TECHNICAL ARTICLE

Coupling Variable Renewable Electricity Production to the Heating Sector through Curtailment and Power-to-heat Strategies for Accelerated Emission Reduction

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The Paris Climate Accord and recent IPCC analysis urges to strive towards carbon neutrality by the middle of this century. As most of the end-use energy in Europe is for heating, or well above 60%, these targets will stress more actions in the heating sector. So far, much of the focus in the emission reduction has been on the electricity sector. For instance, the European Union has set as goal to have a carbon-free power system by 2050. Therefore, the efficient coupling of renewable energy integration to heat and heating will be part of an optimal clean energy transition. This paper applies optimization-based energy system models on national (Finland) and sub-national level (Helsinki) to include the heating sector in an energy transition. The models are based on transient simulation of the energy system, coupling variable renewable energies (VRE) through curtailment and power-to-heat schemes to the heat production system. We used large-scale wind power schemes as VRE in both cases. The results indicate that due to different energy system limitations and boundary conditions, stronger curtailment strategies accompanied with large heat pump schemes would be necessary to bring a major impact in the heating sector through wind power. On a national level, wind-derived heat could meet up to 40% of the annual heat demand. On a city level, the use of fossil fuel in combined heat and power production (CHP), typical for northern climates, could significantly be reduced leading even close to 70% CO_2 emission reductions in Helsinki. Though these results were site specific, they indicate major opportunities for VRE in sectoral coupling to heat production and hence also a potential role in reducing the emissions.

Keywords: power-to-heat; energy system flexibility; urban energy system

Introduction

Renewable energies play an important role in climate change mitigation (International Energy Agency 2017). When introduced massively, integration of renewables on a different scale from stand-alone buildings to cities and nations or regions will be necessary. The challenges ahead with the decarbonization of the energy systems are huge as major part of the carbon emissions needs to be eliminated by the middle of this century. For example, the European Union has planned to reduce its emissions by about 80% to 95% and to reach a 55% share of renewable energy in final energy consumption by 2050 (Oettinger 2012). In addition to carbon emission reductions, access, security, reliability, and affordability need to be addressed in the energy transition (Dastur 2009).

While the clean energy transition is often dominated by variable renewable electricity sources such as solar PV and wind power for power production, the future focus needs also to better include the heating sector, as most of the final energy use is in the form of thermal energy. For example, in Finland over 80% of the final energy use of households is for heating and domestic hot water (Statistics Finland 2018). In Helsinki, which is the capital of Finland, heat constitutes 60% of whole energy production (Lund, Mikkola and Ypyä 2015). Therefore, the role of the built environment in the energy transition will also be important to be considered; measures of interest include building energy efficiency and on-site renewable energy generation (Lund 2012, Cao et al. 2013, Kayo et al. 2014, WBCSD 2009).

Another interesting development is the need to increase energy system flexibility when the share of variable renewable electricity (VRE) increases, which may include measures such as curtailment of VRE for better energy system management, but also to supply heat through power-to-heat (P2H) conversion e.g. when surplus of VRE were available (Lund et al. 2015, IEA 2008, IEA 2009). One may also foresee 'oversizing' VRE for the power sector needs to provide high coverage of power demand with VRE during less favorable condition, but then use the surplus or curtailed power at favorable conditions for heating purposes. This would mean increased electrification of the heating sector, and if linked to e.g. heat pumps, providing large amounts of renewable-derived heat to end-users.

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This kind of sectoral coupling of VRE would increase the energy system flexibility, but reduce emissions in the heating sector as well. Efficient VRE integration has been studied from different aspects (Bessa 2014, Brown 2013, Galus 2013, Sharif 2014, Gao 2008). Other measures such as energy storage and demand response could also be used in this context (Arabzadeh et al. 2018, Lund 2018).

The novelity of the current study is examining of the VRE coupling with the heating sector using different curtailment strategies not yet reported in the literature, in particular for both the national and city level production systems which are included in this study. For the national level analysis, we use Finland as the case to see how the whole heat production portfolio would change with adding large wind power schemes with sector-coupling to heat through curtailment and P2H. For the sub-national level, we use Helsinki city as the case. In this case, considering the energy system in more detail than the national scale will be important, enabling then to assess how the different VRE curtailment schemes may affect the power plant uses. In particular, existing CHP-based energy production system, which is typical for northern cities such as Helsinki, is analyzed, including the running costs and emissions on a yearly scale. Also, the effects of different energy system limitations and building energy efficiency schemes are analyzed.

