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 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 indicators such as power-to-heat deployment. We do so by introducing 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 (PV)) [3].
VRE integration can be achieved in the heating sector, by utilising 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 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). Lund and Mathiesen [18] have analysed a biomass constraint (7.76 EUR/GJ, presumably 2012-level), but only on DH boilers. Energinet and Flex4RES have explored the impact of constraining interconnection capacity, CHP flexibility, taxes and electricity grid tariffs in the Danish [19] and Nordic [20] energy systems. Sneum et al. [13,21] 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. Further, the results are evaluated according to a broader set of indicators than the commonly applied system cost and greenhouse gas emissions, thereby providing a comprehensive overview of impacts.

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 [21,22]. Good et al. coins this kind of *cannibalisation "discrepancy between substitutable goods"* [23]. PtH is typically considered in tandem with VRE, where the ability of PtH to consume electricity from VRE is considered a desirable synergy [24–26]. 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 [27] or undesired effects of refrigerants in HP [28,29]) 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 [30] concerns about biomass shortage) or because biomass in many cases [13,21] 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 [13,17,21]. As consequence of a steady growth (Figure 1) the share of solid biomass reached 29% of total fuel consumption [31] and a share of 64% of Danish RE [32] in 2018. With 63% of solid biomass used in the CHP and DH generation, 29% for individual heating and 7% in process industry [32] (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.

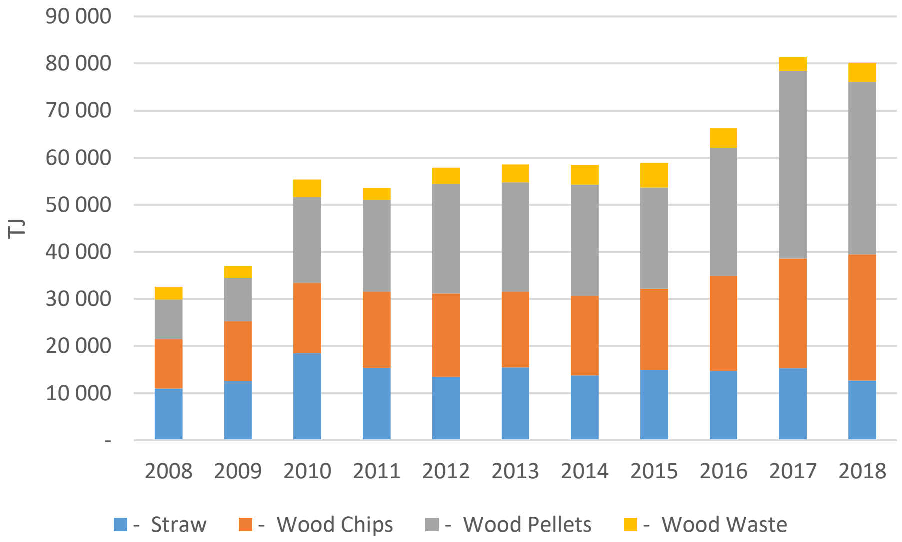


Figure 1 Solid biomass consumption in Denmark 2008-2018 [31]

Beyond the Danish energy context, '*sustainability of biomass for energy is discussed intensively*' [33] in the Nordic context, and the importance of sustainable use of biomass has been noted by the International Renewable Energy Agency, the International Energy Agency and the Renewable Energy Policy Network for the 21st Century (REN21) [34]. Its sustainability and carbon neutrality has been questioned in the public debate, e.g. at the level of Sweden [35,36], Nordics [33] and EU [37]. Further, with 59.2% of the total EU share of renewables, biomass is a substantial part of the energy mix [38]. This is illustrated in Figure 2, where the countries ranking among the highest in per capita use (Denmark, Finland, Sweden) and in total (France and Germany) are incidentally part of this study's modelling area (described in 2.3).

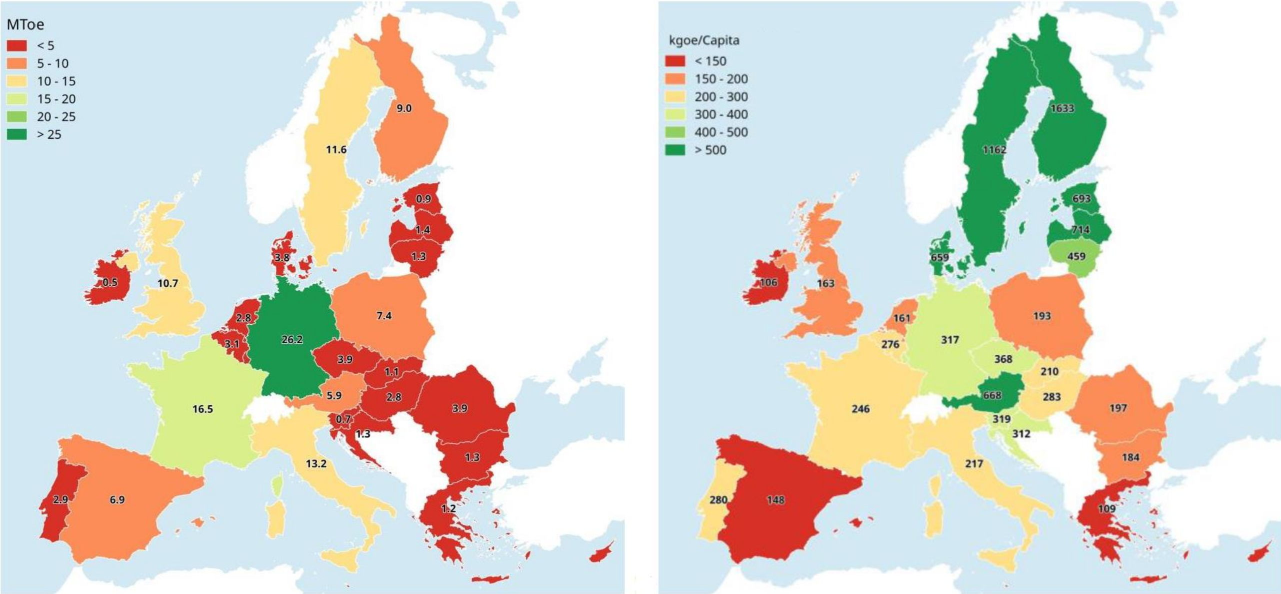


Figure 2 Bioenergy consumption in EU Member States, 2016. Total in Mtoe (left). Per capita in kgoe/per capita (right). Figure from Joint Research Centre [38]**.**

1.2 Research question

Based in the combined hypotheses that increased amounts of variable renewable energy may be integrated through increased electrification of the heating sector, and that biomass use may be necessary to constrain in the energy sector, in order to maintain use at a sustainable level, we ask

> *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 4, before concluding on the findings regarding indicators 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 report the resulting numbers, the study focusses on tendencies, rather than decimals in the specific case.

2.1 Energy system modelling in the Balmorel model

The energy system model Balmorel [39] is used to optimize the capacity development of the power and heat system of Northern Europe towards 2045. Balmorel is open-source [40], has a bottom-up approach, is deterministic, and in this paper it has been used to solve a linear programming problem. The objective function in Balmorel is to minimize discounted system costs, while satisfying the hourly heat and power demand of the sectors included:

$$\min_{INV_y, VC_y, FC_y} \sum_y DF_y \cdot (INV_y + VC_y + FC_y)$$

The costs of future years are discounted with a discount rate of 4% per year [41], which is used to calculate the discount factor (*DF*). The costs in the optimizations correspond to annuitized investments (INV) (use of annuities in Balmorel treated in detail in Gea-Bermúdez et. al [42]), and fixed (FC) and variable operational (VC) 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. Decommissioning can take place due to lifetime or because of economic profitability. 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.

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. [27], 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. [27], 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 [43]. Extensive description of the concept behind the modelling of the heat sector can be found in Gea-Bermúdez et al. [44].

