in the capital cost. The considerable additional cost of the wood chip CHP is explained by the additional costs that electricity generation entails. Those include the steam turbine itself, generator and high-pressure boiler [40]. Similar cost ranges and differences among technologies are found in The Danish Energy Agency's technology overview [45]. Fixed operation and maintenance are the same for all countries under each scenario.

Table 5 presents the technological assumptions. The project period (20-year economic lifetime) is longer than the technical lifetime of the WCB. Hence, reinvestment is necessary. Remaining lifetimes of technologies are included as linearly reduced scrap values.

3. Results

In this section, results from the operational and LCOH analyses are presented based on how heat production is distributed among technologies and based on the

Table 3: 2016 levels of taxes, electricity T&D grid tariffs and subsidies. All numbers in EUR/MWh unless otherwise stated. *DK CHP subsidy active until 2019. For NO and SE, the subsidy is in the form of green certificates. [c] Under capacity component-based tariff. [e] Under energy component-based tariff. Energy and capacity tariffs can vary according to time of day and seasonal variation. ** Maximum subsidy granted in the scheme. 50% subsidy is assumed for this study.

Country	Electricity tax	CO2 tax	Energy tax – oil	Subsidy on bio CHP elec. prod.*	Subsidy on bio CHP heat production	Subsidy on investment	DSO energy component [EUR/MWh]	DSO capacity component [EUR/MW/month based on monthly max.]
DK	28.9	30.3	26.5	20.1	–	–	7.8-30.7[ce]	0
FI	22.5	10.4	8.5	–	20.0	–	6.1-11.4[c] 8.7-21.4[e]	2 900
NO	0.5	8.9	15.7	137.9	–	50%**	1.6-2.7[ce]	860-11 828
SE	30.8	30.4	17.3	137.9	–	–	3.0[c] 5.1[e]	6 759

components that comprise the LCOH. The former indicates whether and how technologies are operated; the latter provides insight into the most economically attractive solution. Both contribute to understanding the incentive to invest in flexible DH for different scenario variations, and are conducted for HS and electricity T&D grid tariffs. Analyses of scenarios with and without taxes and subsidies provide insight on operational impacts, whereas analyses of LCOH without taxes and subsidies are irrelevant in this business economic perspective. Thus, only the operational side is analysed for taxes and subsidies.

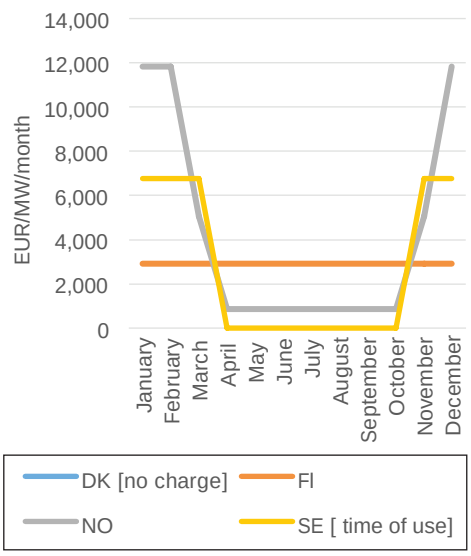


Figure 5: Seasonal variations of capacity component-based tariffs. DK has none. For SE, it applies during certain hours of a day

3.1. Operational and economic impacts of HS

The distribution of heat production for the scenarios used to determine the operational impact of HS is shown in Figure 6. Without exception, HS allows for improved utilisation of least-cost technologies. Therefore, baseload technology displaced mid- and peak load technologies, and mid-load technology displaced peak load technology (except in the Norwegian WCB + EB scenario, where EB displaces WCB due to low electricity cost).

While the CHP, EB and WCB can supply heat during periods with peak demand, their minimum load constraints do not permit operation during periods with a low demand. The absence of HS eliminates the opportunity to save excess production for periods with a low demand, which instead must be supplied by technologies without these constraints. At medium load levels, the WCB can operate, while only the OB can operate during low load levels.

Cost components and LCOH for scenarios with and without HS are presented in Figure 7. The trend is similarly clear to that of heat production: in scenarios

Table 4: Investment costs divided into labour and hardware costs. Cost of CHP is based on electricity output. *No references found for the labour-hardware distribution of costs for HS. Cost data are from the Norwegian Water Resources and Energy Directorate [40] and the Danish Energy Agency [45], while labour cost weights are based on Eurostat statistics

	Labour costs [EUR per MW]				Hardware costs [EUR per MW]
Technology	**DK**	**FI**	**NO**	**SE**	
WCB	3 054	2 538	4 301	3 226	602 151
OB	7 558	6 281	10 645	7 984	55 645
EB	8 016	6 661	11 290	8 468	62 903
Wood chip CHP	1 244 409	1 034 086	1 752 688	1 314 516	3 239 785
EUR for a 2000 m^3 HS*	313 011	260 108	440 860	330 645	

Table 5: Lifetimes, efficiencies and minimum loads for DH technologies [40,41,45]. Flue gas condensation assumed for the CHP, leading to the high total efficiency.

Technology	Heat efficiency	Electric efficiency	Minimum load	Technical lifetime (years)
Wood chip CHP	77%	28%	100%	25
EB	98%	–	100%	20
WCB	89%	–	25%	15
OB	92%	–	0%	20

with HS, the improved utilisation of the least-cost technologies is reflected by lower costs than without HS. The cost difference is most pronounced in scenarios with CHP in Finland, Norway and Sweden. This is explained by the improved ability to utilise the CHP and HS in combination and thereby to enhance the revenue from electricity sales and subsidies. Finally, the Norwegian 50% investment support visibly impacts the investment cost for all Norwegian scenarios.

3.2. Operational and economic impacts of electricity T&D grid tariffs

The distribution of heat production for the scenarios used to determine the operational impact of electricity T&D grid tariff is shown in Figure 8. Because Denmark only has energy component-based tariffs, the values are the same regardless of the type of electricity T&D grid tariff. Differences can be observed between CT and ET in Finland and Norway, where scenarios with ET display a higher production for EB than scenarios with CT. For both countries, operating the EB under CT for relatively few hours with low electricity prices per month, would entail a considerable monthly capacity charge that outweighs the money saved on EB production.

Cost components and LCOH for scenarios with CT and ET are presented in Figure 9. The operational results for Finland and Norway, where OB under CT is replaced by EB under ET, are mirrored in the reduced LCOH. In

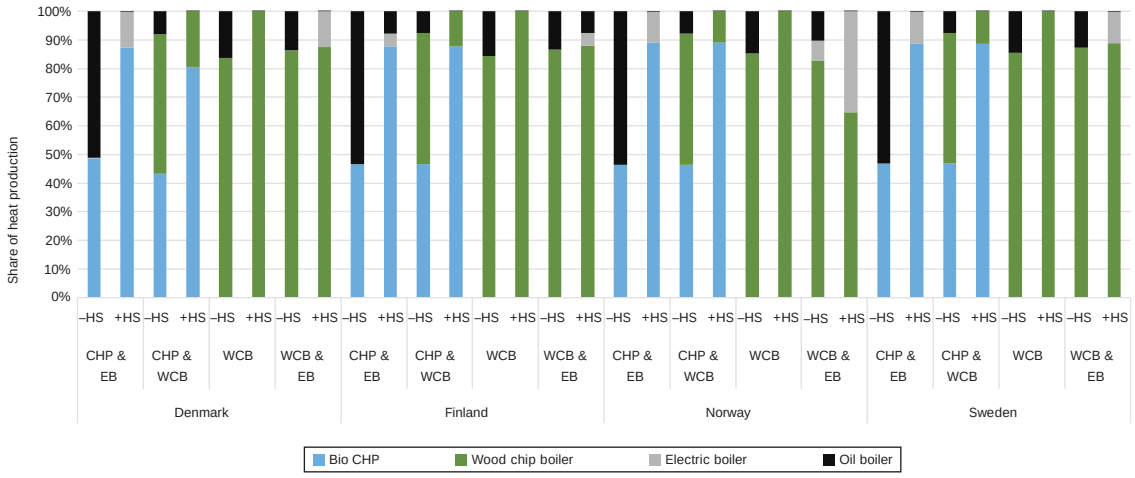


Figure 6: Shares of heat production in scenarios with and without HS, all with tax and ET

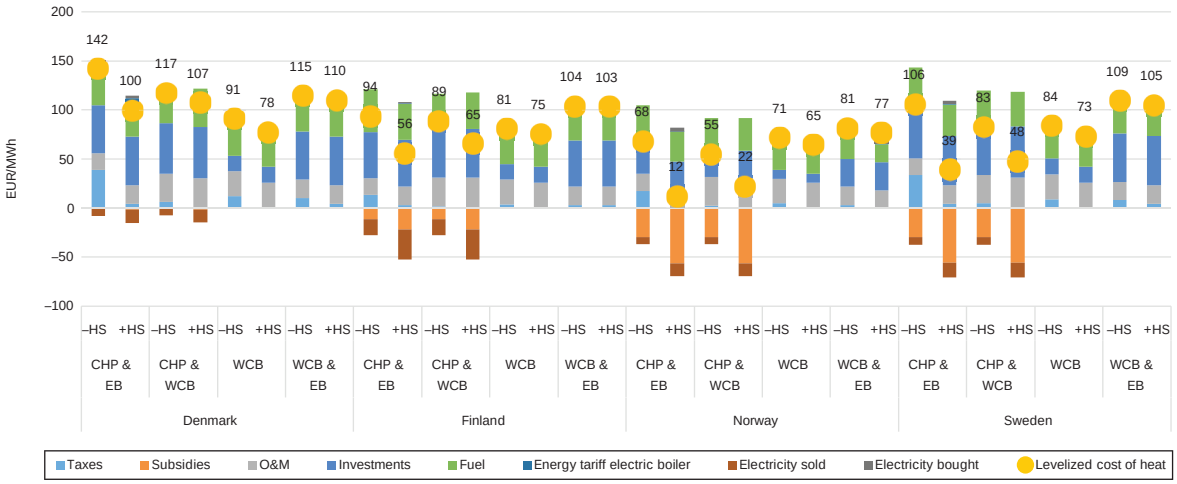


Figure 7: LCOH divided by cost components in scenarios with and without HS, all with tax and ET

Finland only to a limited degree, due to the electricity and ET costs almost outweigh the oil costs. In Norway to a larger degree, since electricity and ET costs are relatively lower.

3.3. Operational impacts of energy taxes and subsidies

The distribution of heat production for the scenarios used to determine the operational impact of taxes and subsidies is shown in Figure 10. Absence of taxes and subsidies in all cases leads to the WCB, EB and OB displacing CHP production. This happens as the CHP is generally subject to subsidies, while EB and OB are subject to taxes. When taxes and subsidies are removed, boiler technologies will become less costly (technologies increasing as PUD), displacing the costlier CHP production (technology decreasing as PUD). This finding applies in all CHP scenarios.

Absent taxes and subsidies, the share of additional EB and OB production, and the distribution among the two technologies, are subject to national fuel and electricity prices, and the electricity T&D grid tariffs. In all countries but Denmark, EB share increases significantly, and to a larger share than OB. In the Danish case, the relatively high winter ET of 24.6 EUR/MWh (lowest is Norway with 2.7 EUR/MWh), impedes operation on EB regardless of taxes.

A further cause of the considerable increase in OB in most cases without taxes and subsidies, is an expected

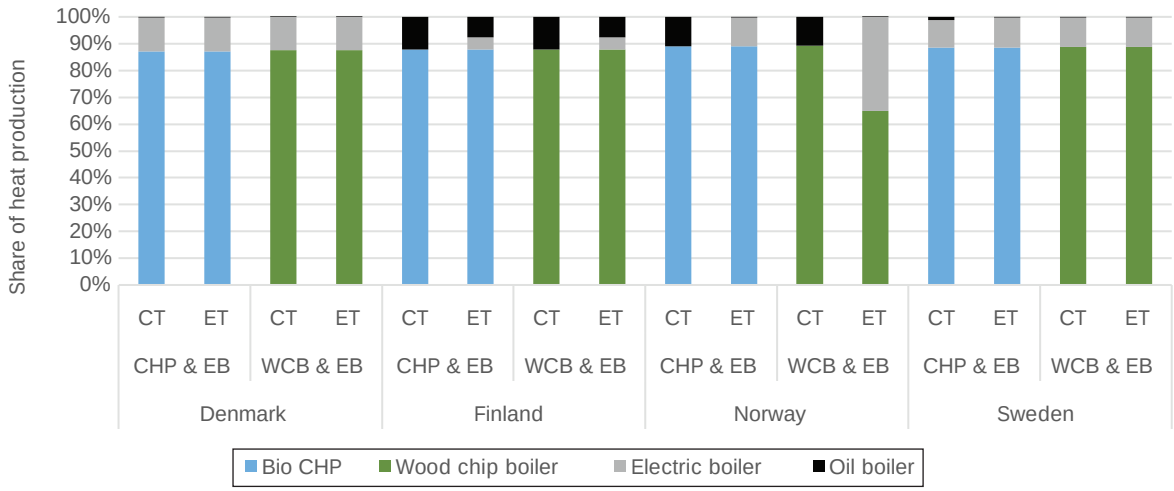


Figure 8: Shares of heat production in scenarios with CT and ET, all with tax and HS

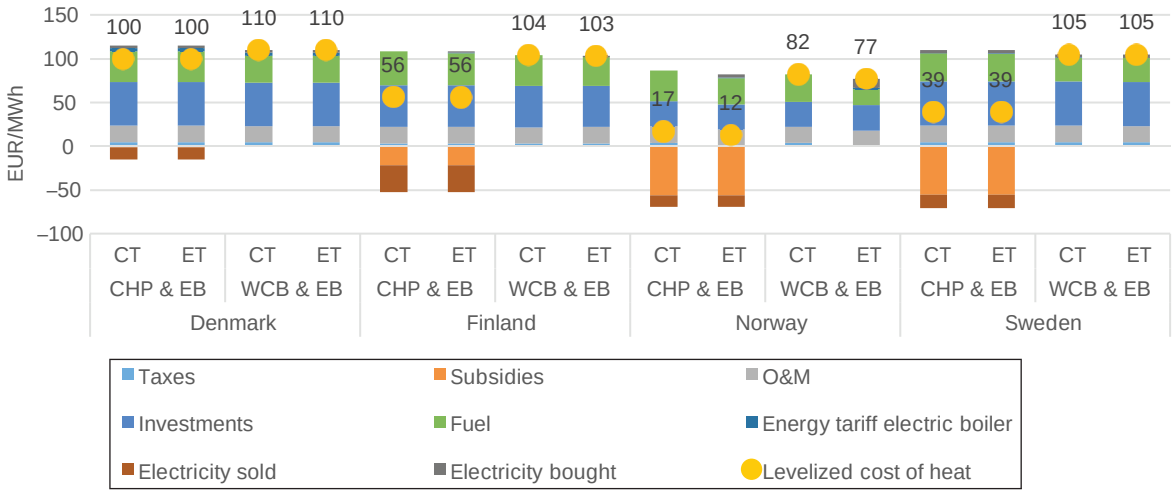


Figure 9: LCOH divided by cost components in scenarios with CT and ET, all with tax and HS

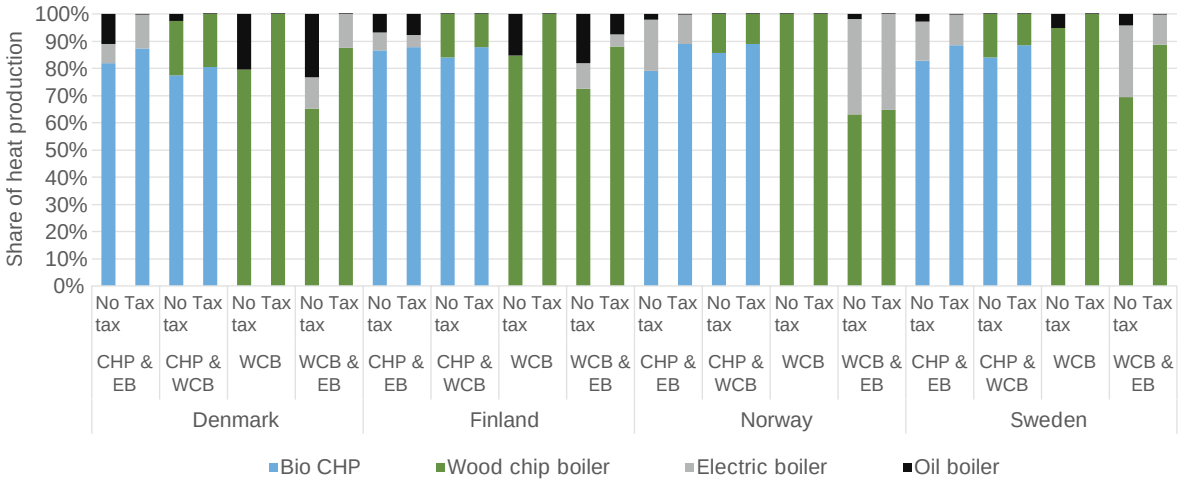


Figure 10: Shares of heat production with and without tax, all with ET and HS

decrease in oil prices around 2020. This temporarily makes oil cheaper than biomass for 1–3 years, depending on country.

3.4. Sensitivity analysis

Considering the LCOH, electricity prices and wood chip prices comprise significant shares, where e.g. electricity revenue reduces the total cost between 11 and 28%. Thus, both electricity prices and wood chip prices might impact the outcome of the analysis because both are significant drivers for revenue from the electricity spot market (and to a smaller degree, costs related to EB consumption) and costs for fuel use in WCB and CHP, respectively.