Methodology

The methodology employed in the study is based on a techno-economic optimization of the energy system, i.e. finding the system configuration which yields the minimum cost under different boundary conditions and limitations. We consider both national (Finland) and sub-national (Helsinki city) levels of the energy production system, for which different optimization techniques will be applied. As clean energy transitions often involve large renewable electricity usage, we take here as the starting point a large wind power scheme. This will be accompanied by different curtailment strategies and power-to-heat conversion to produce carbon-free heat, which is of importance in northern latitudes. Curtailment may also be justified by energy system limitations and power market conditions, thus providing better energy system management.

National model

The national-level analysis is done with a macro-scale energy system model (Pilpola and Lund 2018). The model includes all aspects of an energy system, including electricity, heat, and fuels, thus covering all energy sectors. The model employs a 1-hour step for electricity and heat, while fuel demands are considered on an annual scale. The model seeks for a cost-optimal solution of the energy system while keeping the supply-demand at balance. The optimization problem is defined by Equation (1):

$$Minimize\ Total\ Annual\ Cost = \sum_{t=1}^{tech}(Investment\ cost_t + O\,\&\,M_t) + \sum_{t=1}^{fuels} Fuel\ cost_f + Net\ cost\ of\ power\ import + Emission\ costs \quad (1)$$

The variables in the optimization are the amounts of the fossil primary energy sources and the amounts of conventional conversion, i.e. combined heat and power (CHP), separate production, and heat pumps (HP). The main optimization outputs are the primary energy composition and power and heat production, while the main inputs are historical consumption and temporal data, cost assumptions, and system constraints. The model uses year 2013 as the reference year for input data. A more detailed description of the input data can be found in (Pilpola and Lund 2018). The reference case for the heating sector of interest is shown in **Table 1**.

The hourly distribution of the conventional production, such as CHP, is based on historical production data (2013) to mimic the hourly distribution, but their values are scaled to the yearly amounts of energy (PJ, TWh) resulting from the optimization. The operation of the power-to-heat conversion is rule-based, e.g. linked to VRE levels. The level of industrial CHP and residential heat production (fuel and electric boilers), which accounted for 43% of the heat demand in 2013, are assumed non-variable. The model employs three methods for wind power curtailment (described separately). The model also assumes 60 GWh thermal storage available through the Finnish district heating networks filled with water.

Sub-national model

The objective of the sub-national (city) model is to reduce the marginal costs of the local energy production system while introducing variable renewable electricity. The model is based on an optimizer core frame, minimizing a cost function, which is the sum of the production costs, balancing costs, storage costs, and revenues from electricity sales to the Nordic power exchange. Equation (2) shows the cost function:

$$Minimize\ \sum_t(Production\ costs + Balancing\ costs + Storage\ costs - Revenues\ from\ sales) \quad (2)$$

The details of the model are described in (Mikkola and Lund 2016). The model includes 3 main sets of constraints: the technical properties of the power plants, technical properties of the balancing methods, and the balance of energy demand and supply. Therefore, the frame is appropriate to model the energy production system. We also incorporated several modifications to the original model to enable a heating sector analysis as follows: Firstly, a limitation for heat storage charging and discharging was defined. Secondly, to account for possible heat source restrictions in case of large heat pump schemes with P2H conversion, we defined a dynamic COP, which drops when entering the peak heat demand period (HP has a COP = 3 whenever the heat demand is <50% of the peak heat demand; COP = 2 for heat production between 50% and 70% of the peak demand; COP = 1, i.e. HP is replaced with an electric boiler, when heat demand is >70% of the peak demand). The annual heat demand in Helsinki (60°N) is 6.6 TWh and the electricity use is 4.4 TWh. Two energy

Table 1: Heat production in Finland in 2013 (Statistics Finland 2017).

	CHP-District heating	CHP-Industrial	Separate thermal production	Residential fuel boilers	Residential electric boilers	Heat pumps	Total
TWh	32.6	3.8	14.6	20.2	14.4	4.6	90.3
%	36	4	16	22	16	5	100

efficiency strategies in buildings will be considered leading to 8% and 16% lower heating demand, respectively. The heat demand profiles will be modified accordingly in these cases by using a scaled U-value for the temperature-dependent part of the heat load. The details of the present energy production plants in Helsinki are shown in **Table 2** (Mikkola and Lund 2016). In addition, the district heating system has 5 GWh of storage capacity through its piping network, which can be employed for storing curtailed power in from of thermal energy.