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 [40], is mostly coming from the Flex4RES project [45]. Key differences are explained in this paper. The CorRES tool [46–48] 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 [49]. Wind offshore potentials per RG are based on [50–52]. Solar PV potentials for large scale systems are based on Ruiz et al. [53].

Onshore wind potentials include social acceptance restrictions and are based on the combination of multiple sources [50,54,55]. 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. The total potential in Denmark for wind and solar technologies applied, is

- Onshore wind: 6.2 GW
- Offshore wind: 50 GW
- Solar PV: 69 GW

Technology data development towards 2050 is based on The Danish Energy Agency [41]. Figure 3 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.

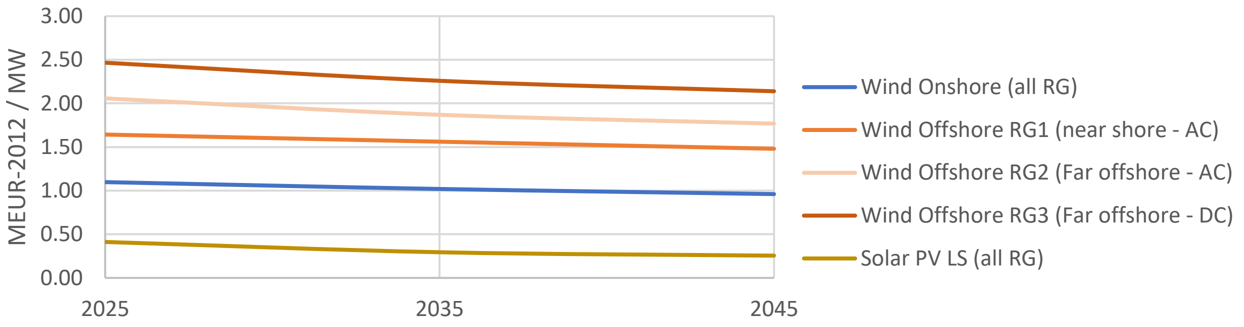


Figure 3. Wind and solar PV technology capex development [41]**. Wind offshore costs are different for each region in the model due to different transmission length assumptions.**

District heating expansion costs (0.396 MEUR-2012/MW) is based on Henning and Palzer [56]. Transmission expansion costs, CO_2 tax development and fuel price development are based on NETP [50]. The modelling of biomass prices is based on step wise price functions from Gea-Bermúdez et al. [27]. Coefficient of performance time series for the different HP included are based on Ruhnau et al. [57]. Power demand, solar heating and district heating demand data comes from the Flex4RES project [45]. Industrial data is based on Wiese and Baldini [58] and Rehfeldt et al. [59]. Individual users' data is based on Eurostat [60] and Ruhnau [61]. Their total demand aggregates both individual users and the tertiary sector. Figure 4 illustrates the development of fuel- and CO_2-prices.

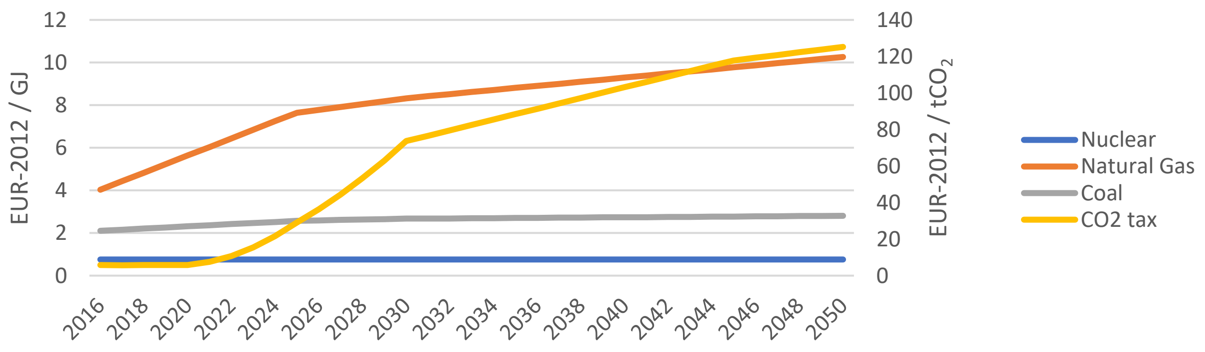


Figure 4. Fuel and CO_2 tax price development [50]**.**

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} [62] deducted 625 2019-DKK/MWh_{el} [63] = 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

2.2 Biomass barriers to sector coupling and flexibility

The concept of flexibility in the interface between the heating and electricity system is illustrated in Figure 5. 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.

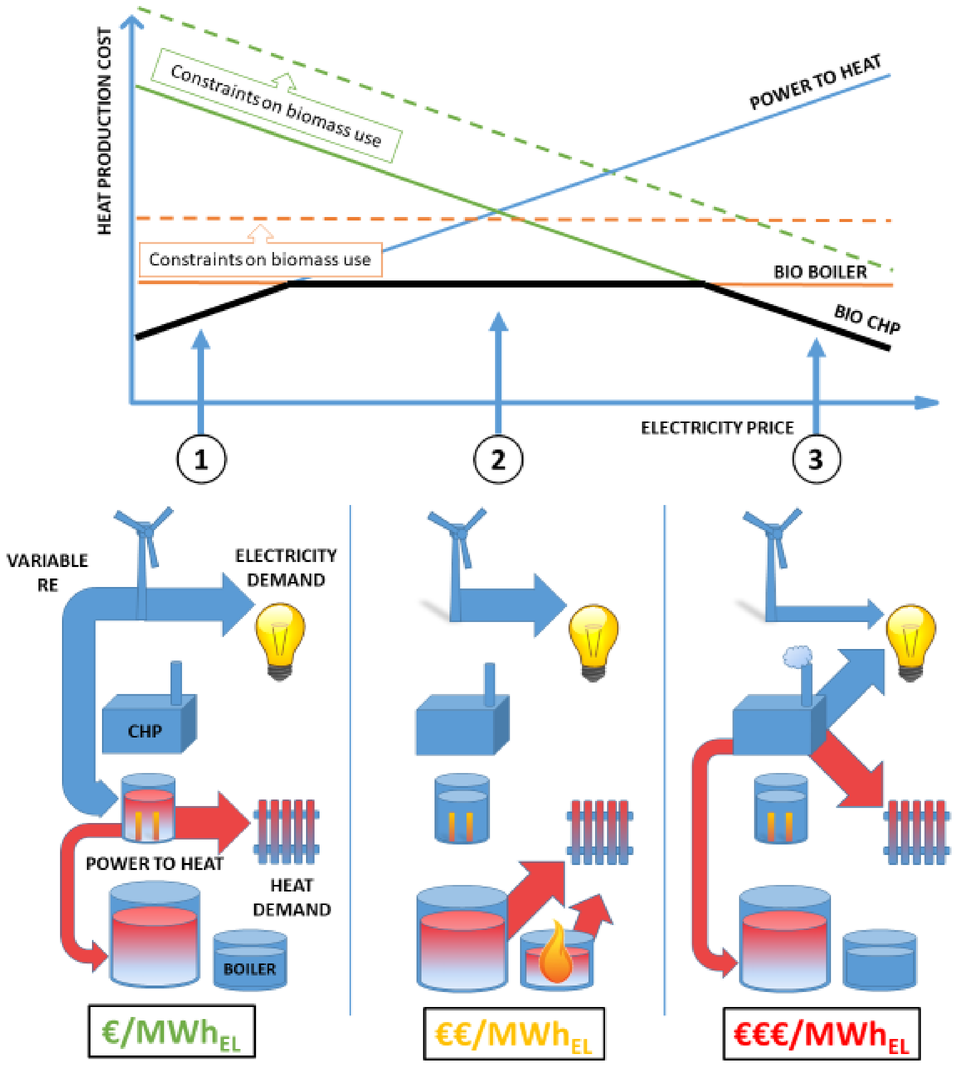


Figure 5 Least cost dispatch and concept of flexible heating. Own illustration based on [64], [65] **and** [20].