When analysing the sensitivity to electricity prices, a span of +/– 10 EUR/MWh on the hourly electricity price was explored. The sensitivity analysis was conducted for the scenario with wood chip CHP + EB, ET, by comparing the results to the LCOH of the combination with a large WCB. Figure 11 displays the results of the sensitivity analyses. The analyses indicated that all scenarios are robust despite the changes in electricity prices because the LCOH of the CHP + EB technological combination remained higher (DK) or lower (FI, NO, SE) than the WCB technological combination regardless of electricity prices.

For the sensitivity analysis of wood chip prices, a span of +/– 5 EUR/MWh was added to the price. As with the electricity prices, the sensitivity analysis on wood chip prices was conducted on the technological combinations CHP + EB and WCB by comparing the

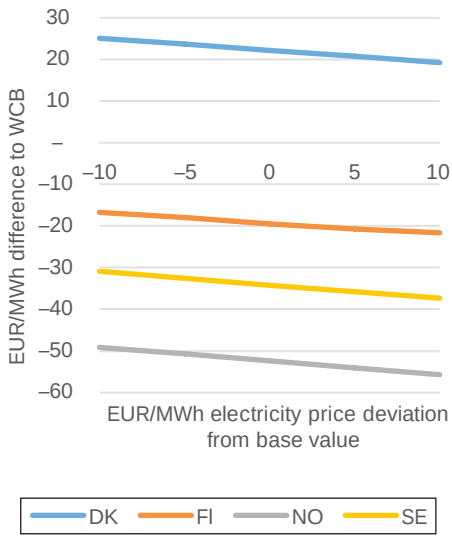


Figure 11: Sensitivity analysis of 5 and 10 EUR/MWh higher or lower electricity spot prices. Horizontal scale depicts the change in electricity prices. Vertical scale depicts the difference in LCOH of the CHP + EB technological combination to WCB. Negative values indicate that the CHP + EB LCOH is lower than that of the WCB

results with the LCOH of CHP + EB and WCB at each wood chip price level. Figure 12 displays the results of the sensitivity analyses. The LCOH of CHP + EB remained higher (DK) or lower (FI, NO, SE) than WCB regardless of biomass prices. This indicates that the price changes would not induce a shift in production technology but would merely increase or decrease the production cost for the same technologies.

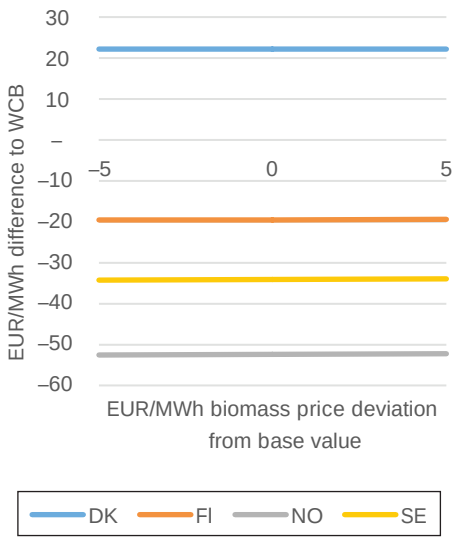


Figure 12: Sensitivity analysis of 5 EUR/MWh higher or lower wood chip prices. Horizontal scale depicts the change in wood chip prices. Vertical scale depicts the difference in LCOH of the CHP + EB technological combination to WCB. Negative values indicate that the CHP + EB LCOH is lower than that of the WCB

The findings of the study are thus robust to changes in electricity prices as well as wood chip prices.

4. Discussion of results on operation and investment incentives

HS increased the use of both CHP and EB and generally allowed for the increased utilisation of the least-cost heat technology, thereby reducing demand for peak load operation.

Electricity T&D grid tariffs had a negligible impact on the operation of EB in Denmark (where there are no CT) and Sweden (where time-of-use tariffs allowed EB to operate at night). In Finland and Norway, CT hindered all operation of EB. Consequently, no CT were paid in either scenario.

Absence of taxes and subsidies showed that CHP in all cases would surrender production to EB, OB and WCB. This is due to the distribution of taxes and subsidies among technologies, where CHP is generally subject to subsidies, and EB and OB are subject to taxes. A general removal or reduction of current taxes and subsidies thus relatively benefits boiler technologies more than CHP.

Also, absence of taxes and subsidies resulted in an increased use of the oil boiler. This indicates that the significant Nordic fossil fuel taxes are working to reduce the consumption of oil.

CHP operates close to baseload with 6-7000 full-load hours in all cases with HS, regardless of subsidies, taxes and electricity T&D grid tariffs. Whereas the subsidies improve the general economy, and thereby the investment incentive for the CHP-based plant significantly, current subsidies have a limited impact on the operation of the CHP. This is exemplified by Figure 13, which shows the baseload operation of the CHP (middle), while the EB charges the HS (bottom) during periods with low electricity prices (top). This operation is higher than the 4 000 full-load hours for biomass CHP as indicated by Norsk Energi and Thema Consulting Group [41].

Regarding LCOH, there is a clear picture of the preferred technologies in Finland, Norway and Sweden, as illustrated in Table 6. In these countries, the subsidised wood chip CHP with EB and storage drives the costs down, while the preferred technology in Denmark is the single WCB.

Previous studies have identified challenges for CHP. Investment and re-investment in small-scale CHP are reported as infeasible in Denmark, Finland, Norway and Sweden [46–50], while subsidised biomass-based CHP can be profitable in Norway [46] if investment costs are lowered or electricity prices rise, as argued by Keppo and Savola [48]. Contrary to the present study, Sneum et al. similar study on the Baltics [27] showed investment incentives for WCB + EB, due to lower subsidies for electricity production. Furthermore, Sneum et al. found smaller impacts of T&D grid tariffs in the Baltics, due to a lower annually paid tariff structure.

5. Conclusion

Four different technology combinations for DH plants in four different countries yielded a total of 96 operation analyses and a subsequent 48 studies of LCOH. The results show the ways HS, current electricity T&D grid tariffs, taxes and subsidies, affect investment incentives for a set of flexible and inflexible technologies in small-scale DH model plants.

Investment incentives are represented by LCOH, and operations have been examined regarding the share of energy production on flexible and non-flexible technologies. The results are robust to variations in biomass and electricity prices.

- HS is in all cases a no-regrets solution because it allows for the increased use of the least expensive technologies, thereby generally reducing LCOH.

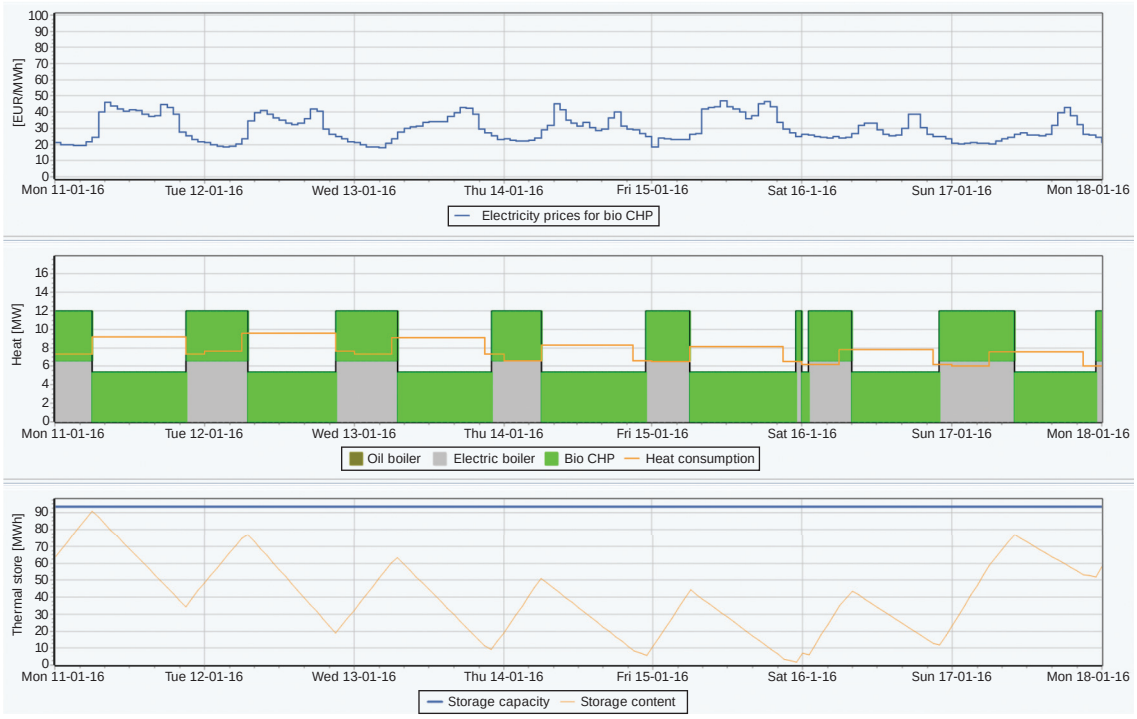


Figure 13: Baseload operation of CHP supplemented with EB. Excerpt of simulation of Denmark in January

Table 6: LCOH (EUR/MWh) for all scenarios with tax. The colour scale is read vertically and indicates the LCOH for each country, where green is low, yellow is intermediate and red is high

Technological combination	Electricity T&D grid tariffs	Storage	DK	FI	NO	SE
A – Wood chip CHP + EB	CT	Storage	100	56	17	39
		No storage	142	94	68	106
	ET	Storage	100	56	12	39
		No storage	142	94	68	106
B – Wood chip CHP + WCB		Storage	107	65	22	48
		No storage	117	89	55	83
C – Large WCB		Storage	78	75	65	73
		No storage	91	81	71	84
D – WCB + EB	CT	Storage	110	104	82	105
		No storage	115	104	82	109
	ET	Storage	110	103	77	105
		No storage	115	104	81	109

- For electricity T&D grid tariffs, CT charged as a monthly cost, triggered by the highest load demand on the grid during that month, is detrimental to the use of P2H. Preferable alternatives include schemes such as the ET explored in this study, time-of-use tariffs varying over the day, or changing CT to be lower and charged annually. More ambitious would be dynamic tariffs that carries through signals to P2H from the electricity market. This approach could potentially also increase use of P2H under the Danish electricity T&D grid

tariffs, which are considerable compared to the other Nordic countries.

- Taxes and subsidies hardly affect the operation of CHP, but subsidies considerably affect LCOH and investment incentive for CHP. Despite the lack of operational impact, subsidies could instead be allocated on investment (as in Norway), to maintain investment incentive, and reduce the distortion of signals from the electricity market.
- Biomass-based heat production outperforms electricity-based heat production in all scenarios. A general removal of taxes and subsidies moderately increases the operation of EB in FI, SE and NO. If there is a fiscal priority for maintaining revenue from energy taxation and/or to increase use of electricity, measures to level the playing field for P2H could be to introduce taxes on the generally untaxed biomass, and to provide targeted reduction of electricity taxes for large-scale P2H.
- In almost all cases, an absence of taxes and subsidies provides an increased incentive for the operation of the OB, a consequence which neither increases operation of flexible technologies nor reduces emissions. Current taxes and subsidies thus generally helps reducing OB use.

4.1. Future work

In this study, barriers for flexibility were considered framework conditions that limit the incentive for investing in CHP and EB. A full removal of these barriers might not necessarily be beneficial because these might simultaneously be drivers for other priorities in society or in the energy system. The adjustments of taxes and subsidies as well as electricity T&D grid tariff structures induce a need for analysing the incentives for the operation and investment of technologies in the DH-electricity interface not only at the plant level but for the energy system as a whole.

5. Acknowledgement

This paper was prepared as part of the research project Flex4RES (www.flex4RES.org) and is supported by Nordic Energy Research, for which we are grateful. Additionally, we extend our gratitude to the reviewers of this article. Their feedback has provided input for relevant revisions of the study, and valuable discussions among the authors.

6. References

[1] European Commission. A policy framework for climate and energy in the period from 2020 to 2030. EUR-Lex – 52014DC0015 – EN 2014.

[2] Nordic Energy Research. Ambitious climate targets and visions for all Nordic countries – Nordic Energy Research. Nord Energy Res Website 2015. http://www.nordicenergy.org/figure/ambitious-climate-targets-and-visions-for-all-nordic-countries/ (accessed October 26, 2017).

[3] IEA. Energy Technology Perspectives 2012. Paris: 2012. doi:10.1787/energy_tech-2012-en.

[4] IEA. The power of transformation. Paris: IEA; 2014. doi:10.1007/BF01532548.

[5] Mathiesen B V., Lund H, Connolly D, Wenzel H, Ostergaard PA, Möller B, et al. Smart Energy Systems for coherent 100% renewable energy and transport solutions. Appl Energy 2015;145:139–54. http://dx.doi.org/10.1016/j.apenergy.2015.01.075.

[6] Lund PD, Lindgren J, Mikkola J, Salpakari J. Review of energy system flexibility measures to enable high levels of variable renewable electricity. Renew Sustain Energy Rev 2015;45:785–807. http://dx.doi.org/10.1016/j.rser.2015.01.057.

[7] Lund H, Werner S, Wiltshire R, Svendsen S, Thorsen JE, Hvelplund F, et al. 4th Generation District Heating (4GDH). Integrating smart thermal grids into future sustainable energy systems. Energy 2014;68:1–11. http://dx.doi.org/10.1016/j.energy.2014.02.089.

[8] Lund H, Andersen AN, Østergaard PA, Mathiesen BV, Connolly D. From electricity smart grids to smart energy systems – A market operation based approach and understanding. Energy 2012;42:96–102. http://dx.doi.org/10.1016/j.energy.2012.04.003.

[9] Kiviluoma J, Meibom P. Influence of wind power, plug-in electric vehicles, and heat storages on power system investments. Energy 2010;2010:1244–55. http://dx.doi.org/10.1016/j.energy.2009.11.004.

[10] Blarke MB. Towards an intermittency-friendly energy system: Comparing electric boilers and heat pumps in distributed cogeneration. Appl Energy 2012;91:349–65. http://dx.doi.org/10.1016/j.apenergy.2011.09.038.

[11] Lislebø O, Havskjold M, Langseth B. Fleksibilitet i fremtidens kraftsystem: Kan varmemarkedet bidra? Sandvika: 2011.

[12] Kirkerud JG, Trømborg E, Bolkesjø TF, Tveten ÅG. Modeling the Power Market Impacts of Different Scenarios for the Long Term Development of the Heat Sector. Energy Procedia 2014;58:145–51. http://dx.doi.org/10.1016/j.egypro.2014.10.421.

[13] Lund H, Hvelplund F, Østergaard PA, Möller B, Mathiesen BV, Karnøe P, et al. System and market integration of wind power in Denmark. Energy Strateg Rev 2013;1:143–56. http://dx.doi.org/10.1016/j.esr.2012.12.003.

[14] Tveten ÅG, Bolkesjø TF, Ilieva I. Increased demand-side flexibility: market effects and impacts on variable renewable energy integration. Int J Sustain Energy Plan Manag 2016;11:33–50. http://dx.doi.org/10.5278/ijsepm.2016.11.3.

[15] Connolly D, Mathiesen BV. A technical and economic analysis of one potential pathway to a 100% renewable energy system. Int J Sustain Energy Plan Manag 2014;1:7–28. http://dx.doi.org/10.5278/ijsepm.2014.1.2.

[16] Østergaard PA. Comparing electricity , heat and biogas storages ' impacts on renewable energy integration. Energy 2012;37:255–62. http://dx.doi.org/10.1016/j.energy. 2011 11.039.

[17] Rolfsman B. Combined heat-and-power plants and district heating in a deregulated electricity market. Appl Energy 2004;78:37–52. http://dx.doi.org/10.1016/S0306-2619(03) 00098-9.

[18] Schulz K, Schacht M, Werners B. Influence of Fluctuating Electricity Prices due to Renewable Energies on Heat Storage Investments. Oper Res Proc 2013:421–7. http://dx.doi.org/10.1007/978-3-319-07001-8.

[19] Lund H, Østergaard PA, Connolly D, Ridjan I, Mathiesen BV, Hvelplund F, et al. Energy storage and smart energy systems. Int J Sustain Energy Plan Manag 2016;11:3–14. http://dx.doi.org/10.5278/ijsepm.2016.11.2.

[20] Eurostat. Supply, transformation and consumption of heat – annual data. Code: nrg_106a. Online Table 2016. http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=nrg_105a&lang=en (accessed October 20, 2016).

[21] Euroheat & Power. District Heating and Cooling Statistics 2015. Brussels: Euroheat & Power; 2015.

[22] Sneum DM, Sandberg E, Soysal ER, Skytte K, Olsen OJ. Framework conditions for flexibility in the district heating-electricity interface. Lyngby: 2016.

[23] Difs K. National energy policies: Obstructing the reduction of global CO2 emissions? An analysis of Swedish energy policies for the district heating sector. Energy Policy 2010;38:7775–82. http://dx.doi.org/10.1016/j.enpol.2010.08.037.

[24] Klinge Jacobsen H, Zvingilaite E. Reducing the market impact of large shares of intermittent energy in Denmark. Energy Policy 2010;38:3403–13. http://dx.doi.org/10.1016/j.enpol.2010.02.014.

[25] Sandberg E, Sneum DM, Trømborg E. Framework conditions for Nordic district heating – Similarities and differences, and why Norway sticks out. Energy 2018;149:105–19. http://dx.doi.org/10.1016/j.energy.2018.01.148.

[26] Skytte K, Olsen OJ, Rosenlund Soysal E, Møller Sneum D. Barriers for district heating as a source of flexibility for the electricity system. J Energy Mark 2017;10:1–19. http://dx.doi.org/10.21314/JEM.2017.161.

[27] Møller Sneum D, Sandberg E, Koduvere H, Olsen OJ, Blumberga D. Policy incentives for flexible district heating in the Baltic countries. Util Policy 2018:1–12. http://dx.doi.org/10.1016/j.jup.2018.02.001.