Curtailment cases

Three different methods for wind energy curtailment will be employed, illustrated in **Figure 1**. "Peak-shaving" curtailment is based on shaving a fixed percentage of the wind power peaks. In "Wind-following", wind power is curtailed with a constant fixed percentage. In "Load-following", wind power is curtailed above a fixed level (percentage) of the electrical load. The curtailed wind power is used with a power-to-heat (P2H) strategy, i.e. all curtailed wind power will be directed to heat pumps. As wind power is a renewable and zero-marginal-cost resource, we argue that the heat produced by this "forced" heat pump operation offers a renewable and low-cost, albeit non-dispatchable, source of heat, which in turn may have the possibility to decrease the marginal costs of energy production. In the sub-national level, the forced implementation of the HP, limits the available HP capacity for the dispatch optimization.

Results

In this section, we analyze the effects on the heat production system when applying large wind power schemes and curtailment with the P2H conversion. On the national level, the effect of each curtailment method is discussed in term of system operation and energy conversion. On the sub-national level, the focus is on the heating demand profile modification through building energy efficiency measures in addition to heat resource limitations for heat pumps.

National case

In the national case, the three wind power curtailment strategies described previously resulted in very different levels of curtailed wind power shown in **Table 3**. Two levels of wind power use were investigated: 20 TWh and 40 TWh, corresponding to 24% and 48% of the yearly electricity use of Finland. The "Peak-shaving" strategy yielded the least heat, even at a high curtailment level. The "Load-following" did not produce any heat with 20 TWh of wind, but clearly more with 40 TWh than the "Peak-shaving" strategy. "Wind-following" gave the highest level of curtailment: With 30% curtailment and 40 TWh of wind it resulted in 36 TWh of heat production, which would account for 40% of the total annual heat demand. Note that the curtailed wind power was used in heat pumps (COP = 3). **Figure 2** shows the change in the heat production mix caused by the different curtailment and P2H schemes. The reference case is Finland in 2013, based on historical data. Most cases exhibited increased CHP production (particularly coal-CHP if the CO_2 and fuel cost remain low) and decreased separate heat production. As decrease of boiler use was also observed in the cases without curtailment and P2H, it can be stated that this effect was caused by the overall cost optimization, suggesting that with increasing wind power, replacing separate heat boilers with CHP may be cost-effective even without any additional P2H measures. However, including curtailment+P2H would emphasize the role of the heat pumps, i.e. the HP heat production increased in all cases with wind power curtailment. The increase in heat pump production was partly caused by the "forced" wind power curtailment strategy, but also partly by the overall cost optimization. Some CHP would, however, remain despite the increased HP production due to the economic reasons: it may be cost-effective to produce CHP-based electricity to be exported to international markets, even if that may simultaneously lead to oversupply of heat.

Figure 2 also illustrates that in cases of a higher amount of wind-power driven ("forced") heat pump operation, the net change of heat production is positive. As the overall heat demand stayed constant in all cases, this positive net change suggests that part of the additional heat production was wasted. In the "Wind-following" curtailment case, heat production was up to 20 TWh higher than the demand. A part of the excess heat production may appear in the losses of thermal storage, but clearly forced, non-dispatchable heat pump operation was not always able to match the heat demand, which leads to oversupply of heat. Some of the surplus heat could, however, disappear if the COP of the heat pumps were lower than anticipated, which could occur in particular during the peak heating season. Increasing the thermal storage capacity could also help to mitigate the heat surplus.

Sub-national case (Helsinki)

For the sub-national level, the effect of heating demand improvement (energy efficiency), wind curtailment, and heat source limitations of heat pumps were investigated through four scenarios:

1. Current energy system (90 MW HP, no curtailment, no heat resource limitation);
2. 1500 MW of heat pumps, no curtailment, no heat

Table 2: Nominal output of energy plants in Helsinki (MW).

	CHP gas	CHP coal	CHP coal	Boiler gas	Boiler Oil	Boiler Coal	HP
Power	630	220	160	–	–	–	–
Heat	580	420	300	360	1900	180	90