Biomass has been shown to be both a potential barrier (biomass boilers [66]) and a potential contributor (CHP [21]) 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 [66]. 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 5 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. The analyses do not measure flexibility per se, but show the impact on various indicators (see 2.4) of constraining biomass use to increase the coupling and flexibility in the interface between heat and electricity systems.

2.3 Scenarios and scenario variations

The study is based on modelling of the Northern European energy system, as seen in Figure 6. The scenario variations described in this section are only introduced in Denmark. Investment and operation can vary in Denmark as well as surrounding countries, according to the scenario variations introduced in Denmark.

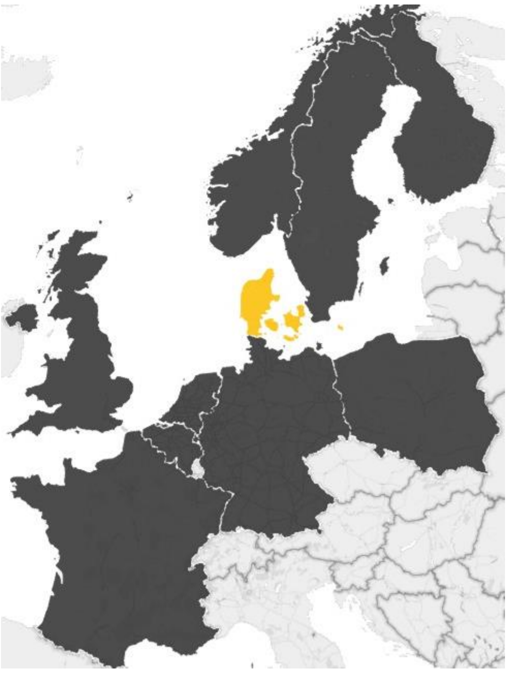


Figure 6 Countries in the modelling: Belgium, Denmark (yellow), Finland, France, Germany, Netherlands, Norway, Poland, Sweden and United Kingdom.

The study is based on analyses of four main scenarios (*Base case*, *Biomass tax*, *No biomass boilers* and *No biomass use*), with one being split into two sub-scenarios, totalling five scenarios – Table 1.

Table 1 Scenarios and their variations.

Scenario	**Base case**	**Biomass tax**		**No biomass boilers**	**No biomass use**
Scenario variation		**Bio tax 14.2**	**Bio tax 28.4**		
#	1	2	3	4	5
Constraint	No con-straints	14.2 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.

2.3.1 Base case – scenario 1

Scenario variations 2-5 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}

2.3.2 Biomass tax – scenario variations 2-3

The *security of supply-tax* (Danish: forsyningssikkerhedsafgift) was a tax on fuels for heating purposes proposed in the Danish Energy Agreement of 2012 [67] and in 2013 set to 29.7 DKK-2013/GJ by 2020 for biomass [68]. The tax was proposed to mitigate declining fiscal revenues from the reduction of other energy taxes [67], with the possible side-effect of increasing PtH and avoiding large deployment of biomass-based technologies. Subsequently (2014), the tax was rolled back [69] due to political and public resistance [70,71]. We explore the tax at two 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 [72].

Variation	Tax level on biomass	Note
#2 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 [68].
#3 200% of 2013-proposal	28.4 2012- EUR/MWh_{fuel}	Level chosen to illustrate the impact of highly increased 2013-biomass tax.

2.3.3 No biomass boilers – scenario 4

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 [73]. 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.

2.3.4 No biomass use – scenario 5

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 [74], while having clear intensions of deploying it only 9 years earlier [75].

2.4 Indicators for analysing barriers

The defined set of indicators is intended to cover a range of aspects relevant to policy makers, electricity transmission companies, DH stakeholders and end-users. The set of indicators aligns with indicators applied by Hedegaard and Münster [76]. To some degree also with Østergaard's overview of indicators [77] (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).

INDICATORS	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
Transmission	Society/state	the degree of transmission-use is impacted

The above indicators do not explicitly measure flexibility (as e.g. proposed by Lannoye et al. [78] or Flex4RES [20]), 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 [79].

The study is conducted as a *ceteris paribus* analysis, i.e. changing one parameter to indicate its impact in the energy system. The approach is used to explore impacts of isolated actions, as seen in Bloess et al. [6], which identifies four such ceteris paribus studies for heat pumps alone. Whitaker [80] justifies the use of ceteris paribus analysis through the following example: *in predicting with an econometric model it would be possible to make careful predictions of the changes in all exogenous variables that accompany a tax cut. But a failure to do so involves no logical inconsistency, and the resulting ceteris-paribus prediction of the tax cut's effects will still have substantive interest.*

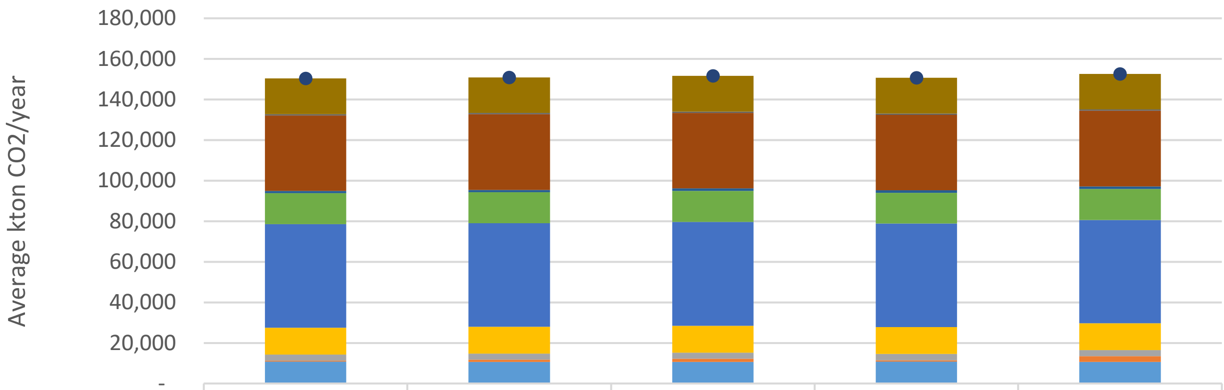
While we model the quantitative consequences of introducing constraints, we do not attempt to derive generalisable quantitative relationships between the introduction of a constraint and the scenario output on a certain indicator. The reason is the context-specificity of the Nordic energy system. Such perspective may be pursued in subsequent studies, based on the present study.

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%). While modelling results are obtained for all modelled countries, results are mainly presented for Denmark to show the national impacts of introducing Danish biomass-constraints.

3.1 Greenhouse gas emissions

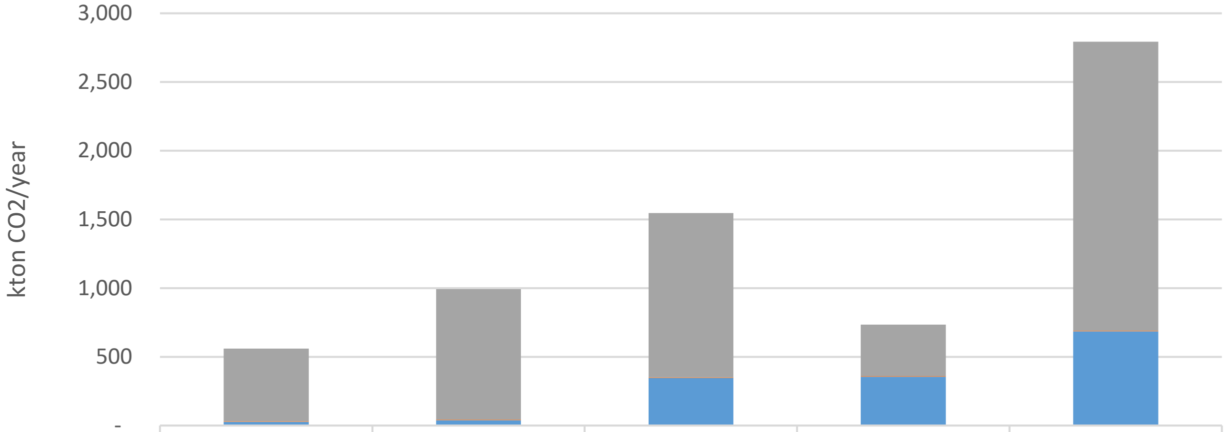
The Danish share of emissions is vanishingly small (*Base case*: 0.37% - Figure 7) in the system as a whole. That said, constraining biomass in Denmark results in broader energy system impacts by increasing overall emissions. Total emissions increase to 101.49% (*No biomass use*), corresponding to 2 244 kton/year.