[28] Trømborg E, Havskjold M, Bolkesjø TF, Kirkerud JG, Tveten ÅG. Flexible use of electricity in heat-only district heating plants. Int J Sustain Energy Plan Manag 2017;12:29–46. http://dx.doi.org/10.5278/ijsepm.2017.12.4.

[29] Olsen OJ, Munksgaard J. Cogeneration and taxation in a liberalized Nordic power market. Util Policy 1998;7:23–33. http://dx.doi.org/10.1016/S0957-1787(98)00002-2.

[30] Kirkerud JG, Trømborg E, Bolkesjø TF. Impacts of electricity grid tariffs on flexible use of electricity to heat generation. Energy 2016:1–9. http://dx.doi.org/10.1016/j.energy. 2016.06.147.

[31] Denholm P, Hand M. Grid flexibility and storage required to achieve very high penetration of variable renewable electricity. Energy Policy 2011;39:1817–30. http://dx.doi.org/10.1016/j.enpol.2011.01.019.

[32] Holttinen H, Tuohy A, Milligan M, Silva V, Müller S, Soder L. The Flexibility Workout. IEEE Power Energy Mag 2013;11:53–62. http://dx.doi.org/10.1109/MPE.2013.2278000.

[33] Salpakari J, Mikkola J, Lund PD. Improved flexibility with large-scale variable renewable power in cities through optimal demand side management and power-to-heat conversion. Energy Convers Manag 2016;126:649–61. http://dx.doi.org/10.1016/j.enconman.2016.08.041.

[34] Østergaard PA, Andersen AN. Booster heat pumps and central heat pumps in district heating. Appl Energy 2015. http://dx.doi.org/10.1016/j.apenergy.2016.02.144.

[35] Streckiene G, Martinaitis V, Andersen AN, Katz J. Feasibility of CHP-plants with thermal stores in the German spot market. Appl Energy 2009;86:2308–16. http://dx.doi.org/10.1016/j.apenergy.2009.03.023.

[36] Connolly D, Lund H, Mathiesen B V., Leahy M. A review of computer tools for analysing the integration of renewable energy into various energy systems. Appl Energy 2010;87:1059–82. http://dx.doi.org/10.1016/j.apenergy.2009.09.026.

[37] Sorknæs P, Lund H, Andersen AN, Ritter P. Small-scale combined heat and power as a balancing reserve for wind – The case of participation in the German secondary control reserve. Int J Sustain Energy Plan Manag 2015;4:31–42. http://dx.doi.org/10.5278/ijsepm.2014.4.4.

[38] Lund H, Andersen a. N. Optimal designs of small CHP plants in a market with fluctuating electricity prices. Energy

Convers Manag 2005;46:893–904. http://dx.doi.org/10.1016/j.enconman.2004.06.007.

[39] Danish Energy Agency. Regneark med tabeller – Samfundsøkonomiske beregningsforudsætninger 2016.

[40] The Norwegian Water Resources and Energy Directorate. Kostnader i energisektoren. Oslo: 2015.

[41] Norsk Energi and Thema Consulting Group. Fjernvarmens rolle i energisystemet. Oslo: 2014.

[42] Nordic Energy Research, IEA. Nordic Energy Technology Perspectives 2016. Paris: 2016. http://dx.doi.org/10.1787/9789264257665-en.

[43] IEA. Nordic Energy Technology Perspectives 2016 – Nordic Energy Research. Nord Energy Technol Perspect 2016 2016. http://www.nordicenergy.org/project/nordic-energy-technology-perspectives/ (accessed October 1, 2017).

[44] European Commission. Weekly Oil Bulletin – European Commission. Wkly Oil Bull 2017. https://ec.europa.eu/energy/ en/data-analysis/weekly-oil-bulletin (accessed June 6, 2017).

[45] Danish Energy Agency. Technology data for energy plants. Copenhagen: 2016.

[46] Kempegowda RS, Skreiberg Ø, Tran KQ. Techno-economic evaluations of various biomass CHP technologies and policy measures under Norwegian conditions. Energy Procedia, vol. 20, ELSEVIER SCIENCE BV; 2012, p. 1–10. http://dx.doi.org/10.1016/j.egypro.2012.03.002.

[47] Salomón M, Savola T, Martin A, Fogelholm CJ, Fransson T. Small-scale biomass CHP plants in Sweden and Finland. Renew Sustain Energy Rev 2011;15:4451–65. http://dx.doi.org/10.1016/j.rser.2011.07.106.

[48] Keppo I, Savola T. Economic appraisal of small biofuel fired CHP plants. Energy Convers Manag 2007;48:1212–21. http://dx.doi.org/10.1016/j.enconman.2006.10.010.

[49] Madsen KB. Afdækning af hvad de decentrale naturgasfyrede kraftvarmeværker investerer i frem mod 2020. Kolding: 2016.

[50] Møller D, Clausen K. Resultater fra rundspørge blandt decentrale kraftvarmeværker. Kolding: 2013.

6. Appendix

Heat production (GWh total) with and without HS. All with taxes and subsidies and ET.

LCOH (EUR/MWh) with and without HS. All with taxes and subsidies and ET.

Heat production (GWh total) with CT and ET. All with HS and taxes and subsidies.

LCOH (EUR/MWh) with CT and ET. All with HS and taxes and subsidies.

Heat production (GWh total) with and without tax. All with HS and ET.

Increased heat-electricity sector coupling by constraining biomass use?

Daniel Møller Sneum[a1], Mario Garzón González[a], Juan Gea-Bermúdez[a]

[a] DTU Management, Produktionstorvet 424, 2800 Lyngby, Denmark

Keywords: sector coupling, biomass, power-to-heat, flexibility, heating, variable renewable energy

Abstract

Flexible sector coupling of heat and electricity is a well-documented way of facilitating efficient and renewables-based energy systems. Heating is characterised by substitutable heat sources, where some facilitate flexibility and sector coupling, while others do not. Earlier studies indicate that sector coupling hindrances from competing biomass-based heat sources. The scientific contribution of this study is an investigation of heat source substitution as a general route to sector coupling. We explore the impacts of constraining biomass use, applying the Danish heat sector as a case, to see impacts on criteria such as power-to-heat deployment. We do so by introducing a range of taxes on biomass use, ban biomass boilers and entirely prohibit use of biomass. These constraints are modelled in the Balmorel model. The results show that system costs decrease along with biomass use. Power-to-heat use, CO_2-emissions, tax- and electricity tariff revenue and end-user heat cost increase, in some cases substantially. It appears that a CO_2 price signal, is sufficient to obtain CO_2-reductions, whereas other motivations, including increased electrification of the heating sector, may justify constraints on biomass use.

Abbreviations[2]

[1] Corresponding author - dasn@dtu.dk,

[2] Capex: Capital expenditure
CHP: Combined heat and power
DH: District heating
DKK: Danish kroner
(M)EUR: (million) Euro
HP: Heat pump
kton: kilo ton
NETP: Nordic Energy Technology Perspectives
PtH: Power-to-heat
PV: Photovoltaic
RG: Resource grade
TS: Thermal storage
(V)RE: (Variable) renewable energy

1 Introduction

Coupling of energy sectors, i.e. sectors based on different energy carriers such as heating and electricity, is a pertinent measure for improving overall energy- and economic efficiency [1,2]. Benefits include the ability to use the least cost technologies to satisfy energy demands, and the ability to flexibly balance and integrate the electricity production from variable renewable energy (VRE - here wind power and solar photovoltaics) [3].
VRE integration can be achieved in the heating sector, which can utilise VRE-based electricity for heating purposes. This can be in power-to-heat (PtH) units such as heat pumps (HP) in periods with abundant VRE production in district- [4,5] and residential heating [6], and by storing heat in thermal storages (TS) enabling a decoupling of heat demand and electricity production/consumption [7,8]. Furthermore, TS combine well with generation of heat and electricity at combined heat and power plants (CHP) [8,9]. Beyond the scientific literature, this has been documented in practice and real-life examples in Denmark (e.g. daily plant operation according to electricity prices [10] and on the broader system scale [11]). While the potential benefits and technological solutions are well-documented, this flexibility in the interface between the electricity and heating systems is not straightforward. Electricity can be *used* in a multitude of ways, as characterised by the term power-to-x. On the other hand, heat can be *generated* in multiple ways (we can call this x-to-heat). Since heat generation thus is characterised by substitute goods (different ways to obtain the same service – heat, i.e. x-to-heat), the choice of heat source is dependent on other factors, including price [12]. Un-level playing-fields between biomass-based boilers and PtH, caused by the absence of tax on biomass in combination with levies on PtH has been documented in e.g. the Baltics [13,14] and Denmark [15,16]. This motivates a further analyses of constraints on biomass-use.

Mathiesen et al. [17] have analysed limitations of biomass for increased heat electrification in a socio-economic perspective, but not in a context of regulatory conditions such as taxes and electricity grid tariffs, or as part of a larger energy system (surrounding countries). Energinet and Flex4RES have explored the impact of constraining interconnection capacity, CHP flexibility, taxes and electricity grid tariffs in the Danish [18] and Nordic [19] energy systems. Sneum et al. [13,20] have explored the competition and heat source substitution between biomass-based generation and PtH in individual DH plants. No studies have evaluated impacts of addressing heat source substitution to increase flexibility and sector coupling, by constraining biomass use on energy system scale and in an existing regulatory environment. This study expands existing research by doing exactly that.

1.1 Problem statement

The transition to increasingly renewables-based energy systems can follow various paths. In the heating sector, biomass and PtH characterise two different paths; the *combustion-heat-path* and the *moving-heat-path*. These are not necessarily mutually exclusive, but may carry a degree of internal competition where one technology pushes the other out of the system, e.g. biomass boilers replacing PtH [20,21]. Good et al. coins this kind of *cannibalisation* "*discrepancy between substitutable goods"* [22]. PtH is typically considered in tandem with VRE, where the ability of PtH to consume electricity from VRE is considered a desirable synergy [23–25]. Biomass, on the other hand, is combusted in boilers and CHP plants to generate heat and possibly electricity. While all technologies face downsides (e.g. compensation costs to facilitate social acceptance of VRE-deployment [26] or undesired effects of refrigerants in HP [27,28]) the focus is here to study constraints on biomass use. Such constraints can be motivated by a desire to reduce biomass consumption to politically defined levels (e.g. based on the recurring [29] concerns about biomass shortage) or because biomass in many cases [13,20] is an untaxed fuel with no fiscal contribution to state budgets. In an energy system perspective, constraining biomass can be motivated by the competitive

advantage of untaxed biomass against especially PtH, which creates a barrier for flexibility in the interface between the heating and electricity sectors [13,17,20]. As consequence of a steady growth (Figure 1) the share of solid biomass reached 29% of total fuel consumption [30] and a share of 64% of Danish RE [31] in 2018. With 63% of solid biomass used in the CHP and DH generation, 29% for individual heating and 7% in process industry [31] (1% assumed to be in other uses), Denmark is increasingly relying on biomass in its well-developed DH sector as well as areas outside DH systems. It is thus relevant to use the Danish case to explore impacts of heat source substitution through biomass constraints.

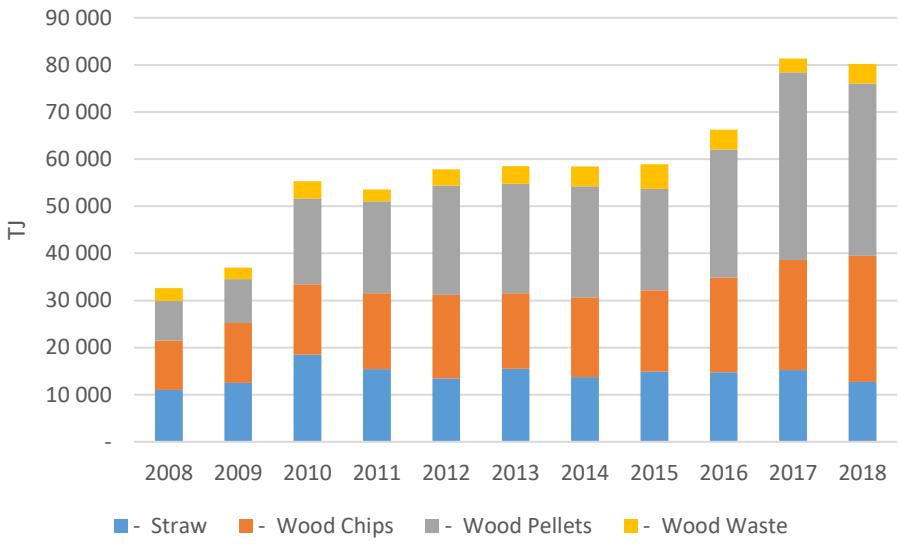


Figure 1 Solid biomass consumption in Denmark 2008-2018 [30]

1.2 Research question

What are the interactions between substitutable heat sources with different flexibility potentials and sector coupling characteristics?

We answer this question by analysing the case for Denmark, with biomass and PtH as exemplary competing technologies.

After elaborating the methodology in Section 2, the results of the techno-economic analysis is presented in Section 3. An in-depth discussion of those results is conducted in Section 3.8, before concluding on the findings regarding criteria and barriers in Section 5.

2 Methodology

The intention with this study is to explore heat source substitution and its impact on flexibility in the interface between heating and the electricity system. This is explored by analysing the impacts of constraining biomass *ceteris paribus*, i.e. keeping other inputs constant to determine the impact of the single constraint. The Balmorel model applies 2012-level input costs and converts these to 2016-level output costs. While we apply the resulting numbers, the study focus on tendencies, rather than decimals in the specific case.

2.1 Biomass barriers to sector coupling and flexibility

The concept of flexibility in the interface between the heating and electricity system is illustrated in Figure 2. It applies regarding flexible response to electricity price signals as well as RE penetration in the electricity grid. In situation 1, electricity costs are low/renewables penetration is high. A PtH unit consumes low cost/low carbon electricity to satisfy heat demand and potentially stores excess heat. In situation 2, intermediate electricity prices and/or renewables penetration incentivises use of stored heat or biomass boiler generation. In situation 3, high electricity prices/low renewables penetration incentivises CHP-based generation, where a potential excess amount of heat can be stored.

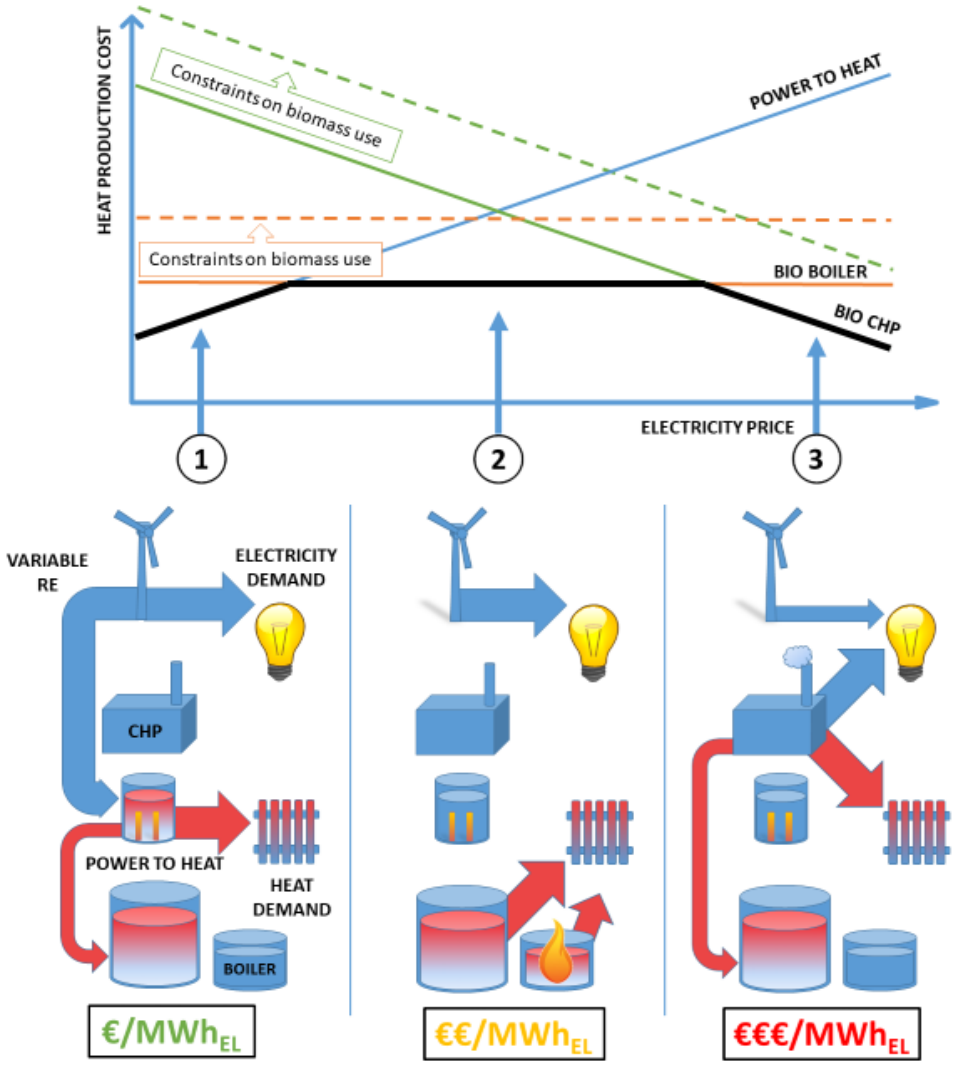


Figure 2 Least cost dispatch and concept of flexible heating. Own illustration based on [32]**,** [33] **and** [19]**.**

Biomass has been shown to be both a potential barrier (biomass boilers [34]) and a potential contributor (CHP [20]) to increased coupling and flexibility in the heat-electricity system interface. A barrier regarding operation is that taxed PtH may be disadvantaged by higher marginal costs than untaxed biomass boilers [34]. This potentially reduces the ability of PtH to respond to price signals and, possibly, the overall investment incentive in the technology. The dotted lines in Figure 2 illustrates the constraints introduced to biomass use in this study. Either by adding a tax on biomass use (the marginal cost of biomass-based

technologies increases) or by removing the option of using biomass or biomass-based technologies altogether (the technology is absent). All these measures will impact the least cost dispatch curve – the bold black line – Figure 2. The analyses do not measure flexibility per se, but show the impact on various criteria (see 2.4) of constraining biomass use to increase the coupling and flexibility in the interface between heat and electricity systems.