	Base case	Bio tax 14.2	Bio tax 28.4	No biomass boilers	No biomass use
United Kingdom	17,650	17,529	17,535	17,576	17,536
Sweden	665	666	665	665	666
Poland	37,114	37,216	37,273	37,187	37,300
Norway	1,220	1,222	1,225	1,223	1,224
Netherlands	15,154	15,251	15,310	15,134	15,385
Germany	51,072	51,047	51,147	51,101	50,836
France	13,205	13,193	13,166	13,226	13,186
Finland	3,052	3,065	3,061	3,062	3,070
Denmark	559	993	1,547	735	2,794
Belgium	10,719	10,678	10,662	10,749	10,658
Grand Total	150,410	150,862	151,591	150,659	152,653

Figure 7 Average annual total CO_2-emissions in Northern Europe. Emissions are accounted in the country where they occur.

Danish national emissions increase in especially gas- and coal-based CHPs (Figure 8).



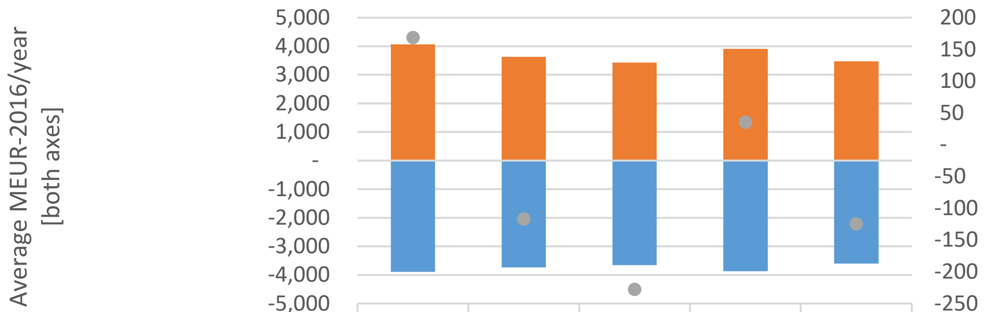
	Base case	Bio tax 14.2	Bio tax 28.4	No biomass boilers	No biomass use
CHP	526	949	1,197	376	2,103
Condensing	5	5	5	5	5
Boilers	28	40	345	354	686

Figure 8 Average annual Danish internally generated CO_2-emissions divided on generation technologies.

3.2 System costs, taxes and electricity grid tariffs

System cost (Figure 9) is aggregated of investment and operation, excluding energy taxes and electricity grid tariffs. *Bio tax 28.4* and *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.

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.

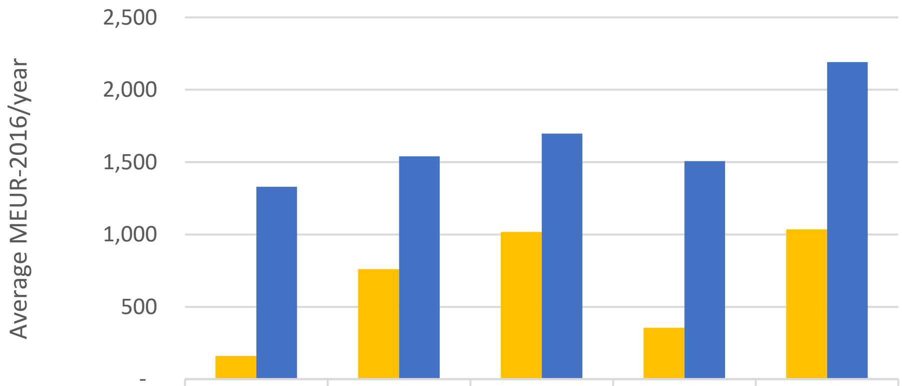


	Base case	Bio tax 14.2	Bio tax 28.4	No biomass boilers	No biomass use
Average annual system cost	4,061	3,625	3,432	3,911	3,472
Average annual electricity trade revenue	-3,893	-3,742	-3,660	-3,876	-3,597
Net annual system costs [Right axis]	169	-117	-228	35	-125

Figure 9 Average annual electricity trade impact on net annual system costs.

Tax revenue increases as constraints are added (Figure 10). Part of the increase is based in CO_2-taxes (increasing up to 5.7 times), but the major increase comes from fuel- and electricity taxes, increasing up to 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.

Relatively smaller increases are seen in electricity grid tariffs (up to 1.6 times), caused by increased electricity use in PtH.

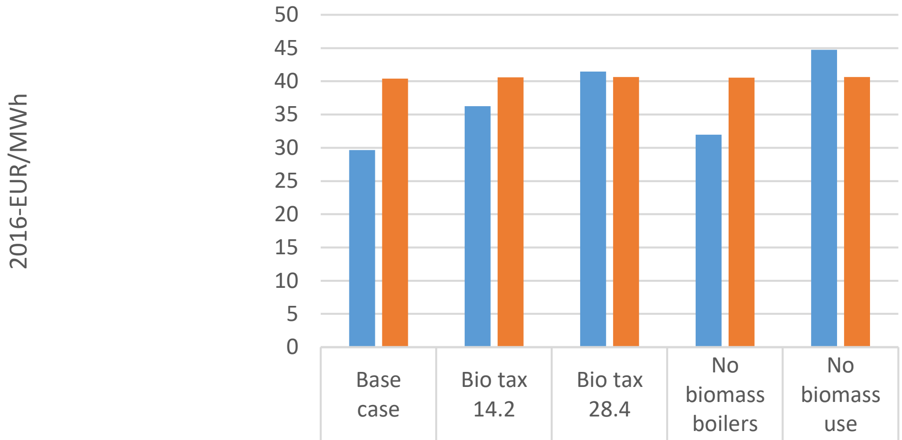


	Base case	Bio tax 14.2	Bio tax 28.4	No biomass boilers	No biomass use
Tax revenue	160	759	1,018	355	1,035
Tariff revenue	1,330	1,540	1,696	1,507	2,190

Figure 10 Average annual system cost, tax revenue and electricity grid tariff revenue.

3.3 End-user energy costs

Constraining biomass makes heat costs increase relatively more (up to 151% - Figure 11) than electricity (up to 101%). 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.

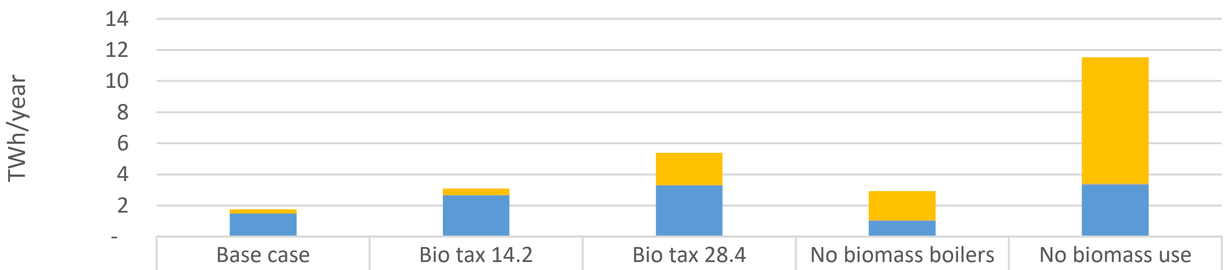


	Base case	Bio tax 14.2	Bio tax 28.4	No biomass boilers	No biomass use
Average cost per MWh heat	29.6	36.2	41.5	31.9	44.7
Average cost per MWh electricity	40.4	40.6	40.6	40.5	40.7

Figure 11 Average long run electricity and heat end-user cost.