2.2 Scenarios and scenario variations

The study is based on analyses of 4 main scenarios (*Base case*, *Biomass tax*, *No biomass boilers* and *No biomass use*), with one being split into 4 sub-scenarios, totalling 7 scenarios – Table 1.

Table 1 Scenarios and their variations.

Scenario	**Base case**	**Biomass tax**				**No biomass boilers**	**No biomass use**
Scenario variation		**Bio tax 7.1**	**Bio tax 14.2**	**Bio tax 21.3**	**Bio tax 28.4**		
#	1	2	3	4	5	6	7
Constraint	No con-straints	7.1 2012-EUR/MWh$_{fuel}$ on biomass use	14.2 2012-EUR/MWh$_{fuel}$ on biomass use	21.3 2012-EUR/MWh$_{fuel}$ on biomass use	28.4 2012-EUR/MWh$_{fuel}$ on biomass use	No use or investment in biomass-based boilers	No use of biomass

The changes apply to all heating. I.e. DH as well as industry and residential heating. The scenarios and their variations are described in the following sections.

2.2.1 Base case – scenario 1

Scenario variations 2-7 are compared to the results in the *Base case*. The *Base case* describes the development under conditions corresponding to the present framework conditions, i.e.

- Biomass boilers allowed
- Biomass tax: 0 2012-EUR/MWh$_{fuel}$

2.2.2 Biomass tax – scenario variations 2-5

The *security of supply-tax* (Danish: forsyningssikkerhedsafgift) was a tax on fuels for heating purposes proposed in the Danish Energy Agreement of 2012 [35] and in 2013 set to 29.7 DKK-2013/GJ by 2020 for biomass [36]. The tax was proposed to mitigate declining fiscal revenues from the reduction of other energy taxes [35], with the possible side-effect of increasing PtH and avoiding large deployment of biomass-based technologies. Subsequently (2014), the tax was rolled back [37] due to political and public resistance [38,39]. We explore the tax at various levels, to explore its impact across a wide economic range. From a legal perspective, a ministerial 2020 regulatory enquiry found no hindrances to a Danish biomass tax in either national regulation or the EU Energy Taxation Directive, as long as there is adherence to EU state aid- and non-discrimination rules [40].

Variation	Tax level on biomass	Note
#2 **50% of 2013-proposal**	7.1 2012- EUR/MWh$_{fuel}$	Level chosen to illustrate the impact of reduced 2013-biomass tax.

#3 2013-proposal	14.2 2012- EUR/MWh_{fuel}	In 2013, the 2020 biomass tax was set to be 29.7 DKK/GJ (2013-level) for biomass [36].
#4 150% of 2013-proposal	21.3 2012- EUR/MWh_{fuel}	Level chosen to illustrate the impact of moderately increased 2013-biomass tax.
#5 200% of 2013-proposal	28.4 2012- EUR/MWh_{fuel}	Level chosen to illustrate the impact of highly increased 2013-biomass tax.

2.2.3 No biomass boilers – scenario 6

A targeted approach to reduction of biomass boilers entered into force in Denmark in 2018. Here, the approval criteria of DH projects were revised, stating that new biomass boilers at DH plants must show a 1 500 DKK (200 EUR)/consumer/year end-user saving compared to installing a HP [41]. In in a similar *command and control* manner, *No biomass boilers* explores the impacts of prohibiting the use of biomass boilers in heating. This is intended as a more targeted measure than the other scenarios, to address the competition among biomass-based boilers and PtH.

2.2.4 No biomass use – scenario 7

The most pervasive measure explored is a complete ban on the use of biomass. The ban acts as an extreme scenario of a society which moves entirely away from combusting biomass for energy purposes. Whereas this measure and the ban on biomass boilers may seem extreme, Denmark took a similar approach to nuclear energy in 1985, banning its use [42], while having clear intensions of deploying it only 9 years earlier [43].

2.3 Energy system modelling in the Balmorel model

The energy system model Balmorel [44] is used to optimize the capacity development of the power and heat system of Northern Europe towards 2045. Balmorel is open-source [45], has a bottom-up approach and is deterministic. The objective function in Balmorel is to minimize the system costs, while satisfying the heat and power demand of the sectors included. The costs in the optimizations correspond to annuitized investments, and fixed and variable operational costs. The variable operational costs include maintenance costs, fuel costs, taxes, and grid tariffs. Investments are allowed in multiple power and/or heat generation and storage units, transmission lines, and DH expansion of users not currently connected to DH. The decommissioning of generation and storage units is also optimized. The representative years in the optimizations are 2025, 2035, and 2045. The optimizations are performed with a rolling horizon of 2-year foresight, which means that when optimizing investments in 2025, 2035 is known, and so on. The costs of future years are discounted with a discount rate of 4% per year [46].

To limit the complexity of the problem and due to the large number of scenarios, 4 weeks spread-over-the-year with 1-every-3 hours are used in the optimizations as the selected representative time steps. To keep the annual statistical representation of the time series with a reduced amount of time steps, the time series are scaled individually based on Gea-Bermúdez et al. [26], except for seasonal hydro inflows that were scaled linearly. For the same reason, unit commitment costs and variables were not considered in this paper.

The model setup is based on Gea-Bermúdez et al. [26], but with some relevant deviations. The modelling of industry is based on three temperature heat demand levels, i.e. low (below 100°C), medium (between

100°C and 500°C, and high (above 500°C). This modelling reflects in a more accurate way the capabilities of different technologies to satisfy the different temperature levels of heat demand. Furthermore, individual users not currently connected to district heating are also included. They are modelled by splitting their demand in hot water and space heating. Like industry, not all technologies are allowed to satisfy all types of heat demand. Vehicle-to-grid and smart charging is allowed for EVs. The assumption on EVs is that by 2050, all individual private users will use EV. The modelling and data are based on [47].

Electricity grid tariffs for district heating units are modelled with a fixed charge that depends on the installed capacity of the unit, and with a variable charge that depends on the use of the technology. For industrial and individual power consumers, electricity grid tariffs are applied based on energy and peak-power demand. Taxes on commodity consumption, emissions, electricity production and heat production are also considered.

The data, which is available in the Balmorel Community [45], is mostly coming from the Flex4RES project [48]. Key differences are explained in this paper. The CorRES tool [49–51] is used to model wind and solar PV time series and capacity factors, for different Resource Grades (RG). The RGs are defined to model that the resource is not uniform inside each of the regions modelled. For the case of wind offshore, the RGs correspond to type of offshore wind farms, i.e. near shore; far from shore, AC-grid connected; and far from shore, DC-grid connected. The capacity factors for the different RGs come from the CorRES tool, whereas for solar PV it is a combination of the CorRES tool and the Global Solar Atlas [52]. Wind offshore potentials per RG are based on [53–55]. Solar PV potentials for large scale systems are based on Ruiz et al. [56]. Onshore wind potentials include social acceptance restrictions and are based on the combination of multiple sources [53,57,58]. The split per RG for wind onshore is based on 10% for the best RG, 40% for the second best, and 50% for the worst locations. For solar PV, only two RG are used (50%-50% split of the potential), except for large regions where the 10%, 40%, 50% is used. Figure 3 illustrates the total potential in Denmark for wind and solar technologies.

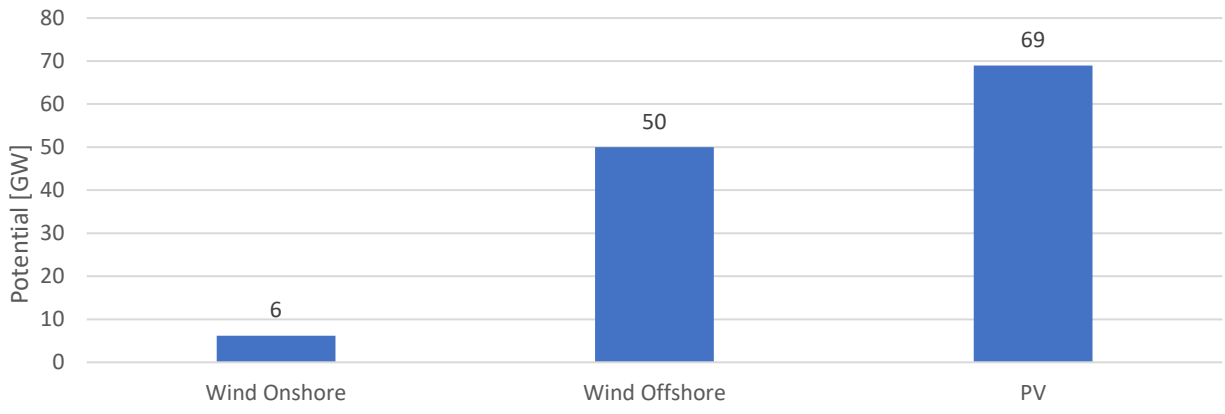


Figure 3. Wind and solar PV total resource potential in Denmark.

Technology data development towards 2050 is based on The Danish Energy Agency [46]. Figure 4 describes the assumed development in investment costs (capex) of wind power and solar PV. Wind offshore capex differs from region to region since they are influenced by transmission distance assumptions.

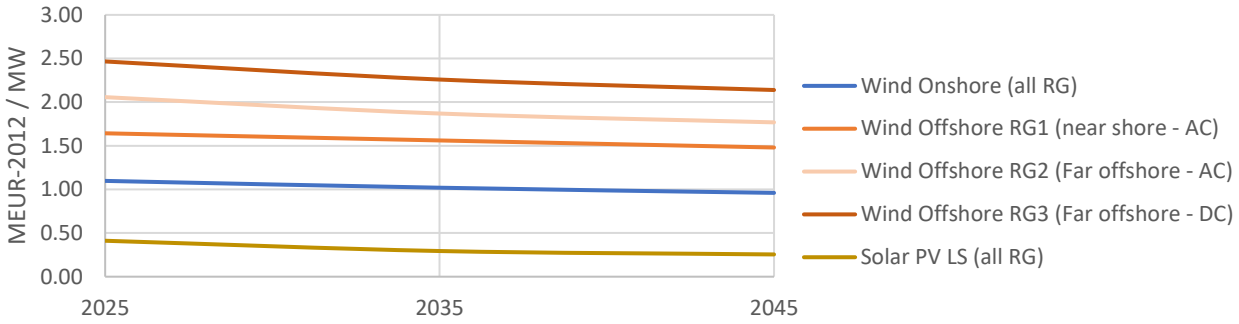


Figure 4. Wind and solar PV technology capex development [46]**. Wind offshore costs are different for each region in the model due to different transmission length assumptions.**

District heating expansion costs (0.396 MEUR-2012/MW) is based on Henning and Palzer [59]. Transmission expansion costs, CO_2 tax development and fuel price development are based on NETP [53]. The modelling of biomass prices is based on step wise price functions from Gea-Bermúdez et al. [26]. Coefficient of performance time series for the different HP included are based on Ruhnau et al. [60]. Power demand, solar heating and district heating demand data comes from the Flex4RES project [48]. Industrial data is based on Wiese and Baldini [61] and Rehfeldt et al. [62]. Individual users' data is based on Eurostat [63] and Ruhnau [64]. Their total demand aggregates both individual users and the tertiary sector. Figure 5 illustrates the development of fuel- and CO_2-prices.

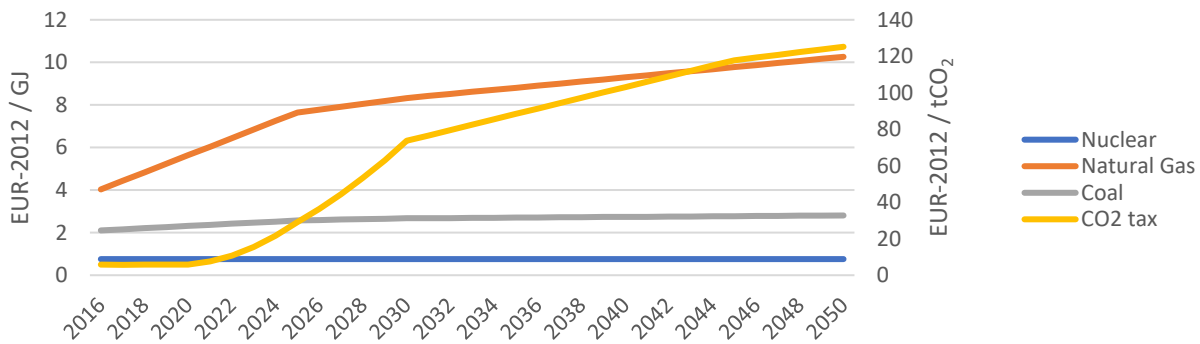


Figure 5. Fuel and CO_2 tax price development [53]**.**

In all scenarios, the PtH tax and electricity grid tariffs have the following values

- PtH tax: 32.3 2012-EUR/$MWh_{electricity}$ (884 2019-DKK/MWh_{el} [65] deducted 625 2019-DKK/MWh_{el} [66] = 259 2019-DKK/MWh_{el})
- Electricity grid tariffs: PtH for individual users is charged with 44 2012-EUR/$MWh_{electricity}$. PtH for industrial users is charged with 23.3 2012-EUR/$MWh_{electricity}$. PtH in district heating is subject to an energy charge of 22.3 2012-EUR/$MWh_{electricity}$ (average of Eastern and Western Danish tariff levels in 2017), and a capacity charge that depends on the installed capacity 0.033 2012-EUR/$kW_{electricity}$ per year

2.3.1 Geography: Northern Europe

The study is based on modelling of the Northern European energy system, as seen in Figure 6. Scenario variations are kept constant for all countries but Denmark. While modelling results are obtained for all

modelled countries, results (Section 3) are mainly presented for Denmark to show the national impacts of introducing Danish biomass-constraints.

Figure 6 Countries in the modelling: Belgium, Denmark (yellow), Finland, France, Germany, Netherlands, Norway, Poland, Sweden and United Kingdom.

2.4 Criteria for analysing barriers

The defined set of criteria is intended to cover a range of aspects relevant to policy makers, electricity transmission companies, DH stakeholders and end-users. The set of criteria aligns with criteria applied by Hedegaard and Münster [67]. To some degree also with Østergaard's overview of criteria [68] (e.g. end-user energy costs (rate impact), CO_2-emissions, societal costs, transmission capacity and use), although in some areas extending beyond these (e.g. tax- and tariff revenue) and in others excluding these (e.g. amount of condensing-based electricity generation, reserve capacity requirement).

CRITERIA	STAKEHOLDER	TO DETERMINE HOW
Electricity- and heat price	End-user	benefits and costs are allocated
Tariff revenue	Grid operators	changes in electricity use impact tariff revenue
System cost	Society	pure (no tax or electricity grid tariffs) societal costs develop
Tax revenue	State	fiscal impacts are impacted by constraining an untaxed fuel
CO_2-emissions	Society	climate is impacted by constraining an assumed carbon neutral fuel
Fuel	Society/state	fuel efficiency is impacted, which may influence priorities on security of supply or reduction in biomass use

Capacities	Society/state	electricity and heat capacity is impacted, especially regarding PtH and VRE
Storage capacity	Society/state	energy storage, especially TS, is impacted in the scenarios
DH expansion	DH systems, end-users, state, society	incentives for expansion of DH systems are impacted
Transmission	Society/state	the degree of transmission-use is impacted

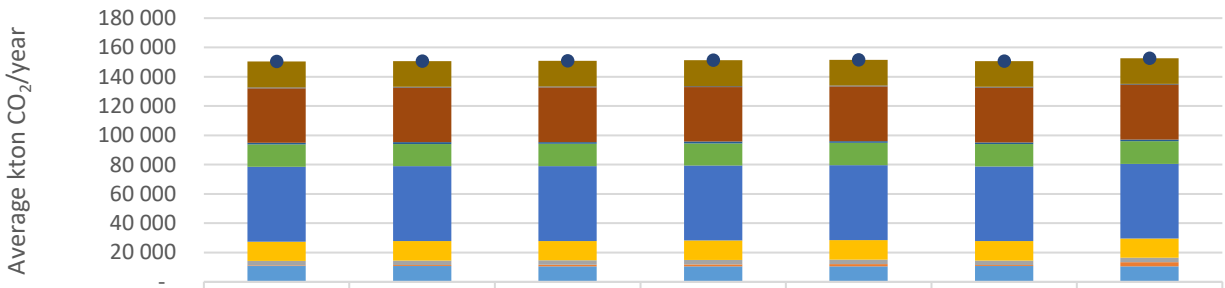
The above criteria do not explicitly measure flexibility (as e.g. proposed by Lannoye et al. [69] or Flex4RES [19]), as the intention is to determine the broader energy system impacts, whereof increased flexibility is a part – similar to the approach on power system transformation applied by IEA and NREL [70].

3 Results: Impacts of biomass constraints

This section presents results of energy modelling with brief factual descriptions, while interpretations are provided in the discussion, Section 4. The intention is, as stated earlier, to gain insight into the impact of substitution among heat sources in relation to flexibility and sector coupling. All in- and decreases are in comparison to the *Base case* (100%).

3.1 Greenhouse gas emissions

Figure 7 – Starting out with a view on the total Northern European emissions-impacts, it is seen that the Danish share of emissions is vanishingly small (*Base case*: 0.37%). That said, constraining biomass in Denmark results in broader energy system impacts by increasing overall emissions. Total emissions increase to between 100.17% (*No biomass boilers*) and 101.49% (*No biomass use*), corresponding to increases of 293-2 244 kton/year. The largest increases are seen in Denmark, reaching 131%-499% in the same two scenarios.



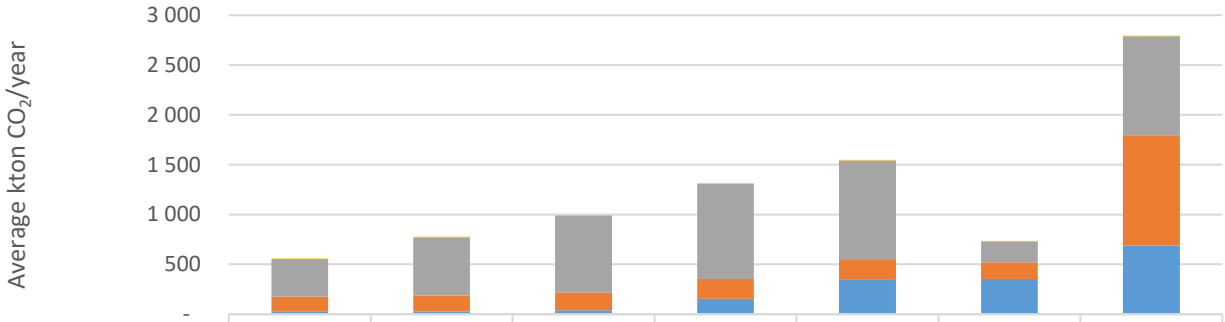
	Base case	Bio tax 7.1	Bio tax 14.2	Bio tax 21.3	Bio tax 28.4	No biomass boilers	No biomass use
United Kingdom	17 650	17 550	17 529	17 539	17 535	17 576	17 536
Sweden	665	667	666	666	665	665	666
Poland	37 114	37 200	37 216	37 231	37 273	37 187	37 300
Norway	1 220	1 225	1 222	1 224	1 225	1 223	1 224
Netherlands	15 154	15 167	15 251	15 251	15 310	15 134	15 385
Germany	51 072	51 107	51 047	51 115	51 147	51 101	50 836
France	13 205	13 206	13 193	13 174	13 166	13 226	13 186
Finland	3 052	3 064	3 065	3 061	3 061	3 062	3 070
Denmark	559	776	993	1 315	1 547	735	2 794
Belgium	10 719	10 741	10 678	10 673	10 662	10 749	10 658
Grand Total	150 410	150 703	150 862	151 249	151 591	150 659	152 653

Belgium, Denmark, Finland, France, Germany, Netherlands, Norway, Poland, Sweden, United Kingdom, Grand Total

Figure 7 Total CO_2-emissions per year in Northern Europe. Emissions are accounted in the country where they occur.

Figure 8 – As indicated above, the increase in Danish internally generated CO_2-emissions is considerable when biomass use is constrained. In the three scenarios standing out with highest emissions (*Bio tax 21.3*, *Bio tax 28.4* and *No biomass use*), the decreased access to biomass leads to increased coal-use and thereby

2.6-2.7 times the emissions from extraction-based CHPs. In the same scenarios, natural gas-based back-pressure CHPs increase their emissions 1.3-7.3 times. The most significant increase in emissions is from natural gas-based boilers in scenarios *Bio tax 28.4*, *No biomass boilers* and *No biomass use*, with respectively 12.4, 12.8 and 24.7 times higher boiler-based emissions.



	Base case	Bio tax 7.1	Bio tax 14.2	Bio tax 21.3	Bio tax 28.4	No biomass boilers	No biomass use
Condensing	5	5	5	5	5	5	5
CHP extraction	376	586	771	957	989	210	1 000
CHP back-pressure	151	159	179	198	209	166	1 102
Boilers	28	27	40	155	345	354	686

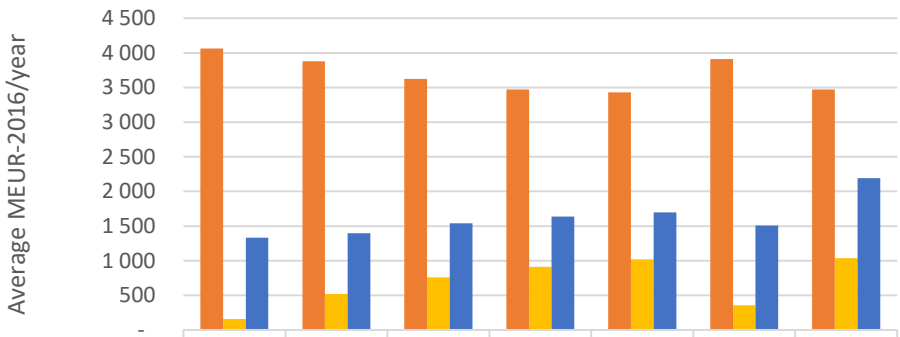
Figure 8 Danish internally generated CO_2-emissions divided on generation technologies.

3.2 System costs, taxes and electricity grid tariffs

Figure 9 – System cost is aggregated of cost of investment and operation, excluding energy taxes and electricity grid tariffs. *Bio tax 21.3*, *Bio tax 28.4*, *No biomass use* displays the least system cost (85%-86%). This is caused by the displacement of Danish electricity generation (and its affiliated costs), with imported electricity and a shift towards fuel-free technologies (VRE, solar thermal and PtH), decreasing the overall fuel cost.

Regarding taxes, *Bio tax 21.3*, *Bio tax 28.4* and *No biomass use* stands out with a 5.7-6.5 times increase in tax revenue. While part of the increase in these scenarios is based in CO_2-taxes (increasing 2.4-5.7 times), the major increase comes from fuel- and electricity taxes, increasing 6.1-6.8 times. This is partially caused by a shift from untaxed biomass to taxed fuels and electricity, and partially by the introduction of biomass taxes in the tax scenarios.

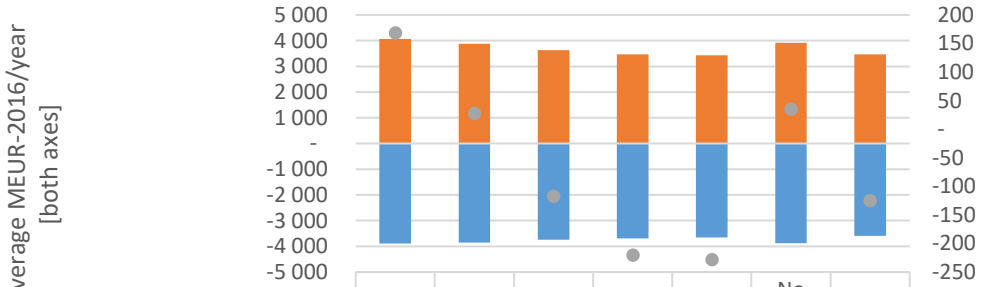
Electricity grid tariffs increase the most (1.2-1.6 times) in scenarios *Bio tax 21.3*, *Bio tax 28.4*, *No biomass use*, due to increased electricity use of PtH, which displaces biomass-based capacity.



	Base case	Bio tax 7.1	Bio tax 14.2	Bio tax 21.3	Bio tax 28.4	No biomass boilers	No biomass use
System cost	4 061	3 877	3 625	3 474	3 432	3 911	3 472
Tax revenue	160	517	759	912	1 018	355	1 035
Tariff revenue	1 330	1 399	1 540	1 638	1 696	1 507	2 190

Figure 9 System cost, tax revenue and electricity grid tariff revenue.

Figure 10 – Electricity trade is a considerable source of revenue in all scenarios, on par with or higher than the system cost. Net system costs decrease as biomass-use is decreased, reaching negative values (i.e. a net system revenue) in the scenarios with the most pervasive biomass constrains.



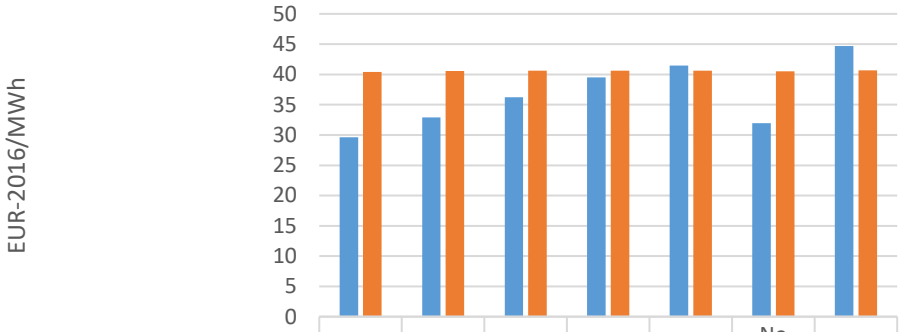
	Base case	Bio tax 7.1	Bio tax 14.2	Bio tax 21.3	Bio tax 28.4	No biomass boilers	No biomass use
Average annual system cost	4 061	3 877	3 625	3 474	3 432	3 911	3 472
Average annual electricity trade revenue	-3 893	-3 849	-3 742	-3 694	-3 660	-3 876	-3 597
Net annual system costs [Right axis]	169	28	-117	-220	-228	35	-125

Figure 10 Electricity trade impact on net annual system costs.

3.3 End-user energy costs

As seen in Figure 11, the heat costs increase relatively more (108%-151%) than electricity prices (100%-101%), as a consequence of the biomass constraints. It should be noted that the costs are long run, i.e.

including capital costs, and weighted according to the cost-distribution among heat consumers and the respective heat demand within each heat consumer-category.

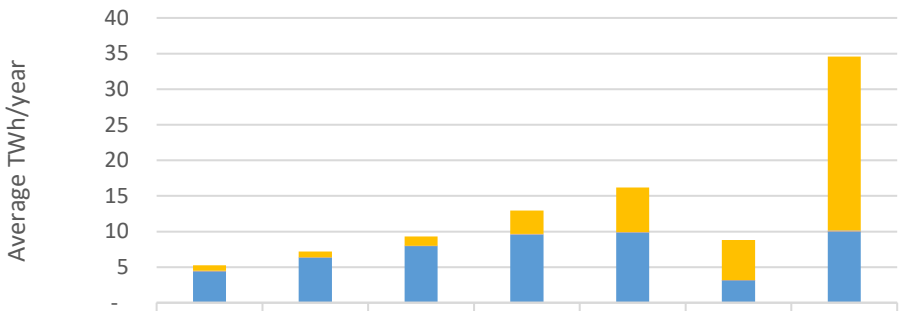


	Base case	Bio tax 7.1	Bio tax 14.2	Bio tax 21.3	Bio tax 28.4	No biomass boilers	No biomass use
Average cost per MWh heat	29.6	32.9	36.2	39.5	41.5	31.9	44.7
Average cost per MWh electricity	40.4	40.5	40.6	40.6	40.6	40.5	40.7

Figure 11 Long run electricity and heat end-user cost.

3.4 Fuel use

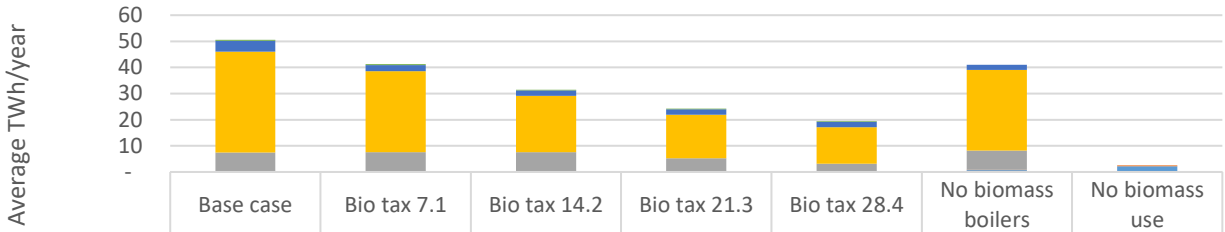
Figure 12 – As can be expected, use of fossil fuels follows a similar pattern as seen regarding emissions in Section 3.1. Restrictions on biomass entail a compensation with natural gas and coal as seen in *Bio tax 28.4* and *No biomass use*, which respectively increases fossil fuel use by 3.1 and 6.6 times. *No biomass boilers* shows a reduction in coal use, but a 7.2 times increase in natural gas use. This stems from increased use in natural gas-based boilers.



	Base case	Bio tax 7.1	Bio tax 14.2	Bio tax 21.3	Bio tax 28.4	No biomass boilers	No biomass use
Natural gas	1	1	1	3	6	6	24
Light oil	0	0	0	0	0	0	0
Fuel oil	0	0	0	0	0	0	0
Coal	4	6	8	10	10	3	10

Figure 12 Fossil fuel use.

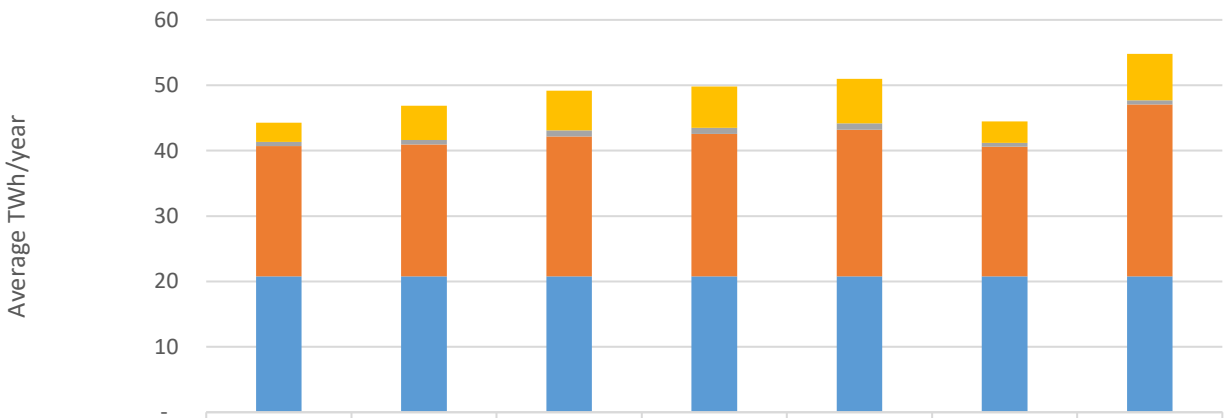
Figure 13 – Unsurprisingly, biomass use is reduced in the biomass-constrained scenarios. Beyond the scenario *No biomass use*, which minimises biofuel use to small amounts of non-solid biomass (biogas and biooil), the biomass taxation scenarios shows biofuel reductions to between 38% (*Bio tax 28.4*) and 82% (*Bio tax 7.1*). The latter in the same range as *No biomass boilers* with 81%.



	Base case	Bio tax 7.1	Bio tax 14.2	Bio tax 21.3	Bio tax 28.4	No biomass boilers	No biomass use
Woodwaste	0	0	0	0	0	-	-
Woodpellets	4	2	2	2	2	2	-
Woodchips	39	31	22	17	14	31	-
Straw	7	7	7	5	3	7	-
Biooil	0	0	0	0	0	0	0
Biogas	0	0	0	0	0	1	2

Figure 13 Biomass fuel use.

Figure 14 – Regarding VRE, offshore wind increases moderately with a tax (101-113%), is reduced with a boiler ban (97%) and increases the most with a complete ban (132%). Onshore wind is fully utilised in all scenarios. The largest single increase is seen in solar thermal, with taxes leading to 178%-231%, boiler ban to 112% and complete ban to 242%. Solar PV deployment is generally limited.

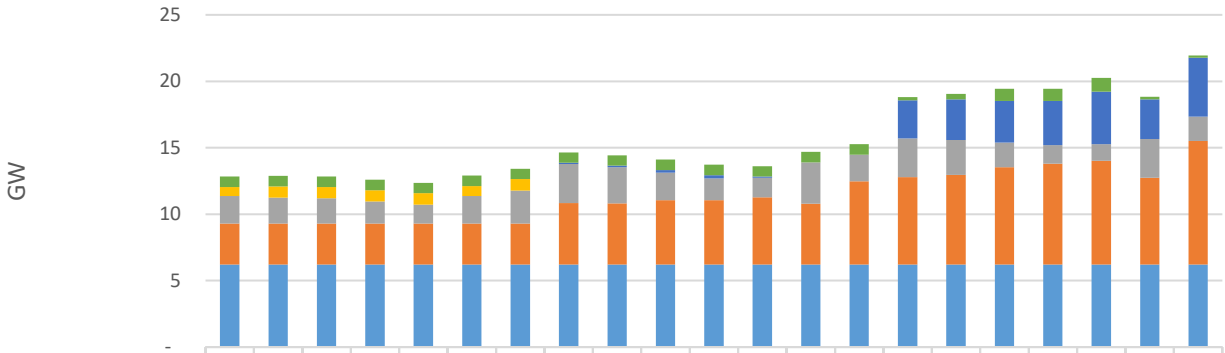


	Base case	Bio tax 7.1	Bio tax 14.2	Bio tax 21.3	Bio tax 28.4	No biomass boilers	No biomass use
SOLAR-HEATING	3	5	6	6	7	3	7
SOLAR-PV	1	1	1	1	1	1	1
WIND-OFF	20	20	21	22	22	20	26
WIND-ON	21	21	21	21	21	21	21

Figure 14 Variable renewable energy use.