3.4 Fuel use

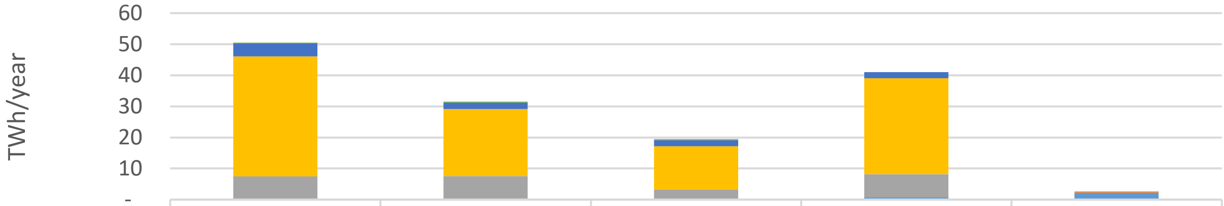
Use of fossil fuels follows a similar pattern (Figure 12) as seen regarding emissions in Section 3.1. Restrictions on biomass is compensated by use of natural gas and coal (fossil use increasing up to 6.6 times).



	Base case	Bio tax 14.2	Bio tax 28.4	No biomass boilers	No biomass use
Natural gas	0	0	2	2	8
Light oil	0	0	0	0	0
Fuel oil	0	0	0	0	0
Coal	1	3	3	1	3

Figure 12 Average annual fossil fuel use.

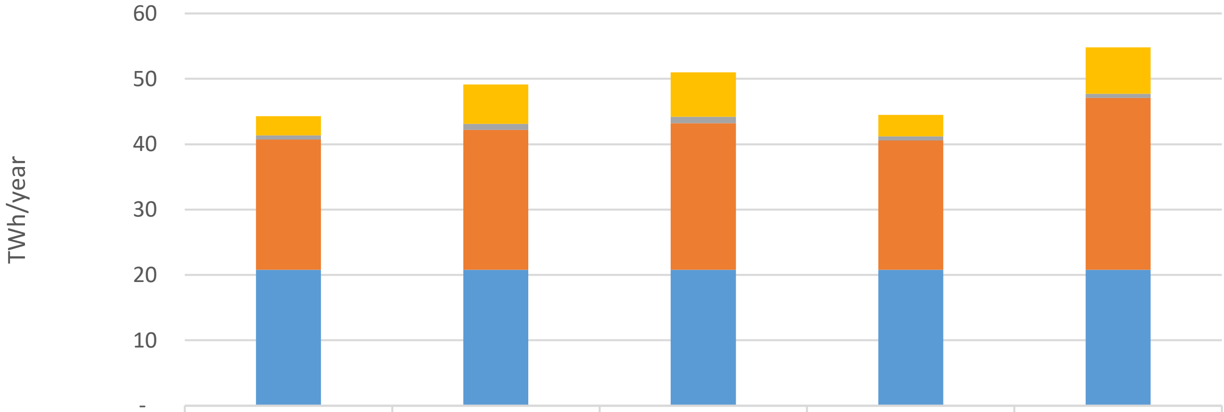
Unsurprisingly, biomass use is reduced in the biomass-constrained scenarios (Figure 13). Beyond the scenario *No biomass use*, which minimises biofuel use to small amounts of non-solid biomass (biogas and biooil), the biomass taxation scenarios shows the largest decrease.



	Base case	Bio tax 14.2	Bio tax 28.4	No biomass boilers	No biomass use
Woodwaste	0	0	0	-	-
Woodpellets	4	2	2	2	-
Woodchips	39	22	14	31	-
Straw	7	7	3	7	-
Biooil	0	0	0	0	0
Biogas	0	0	0	1	2

Figure 13 Average annual biomass fuel use.

Regarding VRE (Figure 14), offshore wind increases the most with a complete ban (132%). The largest relative increase (231-242%) is seen in solar thermal, resulting from *Bio tax 28.4* and the complete ban.

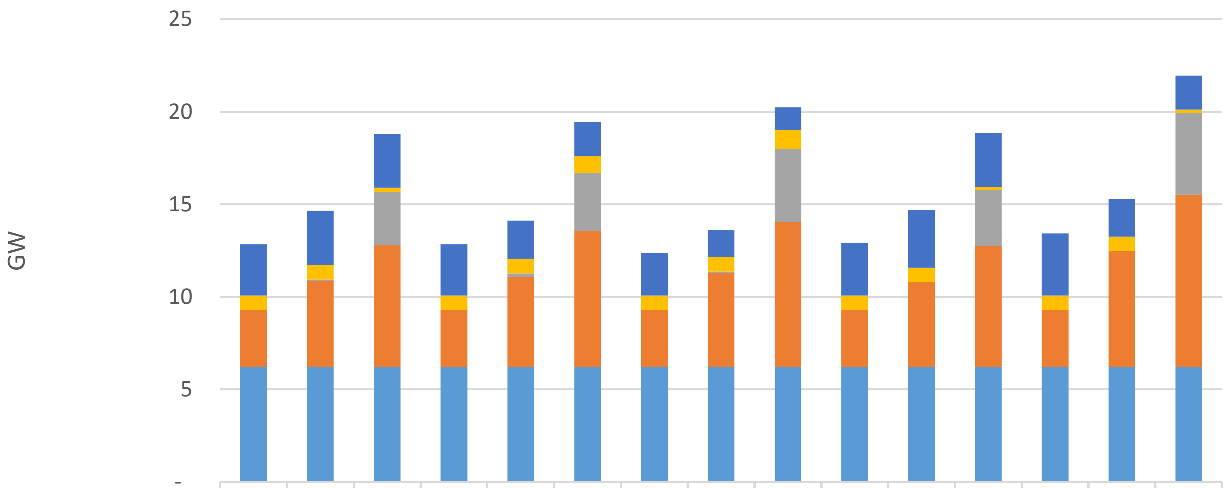


	Base case	Bio tax 14.2	Bio tax 28.4	No biomass boilers	No biomass use
Solar heating	3	6	7	3	7
Solar PV	1	1	1	1	1
Offshore wind	20	21	22	20	26
Onshore wind	21	21	21	21	21

Figure 14 Average annual variable renewable energy use.

3.5 Generating capacity

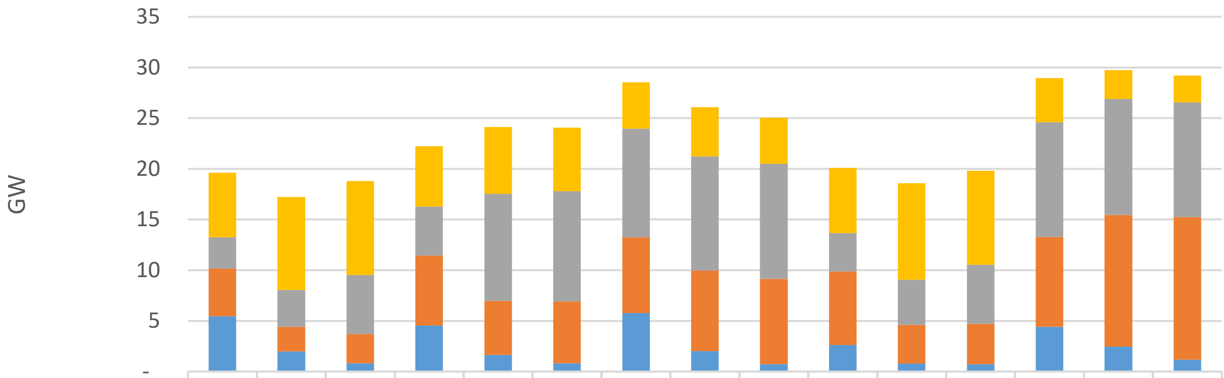
Electric capacities (Figure 15) over the period shows that onshore wind is fully utilised in all scenarios (as seen in Section 2.1: 6.2 GW total). Offshore wind capacity increases over the period, most pronounced in the highly constrained scenarios. CHP is mostly maintained, but trending downwards. Electricity storage sees significant deployment towards 2045 in all scenarios.