3.5 Generating capacity

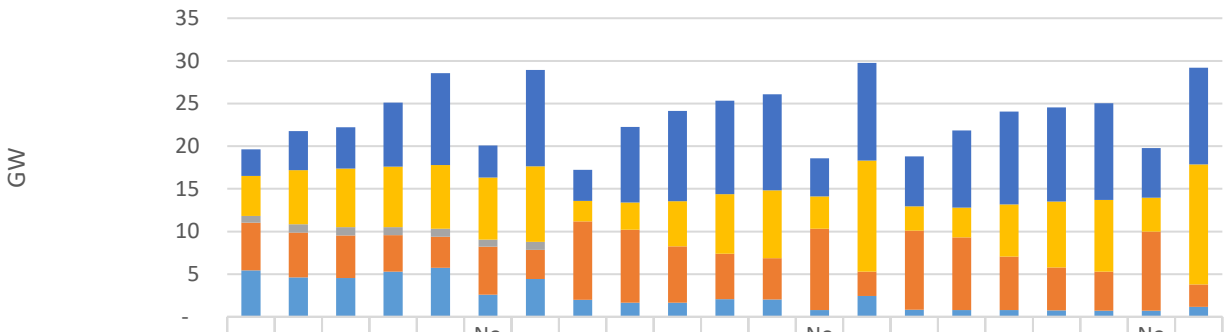
Figure 15 – Electric capacities over the period shows that onshore wind is fully utilised in all scenarios (as seen in Section 2.3: 6.2 GW total). Offshore wind capacity increases over the period, most pronounced in the highly constrained scenarios (*Bio tax 28.4*: 2035 – 112%, 2045 – 119%; *No biomass use*: 2035 – 109%, 2045 – 141%). Extraction-based CHP is phased out towards 2035, while backpressure-based CHP is mostly maintained, trending downwards in the tax scenarios. In *No biomass boilers*, the absent boiler capacity is compensated by backpressure-based CHP (2035 – 106%, 2045 – 100%). Electricity storage sees significant deployment towards 2045 in all scenarios.



	2025							2035							2045						
	Base case	Bio tax 7.1	Bio tax 14.2	Bio tax 21.3	Bio tax 28.4	No biomass boilers	No biomass use	Base case	Bio tax 7.1	Bio tax 14.2	Bio tax 21.3	Bio tax 28.4	No biomass boilers	No biomass use	Base case	Bio tax 7.1	Bio tax 14.2	Bio tax 21.3	Bio tax 28.4	No biomass boilers	No biomass use
Solar PV	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	1	1	1	0	0
Electricity storage								0	0	0	0	0			3	3	3	3	4	3	4
CHP extraction	1	1	1	1	1	1	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-
CHP back-pressure	2	2	2	2	1	2	2	3	3	2	2	1	3	2	3	3	2	1	1	3	2
Offshore wind	3	3	3	3	3	3	3	5	5	5	5	5	5	6	7	7	7	8	8	7	9
Onshore wind	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6

Figure 15 Generating capacity - electricity.

Figure 16 – The most significant impact on capacity is seen for solar thermal capacity, which increases along with the introduction of biomass-constraints (e.g. *Bio tax 28.4*: 2025 – 346%, 2035 – 310%). Boiler capacity follows a downward trend in all scenarios, while backpressure-based CHP capacity is increased in all scenarios in 2035, except *No biomass use* (which is most reliant on PtH – 4.9-5.4 times larger than *Base case*). While PtH generally increases in biomass-constrained scenarios, 2035 and 2045 display a reduction or levelling out (with *No biomass use* as the exception), compared to the initial large deployment in 2025. The DH sector reaches a level of PtH around 3 GW in 2035 and remains constant, while most of the PtH development happens in the individual heating sector.



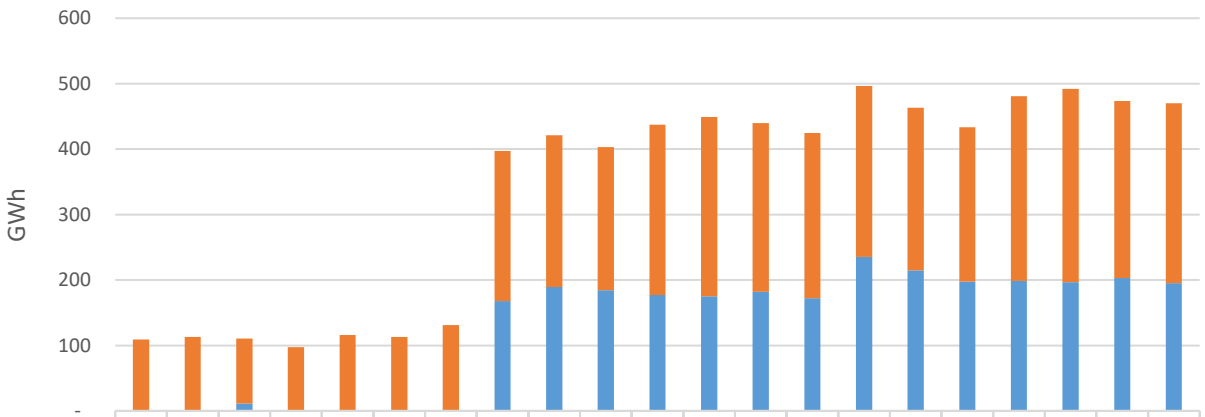
	2025							2035							2045						
	Base case	Bio tax 7.1	Bio tax 14.2	Bio tax 21.3	Bio tax 28.4	No biomass boilers	No biomass use	Base case	Bio tax 7.1	Bio tax 14.2	Bio tax 21.3	Bio tax 28.4	No biomass boilers	No biomass use	Base case	Bio tax 7.1	Bio tax 14.2	Bio tax 21.3	Bio tax 28.4	No biomass boilers	No biomass use
Solar thermal	3	5	5	8	11	4	11	4	9	11	11	11	4	11	6	9	11	11	11	6	11
Power-to-heat	5	6	7	7	7	7	9	2	3	5	7	8	4	13	3	3	6	8	8	4	14
Extraction CHP	1	1	1	1	1	1	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Back pressure CHP	6	5	5	4	4	6	3	9	9	7	5	5	10	3	9	8	6	5	5	9	3
Boiler	5	5	5	5	6	3	4	2	2	2	2	2	1	2	1	1	1	1	1	1	1

Figure 16 Generating capacity - heat.

3.6 Energy storage

Figure 17 – The constraints on biomass use leads to a mixed picture on deployment of storage, where *Bio tax 14.2* dips in later years, before capacity is increasing again with higher biomass tax. This is caused by a relatively large drop in backpressure CHP-generation, which is not compensated by equally large increases in other TS-dependent technologies like PtH, until biomass use is constrained even more. Intraseasonal TS more than doubles in all scenarios from 2025 to 2035. While interseasonal TS is initially almost absent, it is deployed at large scale from 2035. Charge/discharge capacities in the intraseasonal storages are significant, ranging 19-41 GW.

Electricity storage is deployed with capacity considerably smaller than TS towards 2045, ranging 11-19 GWh. Electricity storage increases as biomass use is constrained.



	2025							2035							2045						
	Base case	Bio tax 7.1	Bio tax 14.2	Bio tax 21.3	Bio tax 28.4	No biomass boilers	No biomass use	Base case	Bio tax 7.1	Bio tax 14.2	Bio tax 21.3	Bio tax 28.4	No biomass boilers	No biomass use	Base case	Bio tax 7.1	Bio tax 14.2	Bio tax 21.3	Bio tax 28.4	No biomass boilers	No biomass use
Intra. TS	109	112	100	97	115	113	131	229	232	219	260	274	258	252	261	248	235	282	296	270	275
Inter. TS		1	11	1	1		1	168	189	185	177	175	182	172	235	215	198	199	197	203	195

Figure 17 Inter- and intraseasonal TS.

3.7 Electricity transmission

Figure 18 – Electricity transmission capacity is largely unaffected by the biomass constraint. In contrast to the transmission capacities, the share of net imports and exports displays larger variation. Biomass-constrained scenarios shift towards import, since the national CHP-based generation is reduced, while PtH, and thereby electricity demand, increases (*No biomass use* is most significant with 35 TWh import).

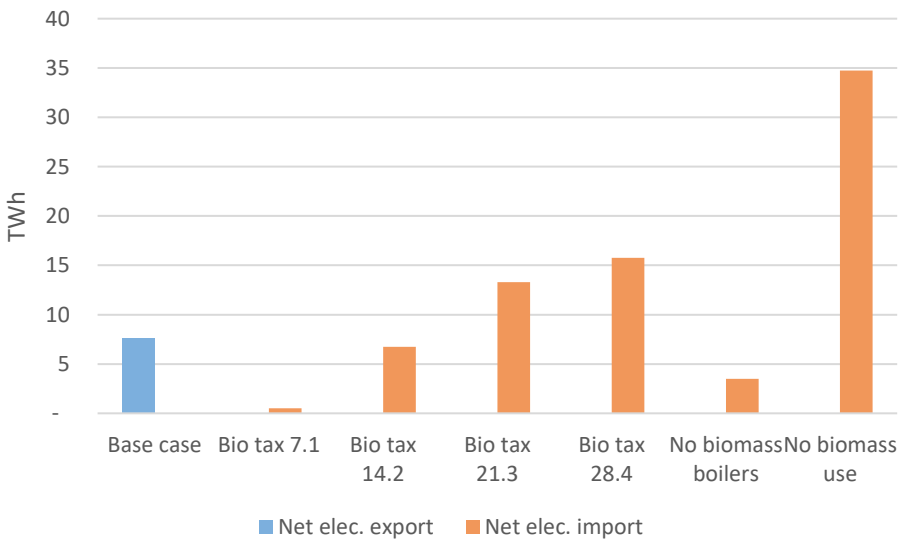
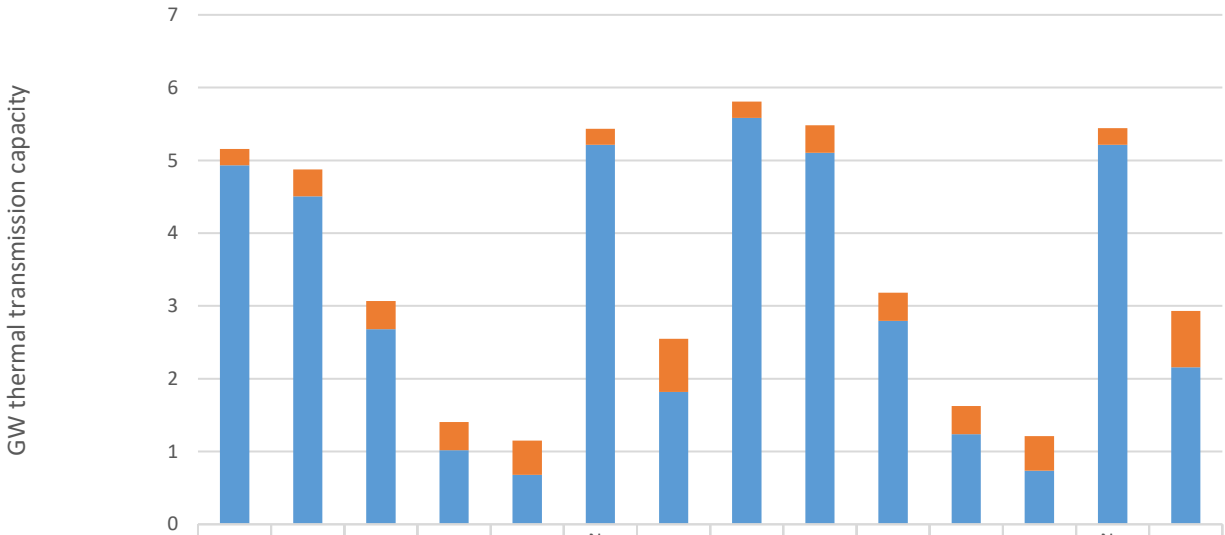


Figure 18 Electricity net export and import.

3.8 DH expansion

Figure 19 – Transmission capacity indicates connection between the large DH systems and areas previously without DH. Mainly individual heat supply is converted to DH, which can be ascribed to the higher fuel taxes and grid tariffs paid by individual consumers, compared to industry, but also the fact that industry may require higher temperature than available from DH. As biomass taxation increase, the benefit of conversion is lost due to lost competitiveness of the *Base case*'s mainly biomass-based DH generation. Conversely, *No biomass boilers* shows that conversions remain at the *Base case*-level, due to the competitiveness from especially biomass-based CHP generation in DH.

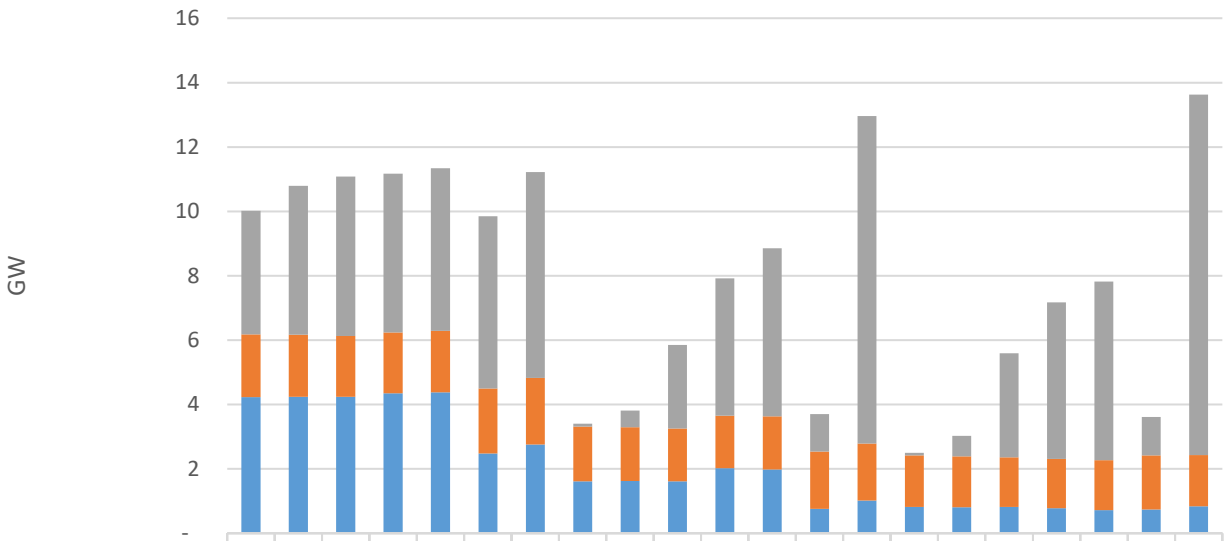


	2035							2045						
	Base case	Bio tax 7.1	Bio tax 14.2	Bio tax 21.3	Bio tax 28.4	No biomass boilers	No biomass use	Base case	Bio tax 7.1	Bio tax 14.2	Bio tax 21.3	Bio tax 28.4	No biomass boilers	No biomass use
Industry <100°C	0.2	0.4	0.4	0.4	0.5	0.2	0.7	0.2	0.4	0.4	0.4	0.5	0.2	0.8
Individual heating	4.9	4.5	2.7	1.0	0.7	5.2	1.8	5.6	5.1	2.8	1.2	0.7	5.2	2.2

Figure 19 Thermal transmission capacity to areas without DH.

Electricity capacity in industry with no option to connect to DH remains fairly constant, except in the case of a complete ban on biomass, where natural gas based back-pressure CHP is more economically feasible than replacing biomass-based capacity with fossil-based boilers.

Figure 20 – Heat generating capacity on PtH increases gradually with the size of the tax on biomass. Largest deployment of PtH happens with *No biomass use*.



	2025							2035							2045						
	Base case	Bio tax 7.1	Bio tax 14.2	Bio tax 21.3	Bio tax 28.4	No biomass boilers	No biomass use	Base case	Bio tax 7.1	Bio tax 14.2	Bio tax 21.3	Bio tax 28.4	No biomass boilers	No biomass use	Base case	Bio tax 7.1	Bio tax 14.2	Bio tax 21.3	Bio tax 28.4	No biomass boilers	No biomass use
Power-to-heat	4	5	5	5	5	5	6	0	1	3	4	5	1	10	0	1	3	5	6	1	11
Back pressure CHP	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Boiler	4	4	4	4	4	2	3	2	2	2	2	2	1	1	1	1	1	1	1	1	1

Figure 20 Generating capacity – heat, outside DH areas.

4 Discussion of results

We use results from Section 3 to identify general tendencies. As in Section 3, numbers are provided in comparison to the Base case, unless otherwise stated.

As summarised in Figure 21, there is a general tendency to decreased system costs and increased emissions, regardless of how biomass is constrained. Completely banning use of biomass increases emissions 5 times, while a biomass tax of 28.4 2012-EUR/MWh reduces total system cost to a net positive revenue of 228 MEUR-2016/year. Compared to *Base case*, a ban on biomass boilers and *Bio tax 7.1* have the least overall reduction in system cost (17%-21%) and least increase in emissions (131%-139%). These findings underline the relevance of introducing biomass constraints as a part of other initiatives, since stand-alone introduction requires a trade-off between the desire to substitute biomass and reduce emissions.