	Base case			Bio tax 14.2			Bio tax 28.4			No biomass boilers			No biomass use		
	2025	2035	2045	2025	2035	2045	2025	2035	2045	2025	2035	2045	2025	2035	2045
CHP	3	3	3	3	2	2	2	1	1	3	3	3	3	2	2
Solar PV	1	1	0	1	1	1	1	1	1	1	1	0	1	1	0
Electricity storage		0	3		0	3		0	4			3			4
Offshore wind	3	5	7	3	5	7	3	5	8	3	5	7	3	6	9
Onshore wind	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6

Figure 15 Generating capacity - electricity.

The most significant increase in heat capacity (Figure 16) is seen for solar thermal (e.g. *Bio tax 28.4*: 2025 – 346%) along with the introduction of biomass-constraints. Boiler capacity follows a downward trend in all scenarios, while CHP thermal capacity is highly dependent on scenario. While PtH increases in the most biomass-constrained scenarios, 2035 and 2045 display a reduction or levelling out among the less constrained scenarios. 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. TS is treated separately in the following section.



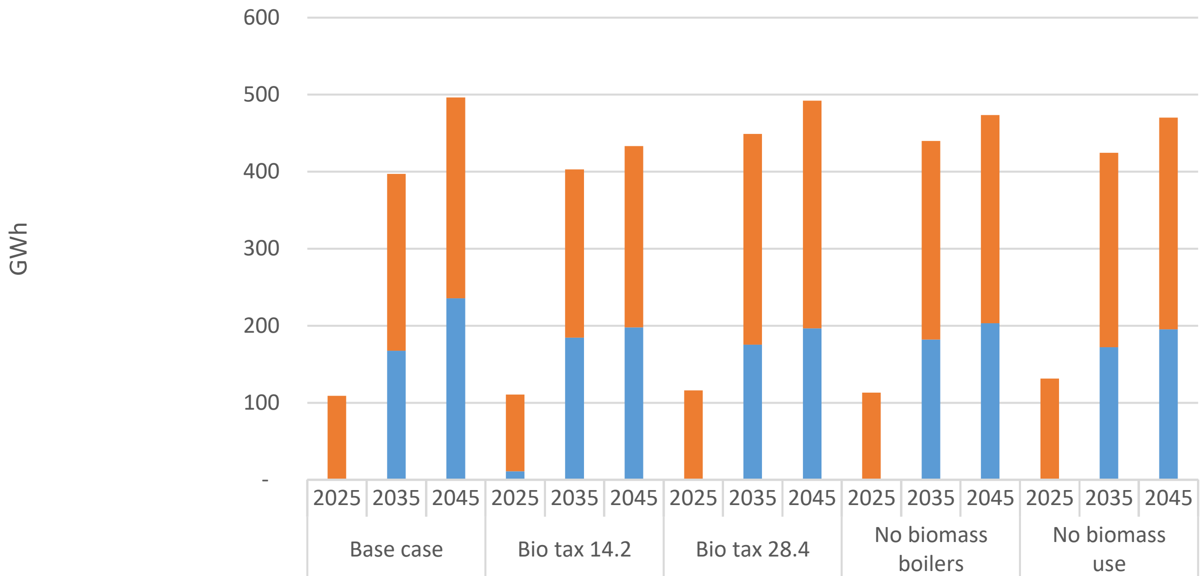
	Base case			Bio tax 14.2			Bio tax 28.4			No biomass boilers			No biomass use		
	2025	2035	2045	2025	2035	2045	2025	2035	2045	2025	2035	2045	2025	2035	2045
CHP	6	9	9	6	7	6	5	5	5	6	10	9	4	3	3
Solar thermal	3	4	6	5	11	11	11	11	11	4	4	6	11	11	11
Power-to-heat	5	2	3	7	5	6	7	8	8	7	4	4	9	13	14
Boiler	5	2	1	5	2	1	6	2	1	3	1	1	4	2	1

Figure 16 Generating capacity - heat.

3.6 Energy storage

The constraints on biomass use leads to a mixed picture on deployment of storage (Figure 17). 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.



	Base case 2025	Base case 2035	Base case 2045	Bio tax 14.2 2025	Bio tax 14.2 2035	Bio tax 14.2 2045	Bio tax 28.4 2025	Bio tax 28.4 2035	Bio tax 28.4 2045	No biomass boilers 2025	No biomass boilers 2035	No biomass boilers 2045	No biomass use 2025	No biomass use 2035	No biomass use 2045
Intraseasonal heat storage	109	229	261	100	219	235	115	274	296	113	258	270	131	252	275
Interseasonal heat storage		168	235	11	185	198	1	175	197		182	203	1	172	195

Figure 17 Inter- and intraseasonal TS.

3.7 Electricity transmission

Electricity transmission capacity (Figure 18) is largely unaffected by the biomass constraint. In contrast, 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).

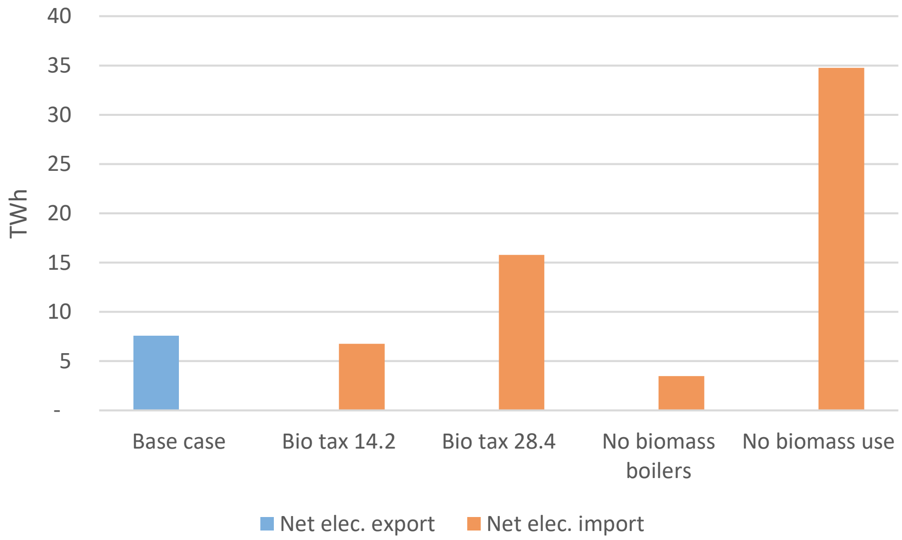


Figure 18 Electricity net export and import.

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 19, 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 fivefold, while a biomass tax of 28.4 2012-EUR/MWh reduces total system cost to a net positive revenue of 228 MEUR-2016/year. A ban on biomass boilers has the least overall reduction in system cost (21%) and least increase in emissions (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.