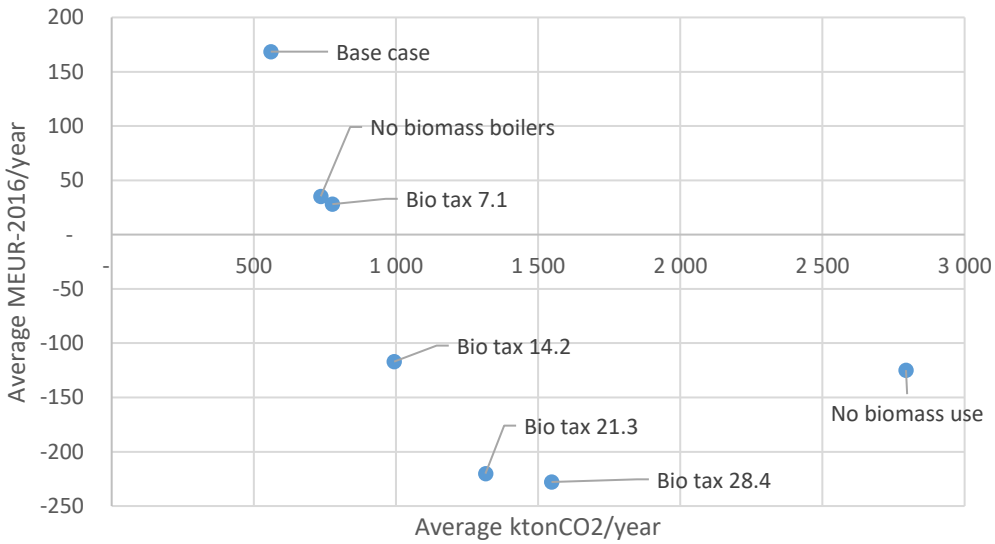
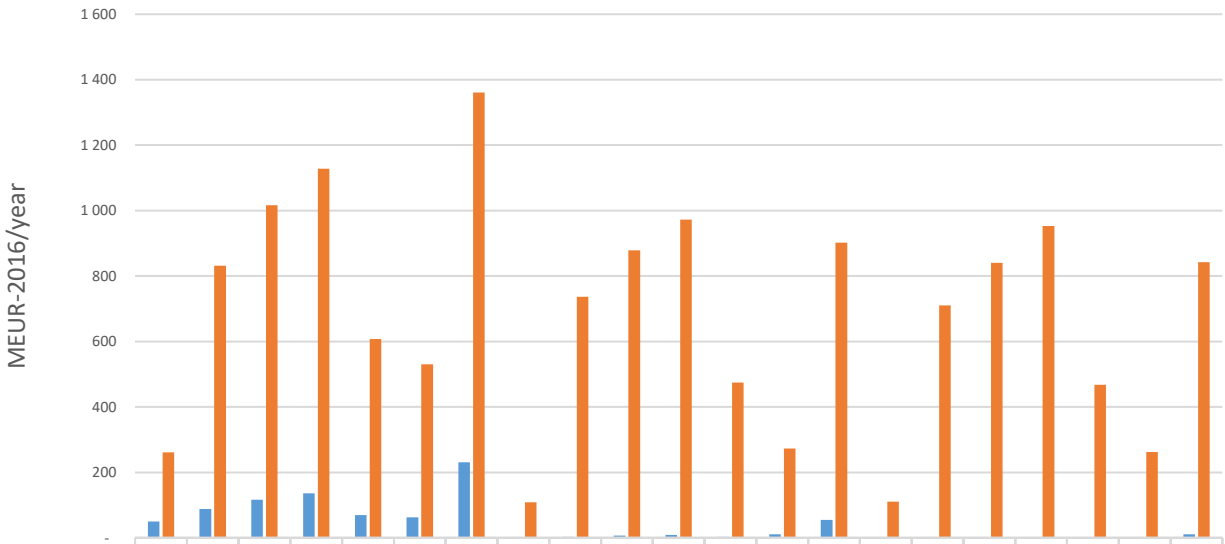


Figure 21 Average annual CO_2-emissions and system costs, net of electricity trade, in the scenarios analysed.

System costs are generally lower in the biomass-constrained scenarios, since increased imports replace national generation, while revenue from electricity trade remains relatively high. At the same time, capital costs for investment increase to 109-115%. These investments are directed solar thermal, PtH, wind and electric storage, which in turn decrease fuel cost to 32%-54%. A shift away from biomass would thus require larger up-front investments than the *Base case* and (except in the case of *No biomass boilers*) an acceptance of decreased national CHP capacity – a security of supply question (or an opportunity to co-optimise the energy system with neighbouring countries as advocated in the Flex4RES project [19]).

Tax revenue increases significantly (2-6 times) in all biomass-constrained scenarios, as increasing amounts of taxed fuels are used – and as the biomass tax increases. In theory, this amount could be spent to compensate for the increased emissions, compared to the *Base case*. From an economic perspective, this is feasible at all the CO_2-price levels (see 2.3) of respectively 2025, 2035 and 2045 – see Figure 22.



	2025							2035							2045						
	Base case	Bio tax 14.2	Bio tax 21.3	Bio tax 28.4	Bio tax 7.1	No biomass boilers	No biomass use	Base case	Bio tax 14.2	Bio tax 21.3	Bio tax 28.4	Bio tax 7.1	No biomass boilers	No biomass use	Base case	Bio tax 14.2	Bio tax 21.3	Bio tax 28.4	Bio tax 7.1	No biomass boilers	No biomass use
Mitigation cost	50	88	116	136	69	63	231	2	3	6	9	2	10	54	-	-	-	-	-	-	11
Tax revenue	261	832	1 017	1 128	607	530	1 361	108	736	878	973	474	273	902	110	710	841	953	468	263	842

Figure 22 Tax revenue and potential CO_2 mitigation costs.

Electricity grid tariff revenue increases in all scenarios, as the share of PtH increases. This happens along with a reduction in conversion of individual heating to DH, caused by the decreased low-cost biomass-based CHP generation and increasing dependence on PtH in both the DH- and individual heating sector. Möller and Lund explored DH expansion into natural gas-heated areas and found potentials of DH coverage up to 50%-70% of total Danish heat demand. With 64% of heat generated by DH, *Base case* are within these bounds, while not so with 44% in *No biomass use*.

The relatively large increases in heat cost for end-users indicate that the biomass-constraints comes at a cost for heat consumers. In theory, this may be a Ramsey problem (as discussed regarding cost-allocation between heat and electricity by Olsen and Munksgaard [71]), while in practice it may be a political question, whether the heat-consumers should pay the cost for decreased biomass use and increased electrification. Large investments (in the order of 100s of MWs) in Danish biomass-based boiler and CHP capacity have been made in recent years. With an assumed technical lifetime of 25 years, the Danish Energy Agency assumes that the payback of these investments will extend into the 2040s. [31]. All things being equal, recovering these costs will be slowed down by biomass-constraints.

While the intention of a biomass constraint may be to increase the national share of variable renewable electricity capacity, the major increase is seen within solar thermal. Contrary to the notion that increased solar thermal entails increased interseasonal TS [72], this is not the case here. The limited impact in interseasonal TS-size indicates that a certain degree of saturation may be met at large-scale deployment. The overall large deployment of TS confirms Sneum and Sandberg's [20] and Lund's [2] finding that TS is indeed a *no-regrets* solution.

The biomass constraints have a dampening effect on the biomass consumption, but coal and natural gas use partially compensates for the absent biomass; a potentially undesired consequence, which requires

additional measures to mitigate. The Danish annual biomass potential is estimated to be 160-180 PJ, excluding biomass crops [73]. The *Base case* slightly exceeds this (182 PJ/year) while the constrained scenarios are within these bounds (9-148 PJ/year).

Figure 23 illustrates the inverse relationship among selected technologies. The biomass constraining measures increase solar thermal and, to a lesser degree PtH, inversely to the decline in CHP capacity. Constraints on biomass thus comes with the trade-off between CHP on one side and PtH and solar on the other, as also found by Sandberg et al. [74]. Boilers display similar tendency, but to a lesser extent as they decline in all scenarios.

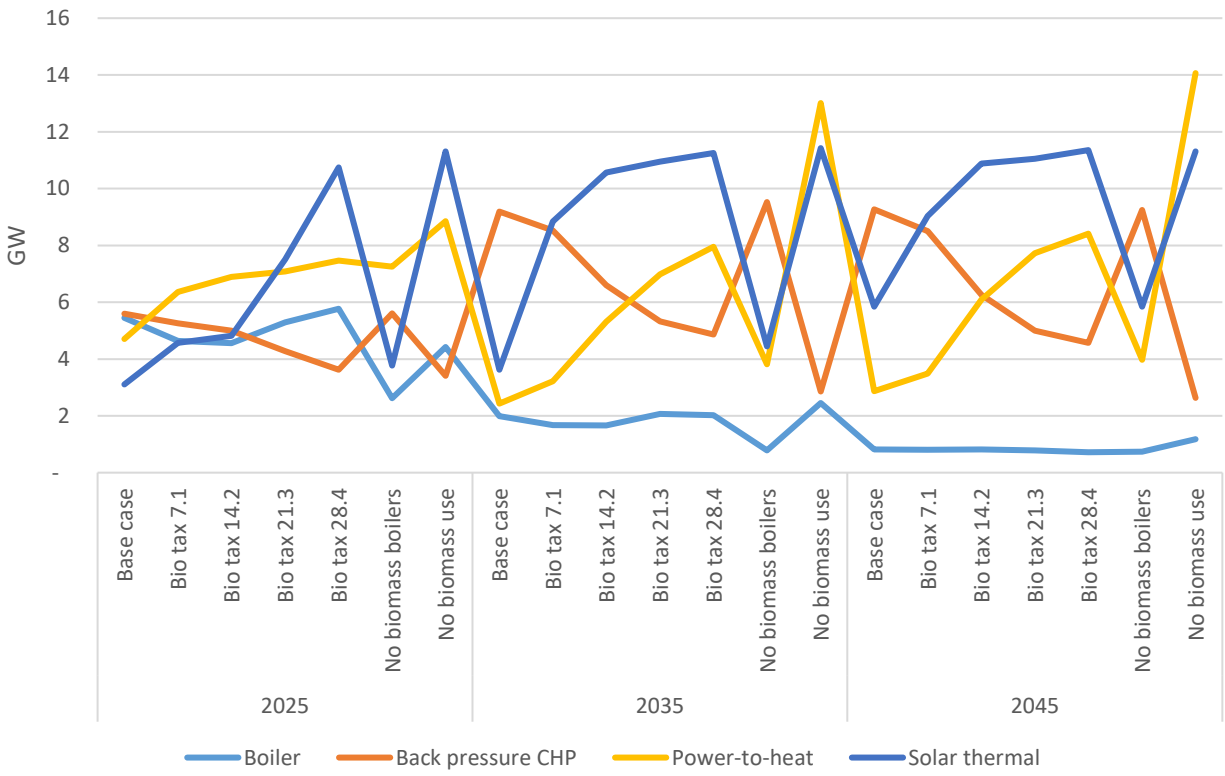


Figure 23 Relationships between capacities of boilers, CHP, solar thermal and PtH.

From being an electricity exporting country, constraints on biomass leads to increased imports to a degree where Denmark becomes a net importer. From a CO_2-perspective, this is not problematic as long as the surrounding areas are also subject to the CO_2-pricing scheme (which is the case in this study). This enables transparency in ensuring that imported electricity has a CO_2-signal factored into the price. Thellufsen and Lund's [75] study of cross-border versus cross-sector interconnectivity indicates benefits of a balance between CHP, PtH and interconnection (and electric vehicles). Whereas the studies are not directly comparable, Thellufsen and Lund's identified balance may indicate that such similar balance between technologies is found in the unconstrained *Base case* scenario's increased deployment of CHP, less PtH and increased exports.

As the visual summary in Figure 24 indicate, a complete ban on the use of biomass would have the highest impact on 9 of the 13 criteria represented in the figure. *No biomass use* can be argued to be the most extreme measure among the ones analysed, so this aligns with having the most pervasive impact.

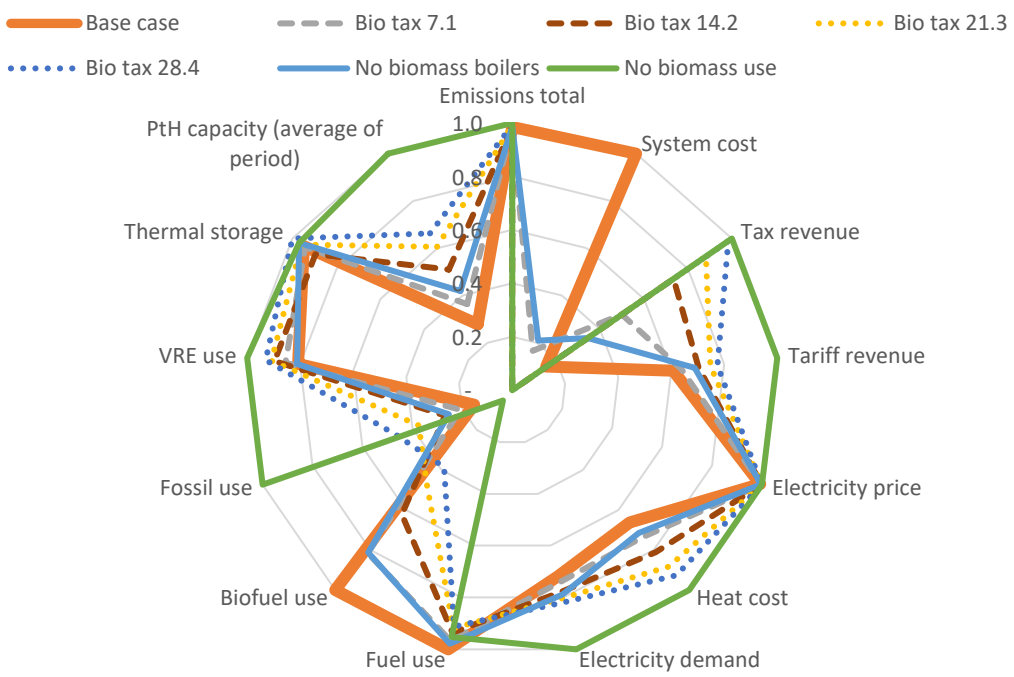


Figure 24 Visual summary of indexed impacts on 13 selected criteria in all seven scenarios. Scenarios with net positive system cost have been set to 0.

Finally, a few words on the shortcomings of the analysis and methodology. While the Balmorel model is valuable as a tool for energy system analyses (see 2.3), the present analyses are limited by several factors, including the

- temporal perspective, where model-runs are conducted for 4 representative weeks to reduce computation time. May be improved by modelling longer periods
- geographical perspective, where expansion of DH may be aggregating over local differences, and where only large DH areas are allowed to expand to non-DH served areas. The former can be mitigated by more detailed GIS analysis, as seen by Petrovic and Karlsson [76] regarding heat savings and and Möller and Lund on DH expansion [77]. The latter can be mitigated by further developing the Balmorel model to include additional areas for potential conversion
- representation of economic- and regulatory conditions in surrounding countries, where the study draws on detailed data in many cases (see 2.3), but lacks detailed data (e.g. detailed data on subsidies) on some of the surrounding countries. While the obvious solution is to collect these data, it may not always be possible to dedicate the significant amount of resources to do so. Therefore, the ideal solution would be a common and frequently updated database enabling comparable analyses on up-to-date data
- representation of ancillary services markets is omitted in this study. So-called *special regulation* and other types of non-spot markets may drive deployment of especially electric boilers [7,78]. This could be defined exogenously, based on statistical data

5 Conclusion

In this study, we have explored the impacts of heat source substitution as a measure to increase sector coupling and flexibility. We find that constraints on biomass does indeed lead to heat source substitution, increasing electrification of the heating sector. Compared to the *Base case*, the PtH capacity increases to 122%-491%.

Beyond electrification, there may be other reasons for constraining the use of biomass. The broader energy system impacts shows that a carbon price trumps biomass-constraining measures, considering the CO_2-emissions among the scenarios. Constraining biomass is thus a trade-off against CO_2-emissions, unless other measures are taken to mitigate increased emissions. That said, other motivations for constraining biomass may be to reduce the biomass use to a politically desirable level, or to replace biomass-based heat production with VRE and PtH-based capacity. The biomass constrained scenarios show decreased system cost and increased tax revenue, potentially useful for financing mitigation of the increased CO_2-emissions.

A shift away from biomass incur larger up-front investments than the *Base case* and decreased national CHP capacity. The latter may become a security of supply question. While electricity prices are largely unchanged, heat prices increase considerably. The question is to what degree the cost should be levied on the heat consumers.

While it is important to underline that energy systems are highly context specific, and that results may change with geography, time and regulatory environment, a few commonly perceived truths regarding VRE and heat-electricity system interface is challenged by the findings in this study

- Increased electric VRE capacity does not necessarily induce a need for a significantly larger TS capacity. The reason may be that the TS capacity is already sufficiently large (e.g. for 2045 *Base case*: 496 GWh TS/13 GW VRE; *Biomass tax 28.4*: 492 GWh TS/15 GW VRE)
- Increased solar thermal does not necessarily induce a larger interseasonal TS (e.g. for 2035 *Base case*: 4 GW solar thermal/449 GWh TS; *Bio tax 28.4*: 11 GW solar thermal; 397 GWh TS)
- Banning biomass boilers, the direct competitor to PtH, leads to more PtH, but does not increase VRE (*Base case* and *No biomass boilers* equal in 2025 and 2035)
- Constraining biomass use may increase PtH and higher VRE-utilisation, but not necessarily lower overall CO_2-emissions (e.g. 2025 *Base case*: 5 GW PtH/371.6 $MtCO_2$; *Bio tax 7.1*: 6 GW PtH; 372.8 $MtCO_2$)
- TS is more relevant than electric storage, as TS is deployed to a much larger scale (e.g. 2045 *Base case*: electric storage 3 GW/15 GWh vs. TS 42 GW/496 GWh)

Constraining biomass use will facilitate a shift in the heating system towards *moving* heat through PtH instead of *combusting* to generate heat. If there is a strong enough CO_2-price signal, constraining biomass will not reduce emissions, but system cost may decline, tax revenue may increase and the heat consumers may finance this transition through higher prices.

5.1 Future work

The present study assumes biomass to be CO_2-neutral. As there is discussion (e.g. regarding Sweden [79,80], Nordics [81] and EU [82]) regarding the true CO_2-emissions and sustainability of biomass, the impact could be relevant to explore further.

Additional future paths to explore include impacts of economic conditions such as electricity taxation or electricity grid tariffs, or technical conditions such as thermal storages and turbine bypass. Regulation may have different impacts than intended when originally put in place: Topics could be discount rate (currently set at 4% in Denmark) or the detailed DH regulation stipulated in the Danish Announcement on approval of projects for collective heat supply (*Projektbekendtgørelsen* [83]) and the Danish Energy Agency's Guidance to socioeconomic analyses on energy [84], which both have significant impacts on the deployment of DH technologies in Denmark.