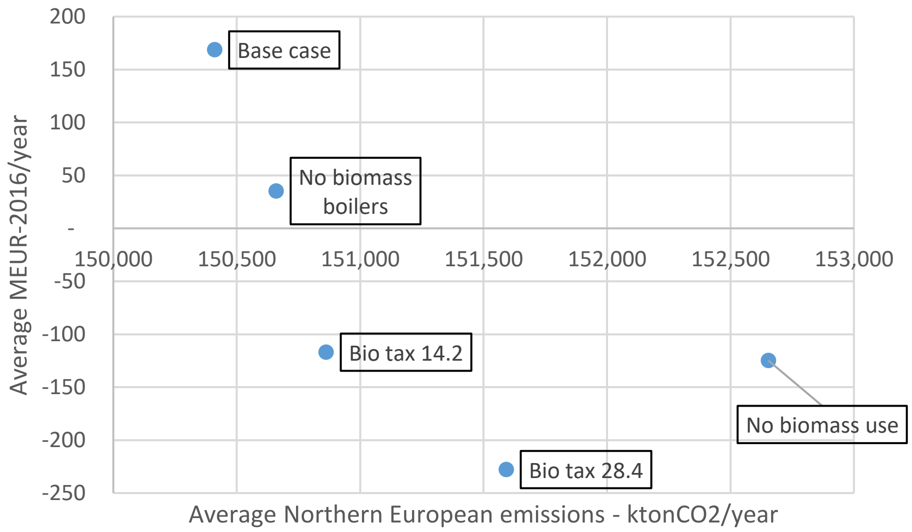
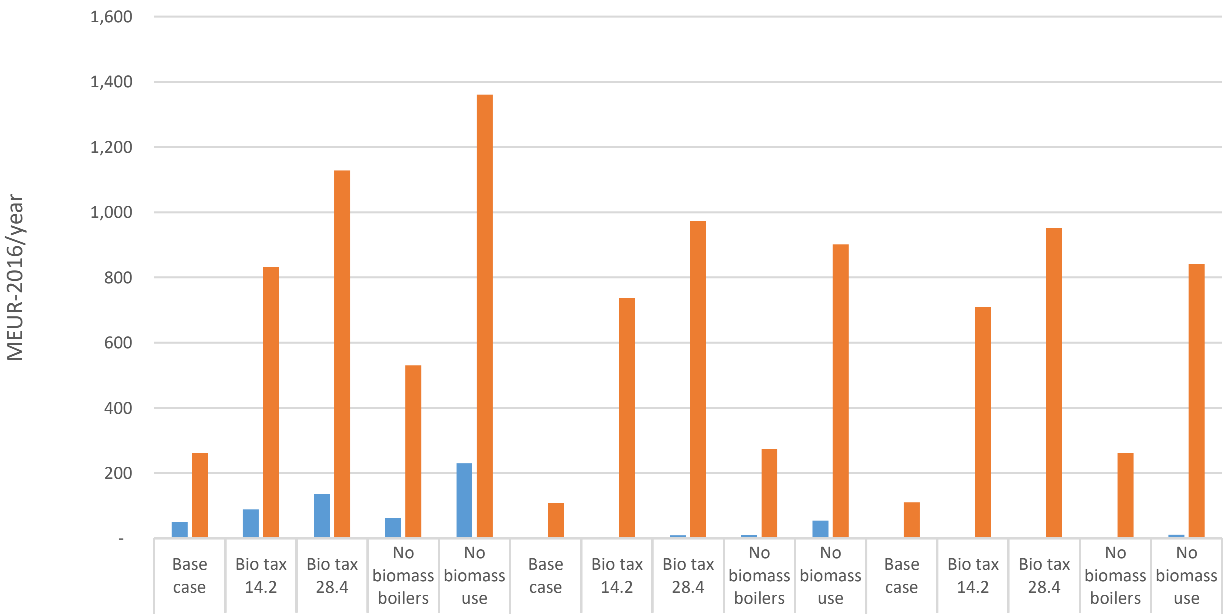


Figure 19 Average annual CO_2-emissions and Danish system costs, net of electricity trade.

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 [20]).

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. From an economic perspective, this is feasible at all the CO_2-price levels of respectively 2025, 2035 and 2045 – see Figure 20.



	2025					2035					2045				
	Base case	Bio tax 14.2	Bio tax 28.4	No biomass boilers	No biomass use	Base case	Bio tax 14.2	Bio tax 28.4	No biomass boilers	No biomass use	Base case	Bio tax 14.2	Bio tax 28.4	No biomass boilers	No biomass use
Mitigation cost	50	88	136	63	231	2	3	9	10	54	-	-	-	-	11
Tax revenue	261	832	1,128	530	1,361	108	736	973	273	902	110	710	953	263	842

Figure 20 Tax revenue and potential CO_2 mitigation costs.

Electricity grid tariff revenue increases in all scenarios, as the share of PtH increases. While no detailed analysis has been conducted on distribution grid deployment in this study, it is expected that the increased tariff revenue will be necessary to cover grid reinforcements for deployment of PtH.

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 [81]), 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. [32]. 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 [82], this is not the case here. Further analysis should clarify whether this is a result of the time-steps used in the modelling. If not, 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 [21] 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 [83]. The *Base case* slightly exceeds this (182 PJ/year) while the constrained scenarios are within these bounds (9-148 PJ/year).

Figure 21 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. Thus, the correlation coefficient between CHP and respectively PtH and solar thermal is -0.95 and -0.97, indicating strong inverse relations in these scenarios. This nuances an argument by Mathiesen et al., who underline the importance of combined use of CHP, solar thermal and PtH, to reduce biomass-use [17]. In a later study, Lund and Mathiesen 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. [84]. Boilers display similar tendency, but to a lesser extent as they decline in all scenarios.

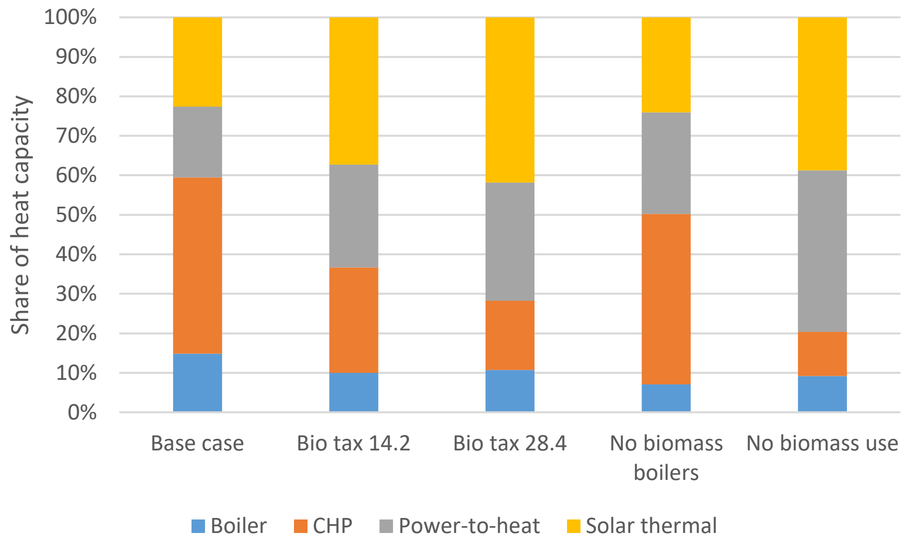


Figure 21 Indication of relationships between capacities of boilers, CHP, solar thermal and PtH. Share of total heat capacity in model years 2025-2035-2045.

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 [85] 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.

The visual summary in Figure 22 aggregates 13 indicators by indexing the scenario values presented in section 3. The summary is not intended to be normative in terms of indicating the preferred scenario, but it enables a comparison of scenarios. The comparison shows that a complete ban on the use of biomass would have the highest impact on 9 of the 13 indicators 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. Based on review of fully renewable energy system-studies, Mortensen et al. [86] argue that a combination of hydrogen use and electrification may be the most efficient measure to reduce biomass use to stay within sustainable biomass use levels. Such an approach may indeed lead to similar reductions in biomass use as in our study, without the strong constraint on biomass use. Introducing constraints on biomass use increases system emissions, tax- and tariff revenue, heat prices, electricity demand, fossil- and VRE use, and capacities of TS and PtH. Conversely, biomass constraints reduce Danish system costs and overall fuel- and biomass use. Lund and Mathiesen [18] confirms the latter finding, pointing out that left to market prices alone, i.e. without biomass constraints, biomass use reaches the highest level among their analysed scenarios.

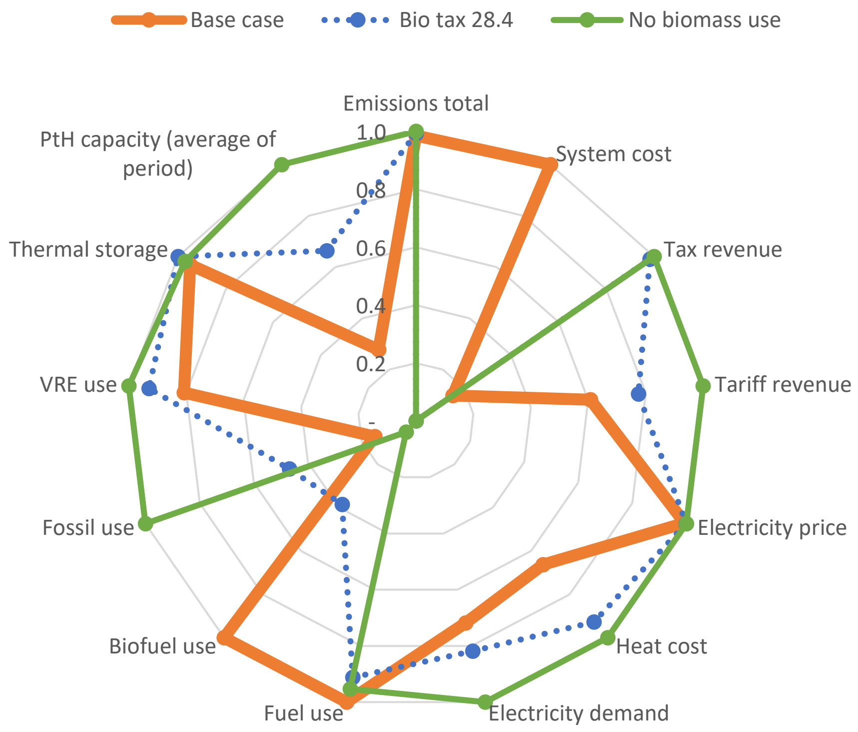


Figure 22 Visual summary of indexed impacts on 13 selected indicators in selected scenarios. Scenarios with net positive system cost have been set to 0.

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, the present analyses are limited by several factors, including the

- assumptions of economic rationality, perfect competition, or the perfect foresight within the year
- temporal perspective, where model-runs are conducted for 4 seasonally representative weeks to reduce computation time. This may, among other things, impact the findings on thermal storages. Can 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 [87] regarding heat savings and and Möller and Lund on DH expansion [88]. 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 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 [7,89]. This could be defined exogenously, based on statistical data
- the study is conducted as a ceteris paribus analysis, limiting the insight into combined impacts of e.g. intertwined policy actions. Next steps may thus include exploration of sensitivities (e.g. through Morris method).
- assumptions on absent non-combustion emissions from the applied technologies. E.g. biomass (CHP/boilers), leakages of refrigerants (heat pumps) and methane (natural gas CHP).

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 show 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 may not 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 may not 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* have equal VRE in 2025 and 2035)
- Constraining biomass use may increase PtH and 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 Denmark [90], Sweden [35,36], Nordics [33] and EU [37]) 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, 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* [91]) and the Danish Energy Agency's Guidance to socioeconomic analyses on energy [92], which both have significant impacts on the deployment of DH technologies in Denmark. Finally, the significant deployment of TS merits further study, since the four weeks applied in this analysis may somewhat skew the picture regarding the seasonality and use of especially the large TS.

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.

Juan Gea-Bermúdez acknowledges the NSON-DK and Flex4RES projects funded by the Danish Energy Agency, EUDP (grant 64018-0032; previously ForskEL) and Nordic Energy Research (grant76084), respectively.

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] Lund R, Mathiesen BV. Large combined heat and power plants in sustainable energy systems. Appl Energy 2015;142:389–95. doi:10.1016/j.apenergy.2015.01.013.

[19] Energinet. Model Analysis of Flexibility of the Danish Power System. 2018.

[20] Skytte K, Bergaentzlé C, Fausto F, Gunkel P, Flex4RES. Flexible Nordic Energy Systems - Summary Report. Lyngby: 2019.

[21] 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.

[22] 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.

[23] 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.

[24] 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.

[25] 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.

[26] 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.

[27] 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.

[28] 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.

[29] 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.

[30] 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.

[31] The Danish Energy Agency. Tabeller - Energistatistik 2018 [Tables Energy statistics 2018] 2019.

[32] 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.

[33] Tunberg M, Hansson P. Sustainable use of biomass for heating and transport fuel. Oslo: 2020.

[34] IRENA, IEA, REN21. Renewable energy policies in a time of transition - Heating and Cooling. 2020.

[35] 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).

[36] 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).

[37] 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).

[38] Scarlat N, Dallemand J-F, Taylor N, Banja M, Sanchez Lopez J, Avraamides M. Brief on biomass for energy in the European Union. EC Publ 2019:1–8.

[39] 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.

[40] Balmorel Community. Balmorel Model. GitHub n.d. https://github.com/balmorelcommunity/Balmorel (accessed March 27, 2020).

[41] 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).

[42] Gea-Bermúdez J, Pade LL, Koivisto MJ, Ravn H. Optimal generation and transmission development of the North Sea region: Impact of grid architecture and planning horizon. Energy 2020;191:116512. doi:10.1016/j.energy.2019.116512.

[43] 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.

[44] Gea-Bermúdez J, Graested Jensen I, Münster M, Koivisto M, Kirkerud JG, Chen Y-K, et al. The role of sector coupling in the green transition: A least-cost energy system development in North Europe towards 2050. TechRxiv 2020.

[45] Flex4RES. Flex4RES – Nordic Energy Research. Flex4RES Proj Website 2019. https://www.nordicenergy.org/flagship/flex4res/ (accessed March 28, 2020).

[46] 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.

[47] 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.

[48] 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.

[49] 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).

[50] 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).

[51] 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.

[52] Koivisto M, Gea-Bermudez J. NSON-DK energy system scenarios – Edition 2. 2018.

[53] 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.

[54] 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/.

[55] The Danish Parliament. Energy Agreement of 29 June 2018 2018:1–19.

[56] 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.

[57] 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.

[58] 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.

[59] 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.

[60] 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).

[61] Ruhnau O. The Impacts of Electricity-Heat Sector Coupling on the Power System Integration of Variable Renewable Energy Sources 2017.

[62] 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).

[63] 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).

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

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

[66] 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.

[67] 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.

[68] The Danish Ministry of Taxation. Beskrivelse af model for forsyningssikkerhedsafgiften [Description of model for the security of supply tax] 2013.

[69] 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.

[70] 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).

[71] 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).

[72] 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.

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

[74] Gyldenkilde L. Folketingsbeslutning om offentlige energiplanlægning uden atomkraft [Parliament decision on public energy planning without nuclear energy] 1985;B 103.

[75] Ministry of Commerce. Dansk energipolitik 1976 [Danish Energy Policy 1976]. Copenhagen: 1976.

[76] 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.

[77] 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.

[78] 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.

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

[80] Whitaker JK. Ceteris Paribus. New Palgrave Dict. Econ., London: Palgrave Macmillan UK; 2008, p. 1–4. doi:10.1057/978-1-349-95121-5_346-2.

[81] 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.

[82] PlanEnergi. Long term storage and solar district heating. Skørping: 2015.

[83] 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.

[84] 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.

[85] 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.

[86] Mortensen AW, Mathiesen BV, Hansen AB, Pedersen SL, Grandal RD, Wenzel H. The role of electrification and hydrogen in breaking the biomass bottleneck of the renewable energy system – A study on the Danish energy system. Appl Energy 2020;275. doi:10.1016/j.apenergy.2020.115331.

[87] 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.

[88] 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.

[89] Detlefsen N. Specialregulering i fjernvarmen. Kolding: 2016.

[90] Nielsen AT, Bentsen NS, Nord-Larsen T. CO2 emission mitigation through fuel transition on Danish CHP and district heat plants. Copenhagen: 2020.

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

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