6 Acknowledgements

This project FlexSUS: Flexibility for Smart Urban Energy Systems (Project nbr. 91352), has received funding in the framework of the joint programming initiative ERA-Net Smart Energy Systems' focus initiative Integrated, Regional Energy Systems, with support from the European Union's Horizon 2020 research and innovation programme under grant agreement No 775970.

Disclaimer: The content and views expressed in this material are those of the authors and do not necessarily reflect the views or opinion of the ERA-Net SES initiative. Any reference given does not necessarily imply the endorsement by ERA-Net SES.

7 References

[1] Münster M, Iliceto A, Berger M, Bramstoft R, Bühler F, Elmegaard B, et al. Sector Coupling: Defitions, state-of-the-art and perspectives 2020.

[2] Lund H. Renewable Energy Systems. 2nd ed. Aalborg: Academic Press; 2014.

[3] IEA. The power of transformation. Paris: IEA; 2014. doi:10.1007/BF01532548.

[4] Blarke MB. Towards an intermittency-friendly energy system: Comparing electric boilers and heat pumps in distributed cogeneration. Appl Energy 2012;91:349–65. doi:10.1016/j.apenergy.2011.09.038.

[5] Kirkerud JG, Bolkesjø TF, Trømborg E. Power-to-heat as a flexibility measure for integration of renewable energy. Energy 2017;128:776–84. doi:10.1016/j.energy.2017.03.153.

[6] Bloess A, Schill WP, Zerrahn A. Power-to-heat for renewable energy integration: A review of technologies, modeling approaches, and flexibility potentials. Appl Energy 2018;212:1611–26. doi:10.1016/j.apenergy.2017.12.073.

[7] Danish Energy Agency. Flexibility in the Power System - Danish and European experiences. Copenhagen: 2015.

[8] Lund PD, Lindgren J, Mikkola J, Salpakari J. Review of energy system flexibility measures to enable high levels of variable renewable electricity. Renew Sustain Energy Rev 2015;45:785–807. doi:10.1016/j.rser.2015.01.057.

[9] Gadd H, Werner S. Thermal energy storage systems for district heating and cooling. Adv. Therm. Energy Storage Syst. Methods Appl., Halmstad: Woodhead Publishing Limited; 2014, p. 467–78. doi:10.1533/9781782420965.4.467.

[10] EMD International A/S. Svendborg District Heating. EMD Website 2020. http://www.energyweb.dk/svendborg/?english&history (accessed March 28, 2020).

[11] Energinet.dk. Nordic Power Market Design and Thermal Power Plant Flexibility. Fredericia: 2018.

[12] Wissner M. Regulation of district-heating systems. Util Policy 2014;31:63–73. doi:10.1016/j.jup.2014.09.001.

[13] Sneum DM, Sandberg E, Koduvere H, Olsen OJ, Blumberga D. Policy incentives for flexible district heating in the Baltic countries. Util Policy 2018;51:61–72. doi:10.1016/j.jup.2018.02.001.

[14] Bergaentzlé C, Skytte K, Soysal ER, Boscàn L, Olsen OJ, Lyngby D-. Regulatory barriers for activating flexibility in the Nordic-Baltic electricity market 2017.

[15] Hvelplund F, Østergaard PA, Meyer NI. Incentives and barriers for wind power expansion and system integration in Denmark. Energy Policy 2017;107:573–84. doi:10.1016/j.enpol.2017.05.009.

[16] Hvelplund F, Djørup S. Denmark: centralised versus decentralised renewable energy systems. In: Burger C, Froggatt A, Mitchell C, Weinmann J, editors. Decent. Energy A Glob. Game Chang. 1st ed., London: Ubiquity Press; 2020, p. 63–81. doi:10.5334/bcf.e.

[17] Mathiesen BV, Lund H, Connolly D. Limiting biomass consumption for heating in 100% renewable energy systems. Energy 2012;48:160–8. doi:10.1016/j.energy.2012.07.063.

[18] Energinet. Model Analysis of Flexibility of the Danish Power System. 2018.

[19] Skytte K, Bergaentzlé C, Fausto F, Gunkel P, Flex4RES. Flexible Nordic Energy Systems - Summary Report. Lyngby: 2019.

[20] Sneum DM, Sandberg E. Economic incentives for flexible district heating in the Nordic countries. Int J Sustain Energy Plan Manag 2018;16:27–44. doi:10.5278/ijsepm.2018.16.3.

[21] Østergaard PA, Jantzen J, Marczinkowski HM, Kristensen M. Business and socioeconomic assessment of introducing heat pumps with heat storage in small-scale district heating systems. Renew Energy 2019;139:904–14. doi:10.1016/j.renene.2019.02.140.

[22] Good N, Ellis KA, Mancarella P. Review and classification of barriers and enablers of demand response in the smart grid. Renew Sustain Energy Rev 2017;72:57–72. doi:10.1016/j.rser.2017.01.043.

[23] Lund H, Østergaard PA, Connolly D, Mathiesen BV. Smart energy and smart energy systems. Energy 2017;137:556–65. doi:10.1016/j.energy.2017.05.123.

[24] Kirkerud JG, Trømborg E, Bolkesjø TF. Impacts of electricity grid tariffs on flexible use of electricity to heat generation. Energy 2016:1–9. doi:10.1016/j.energy.2016.06.147.

[25] Röder J, Beier D, Meyer B, Nettelstroth J, Zondervan E. Design of Renewable and System-Beneficial District Heating Systems Using a Dynamic Emission Factor for Grid-Sourced Electricity 2020. doi:10.3390/en13030619.

[26] Gea-Bermudez J, Koivisto MJ, Münster M. Optimization of the electricity and heating sectors development in the North Sea region towards 2050. Proc. 18th Int'l Wind Integr. Work., 2019.

[27] Arpagaus C, Bless F, Uhlmann M, Schiffmann J, Bertsch SS. High temperature heat pumps: Market overview, state of the art, research status, refrigerants, and application potentials. Energy 2018;152:985–1010. doi:10.1016/j.energy.2018.03.166.

[28] Gaigalis V, Skema R, Marcinauskas K, Korsakiene I. A review on Heat Pumps implementation in Lithuania in compliance with the National Energy Strategy and EU policy. Renew Sustain Energy Rev 2016;53:841–58. doi:10.1016/j.rser.2015.09.029.

[29] Warde P. Early Modern "Resource Crisis": The Wood Shortage Debates in Europe. In: Brown AT, Burn A, Doherty R, editors. Cris. Econ. Soc. Hist. A Comp. Perspect., Rochester, N.Y: Boydell Press; 2015.

[30] The Danish Energy Agency. Tabeller - Energistatistik 2018 [Tables Energy statistics 2018] 2019.

[31] The Danish Energy Agency. Klima-, Energi- og Forsyningsudvalget 2019-20 KEF Alm.del - endeligt svar på spørgsmål 268 [Climate-, Energy- and Utilities committee 2019-29 - Final answer to question 268]. Copenhagen: 2020.

[32] Connolly D. Finding and Inputting Data into the EnergyPLAN Tool. Aalborg: 2015.

[33] Sneum DM, Sandberg E, Soysal ER, Skytte K, Olsen OJ. Framework conditions for flexibility in the district heating-electricity interface. Lyngby: 2016.

[34] Skytte K, Olsen OJ, Soysal ER, Sneum DM. Barriers for district heating as a source of flexibility for the electricity system. J Energy Mark 2017;10:1–19. doi:10.21314/JEM.2017.161.

[35] Danish Parliament (except Liberal Alliance). The Energy Agreement of 2012 [Aftale mellem regeringen (Socialdemokraterne, Det Radikale Venstre, Socialistisk Folkeparti) og Venstre, Dansk Folkeparti, Enhedslisten og Det Konservative Folkeparti om den danske energipolitik 2012-2020] 2012:1–16.

[36] The Danish Ministry of Taxation. Beskrivelse af model for forsyningssikkerhedsafgiften [Description of model for the security of supply tax] 2013.

[37] Danish Government and Parliament majority. Agreement on roll-back of security of supply tax and reduction of PSO [Aftale om tilbagerulning af FSA mv. og lempelser af PSO] 2014:1–7.

[38] Øyen M. The Government postpones wood-fuel tax [Regeringen udskyder brændeafgift]. Altin | Energi Og Klima 2013. https://www.altinget.dk/artikel/131180-regeringen-udskyder-braendeafgift (accessed February 26, 2019).

[39] Ritzau. Industry avoids expensive wood-fuel tax [Erhvervslivet slipper for dyr brændeafgift]. Danish Broadcast Corp 2014. https://www.dr.dk/nyheder/politik/erhvervslivet-slipper-dyr-braendeafgift (accessed February 26, 2019).

[40] The Danish Ministry of Taxation. Skatteudvalget 2019-20 SAU Alm.del - endeligt svar på spørgsmål 274 [Tax committee 2019-20 Final answer on question 274] 2020.

[41] Danish Energy Agency. Vejledning i brugerøkonomisk kontrolberegning januar 2019 [Guidance on user-economic control calculation January 2019] 2019.

[42] Gyldenkilde L. Folketingsbeslutning om offentlige energiplanlægning uden atomkraft [Parliament decision on public energy planning without nuclear energy] 1985;B 103.

[43] Ministry of Commerce. Dansk energipolitik 1976 [Danish Energy Policy 1976]. Copenhagen: 1976.

[44] Wiese F, Bramstoft R, Koduvere H, Pizarro Alonso A, Balyk O, Kirkerud JG, et al. Balmorel open source energy system model. Energy Strateg Rev 2018;20:26–34. doi:10.1016/j.esr.2018.01.003.

[45] Balmorel Community. Balmorel Model. GitHub n.d.

https://github.com/balmorelcommunity/Balmorel (accessed March 27, 2020).

[46] The Danish Energy Agency. Technology Data. Danish Energy Agency Website n.d. https://ens.dk/en/our-services/projections-and-models/technology-data (accessed March 27, 2020).

[47] Gunkel PA, Faust FJ, Skytte K, Bergaentzle C. The Impact of EV Charging Schemes on the Nordic Energy System. Int. Conf. Eur. Energy Mark. EEM, 2019. doi:10.1109/EEM.2019.8916569.

[48] Flex4RES. Flex4RES – Nordic Energy Research. Flex4RES Proj Website 2019. https://www.nordicenergy.org/flagship/flex4res/ (accessed March 28, 2020).

[49] Koivisto M, Maule P, Cutululis N, Sørensen P. Effects of wind power technology development on large-scale VRE generation variability. 2019 IEEE Milan PowerTech, PowerTech 2019 2019. doi:10.1109/PTC.2019.8810687.

[50] Koivisto M, Das K, Guo F, Sørensen P, Nuño E, Cutululis N, et al. Using time series simulation tools for assessing the effects of variable renewable energy generation on power and energy systems. Wiley Interdiscip Rev Energy Environ 2019;8:1–15. doi:10.1002/wene.329.

[51] Nuño E, Maule P, Hahmann A, Cutululis N, Sørensen P, Karagali I. Simulation of transcontinental wind and solar PV generation time series. Renew Energy 2018;118:425–36. doi:10.1016/j.renene.2017.11.039.

[52] The World Bank Group. Global Solar Atlas. Glob Sol Atlas Website n.d. https://globalsolaratlas.info/map?c=11.523088,8.173828,3 (accessed March 28, 2020).

[53] IEA. Nordic Energy Technology Perspectives 2016 – Nordic Energy Research. Nord Energy Technol Perspect 2016 2016. http://www.nordicenergy.org/project/nordic-energy-technology-perspectives/ (accessed October 1, 2017).

[54] Koivisto M, Gea-Bermudez J, Sorensen P. North Sea offshore grid development: Combined optimization of grid and generation investments towards 2050. IET Renew Power Gener 2019. doi:10.1049/iet-rpg.2019.0693.

[55] Koivisto M, Gea-Bermudez J. NSON-DK energy system scenarios – Edition 2. 2018.

[56] Ruiz P, Nijs W, Tarvydas D, Sgobbi A, Zucker A, Pilli R, et al. ENSPRESO - an open, EU-28 wide, transparent and coherent database of wind, solar and biomass energy potentials. Energy Strateg Rev 2019;26:100379. doi:10.1016/j.esr.2019.100379.

[57] Gehreke L, Oroschakoff K. An ill wind blows for the onshore power industry. Polit Website 2019. https://www.politico.eu/article/an-ill-wind-blows-for-the-onshore-power-industry/.

[58] The Danish Parliament. Energy Agreement of 29 June 2018 2018:1–19.

[59] Palzer A, Henning HM. A comprehensive model for the German electricity and heat sector in a future energy system with a dominant contribution from renewable energy technologies - Part II: Results. Renew Sustain Energy Rev 2014;30:1019–34. doi:10.1016/j.rser.2013.11.032.

[60] Ruhnau O, Hirth L, Praktiknjo A. Time series of heat demand and heat pump efficiency for energy system modeling. Sci Data 2019;6:189. doi:10.1038/s41597-019-0199-y.

[61] Wiese F, Baldini M. Conceptual model of the industry sector in an energy system model: A case study for Denmark. J Clean Prod 2018;203:427–43. doi:10.1016/j.jclepro.2018.08.229.

[62] Rehfeldt M, Fleiter T, Toro F. A bottom-up estimation of the heating and cooling demand in European industry. Energy Effic 2018;11:1057–82. doi:10.1007/s12053-017-9571-y.

[63] Eurostat. Electricity and heat statistics - Statistics Explained. Eurostat Website 2019. https://ec.europa.eu/eurostat/statistics-explained/index.php/Electricity_and_heat_statistics (accessed March 28, 2020).

[64] Ruhnau O. The Impacts of Electricity-Heat Sector Coupling on the Power System Integration of Variable Renewable Energy Sources 2017.

[65] The Danish Customs and Tax Administration. E.A.4.3.6.1 Afgiftssatser og beregning Indhold. Leg Guidel 2019-1 [Den Juridiske Vejl 2019-1] 2019. https://skat.dk/skat.aspx?oID=2061620&chk=215961 (accessed March 20, 2019).

[66] The Danish Customs and Tax Administration. E.A.4.6.4.3 Delvis godtgørelse af elafgift på rumvarme mv. Indhold. Leg Guidel 2019-1 [Den Juridiske Vejl 2019-1] 2019. https://www.skat.dk/SKAT.aspx?oID=2062227 (accessed March 20, 2019).

[67] Hedegaard K, Münster M. Influence of individual heat pumps on wind power integration - Energy system investments and operation. Energy Convers Manag 2013;75:673–84. doi:10.1016/j.enconman.2013.08.015.

[68] Østergaard PA. Reviewing optimisation criteria for energy systems analyses of renewable energy integration. Energy 2009;34:1236–45. doi:10.1016/j.energy.2009.05.004.

[69] Lannoye E, Flynn D, O'Malley M. Evaluation of power system flexibility. IEEE Trans Power Syst 2012;27:922–31. doi:10.1109/TPWRS.2011.2177280.

[70] IEA, NREL. Status of Power System Transformation 2018. Paris: 2018.

[71] Olsen OJ, Munksgaard J. Cogeneration and taxation in a liberalized Nordic power market. Util Policy 1998;7:23–33. doi:10.1016/S0957-1787(98)00002-2.

[72] PlanEnergi. Long term storage and solar district heating. Skørping: 2015.

[73] Jørgensen D. Klima-, Energi- og Forsyningsudvalget 2019-20 KEF Alm.del - endeligt svar på spørgsmål 305 [Climate-, Energy- and Utilities Committee 2019-20 - Final answer to question 305] 2020.

[74] Sandberg E, Kirkerud JG, Trømborg E, Bolkesjø TF. Energy system impacts of grid tariff structures for flexible power-to-district heat. Energy 2018. doi:10.1016/j.energy.2018.11.035.

[75] Thellufsen JZ, Lund H. Cross-border versus cross-sector interconnectivity in renewable energy systems. Energy 2017;124:492–501. doi:10.1016/j.energy.2017.02.112.

[76] Petrović S, Karlsson K. Ringkøbing-Skjern energy atlas for analysis of heat saving potentials in building stock. Energy 2016;110:166–77. doi:10.1016/j.energy.2016.04.046.

[77] Möller B, Lund H. Conversion of individual natural gas to district heating: Geographical studies of supply costs and consequences for the Danish energy system. Appl Energy 2010;87:1846–57. doi:10.1016/j.apenergy.2009.12.001.

[78] Detlefsen N. Specialregulering i fjernvarmen. Kolding: 2016.

[79] Klein J, Wronski I, Perlman K, Ernsting A, Ballenthien J. Sweden's forest crimes. EURACTIVCom 2020. https://www.euractiv.com/section/biomass/opinion/swedens-forest-crimes/ (accessed March 27, 2020).

[80] Sundqvist H. Environmental measures in Swedish forests will continue to be strong. EURACTIVCom 2020. https://www.euractiv.com/section/biomass/opinion/environmental-measures-in-swedish-forests-will-continue-to-be-strong/ (accessed March 27, 2020).

[81] Tunberg M, Hansson P. Sustainable use of biomass for heating and transport fuel. Oslo: 2020.

[82] van Ypersele JP, Booth MS. Burning trees as climate mitigation: A resort to the Court. EURACTIVCom 2020. https://www.euractiv.com/section/climate-environment/opinion/burning-trees-as-climate-mitigation-a-resort-to-the-court/?utm_source=EURACTIV&utm_campaign=5c93e20f4a-RSS_EMAIL_EN_EnergyEnvironment&utm_medium=email&utm_term=0_c59e2fd7a9-5c93e20f4a-115032507 (accessed March 27, 2020).

[83] Danish Energy Agency. Projektbekendtgørelsen [Announcement on approval of projects for collective heat supply]. Denmark: 2018.

[84] Danish Energy Agency. Samfundsøkonomiske beregningsforudsætninger for energipriser og emissioner, oktober 2018 [Guidance to socioeconomic analyses on energy] 2018.