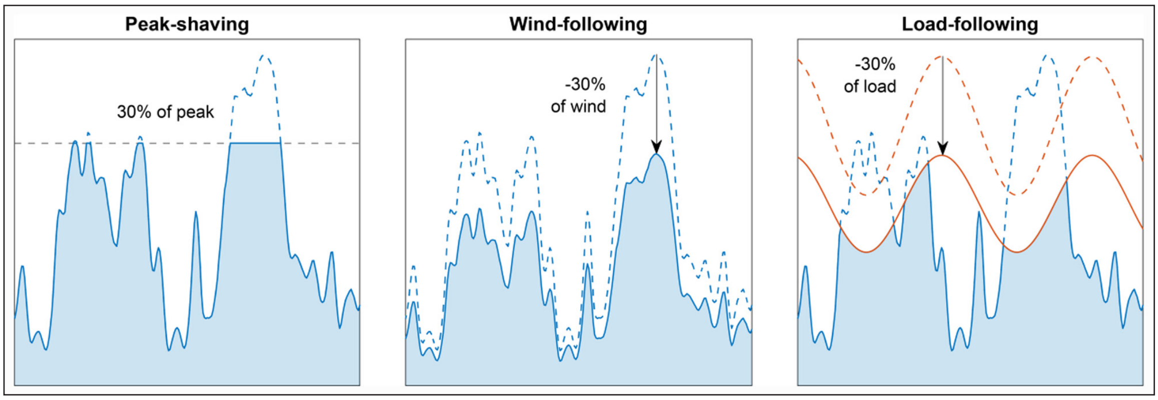

Figure 1: Schematic illustration of the different wind power curtailment methods using a curtailment rate of 30% as an example.

resource limitation;

3. 1500 MW of heat pumps, 30% curtailment, no heat resource limitation;
4. 1500 MW of heat pumps, 30% curtailment, dynamic COP (heat source limitation).

In all scenarios, building energy efficiency improvements are applied: present building U-value is improved by 10% and 20% leading to 8% and 16% lower heat demand, respectively. The building energy efficiency improvement reflects the potential for energy efficiency in the old building stock, typical to Helsinki. The necessary measures could typically involve better thermal insulation, improved heating control, and/or better windows in the building stock. Moreover, 750 MW and 1500 MW of wind power was introduced to the energy production system, representing 43% and 86% of the yearly electricity demand in Helsinki, respectively. The 1500 MW heat pump scheme covers almost 50% of the peak heat demand, the rest of the peak being supplied through boilers. For comparison, the yearly fuel costs and CO_2 emissions are compared with the present system with no measures, for which the system parameters are given in **Table 2**. The results for Scenario 1 are shown in **Table 4**. In this section, in all figures, the term "norm" means heat production with heat pump by electrical power and "curt" means the produced heat with heat pump by curtailed wind power.

Wind power alone would mainly reduce the gas use, but not coal, because of the need to meet the heat demand (coal-CHP produces more heat than gas-CHP). Also, the price difference between coal (€43/MWh) and gas (€56/MWh) would slightly favor coal. No emission cost was applied, but e.g. a €15/MWh CO_2 cost would not change the results due to these system limitations. Wind power would therefore mainly reduce the fuel costs, but marginally the emissions in the Helsinki case with the assumptions used.

Building energy efficiency measures in cases 4 and 6 gave the best results with cost reductions of 19% and 26% and emission decreases of 7% and 12%, respectively. Detailed heat and electricity production are shown in **Figure 3**, which clearly demonstrates that most of the wind power would go to export to the Nordic power exchange. Note that Helsinki presently produces more electricity than it needs, i.e. some 40% is sold to the market (export).

In Scenario 2, 1500 MW of heat pumps is added to Scenario 1. Neither curtailment nor limitation of heat sources for heat pumps is included here. **Table 5** presents the key results.

Adding a large heat pump scheme would significantly reduce the yearly fuel costs and emissions, whereas adding building energy efficiency measures on the top of that had less effect. In the best case 6, the fuel costs and emission dropped by 55% and 58%, respectively. **Figure 4** demonstrates details of the energy production for the Scenario 2. There are slight differences only between cases 4 and 6, which indicates that reducing the heat demand from 8% to 16% does not have any major effect on the operation of the energy production system. Integration of the wind power reduces the gas electricity production by about 42% and the coal electricity production about 70%, respectively. The gas heat production is reduced by 31% and coal heat production is cut 77%. The HP heat production increases by 70%. The heat storage use increased by 70%, i.e. the number of charging-discharging cycles of the 5 GWh capacity in the DH network increased substantially.

In Scenario 3, wind energy curtailment was introduced to Scenario 2. The resulting fuel cost and emissions are in **Table 6**.

Figure 5 demonstrates the details of the effects on the energy production system. The largest reductions in the fuel cost and emissions were for case 6, 66% and

Table 3: Heat pump production with curtailed wind power in the national case.

Wind power before curtailment (TWh)	Curtailment rate (%)	Curtailment method		
		Peak-shaving (TWh)	Wind-following (TWh)	Load-following (TWh)
20 TWh	10	0.1	6.0	0.0
	30	2.2	18.0	0.0
40 TWh	10	0.1	12.0	4.6
	30	4.3	36.0	14.0

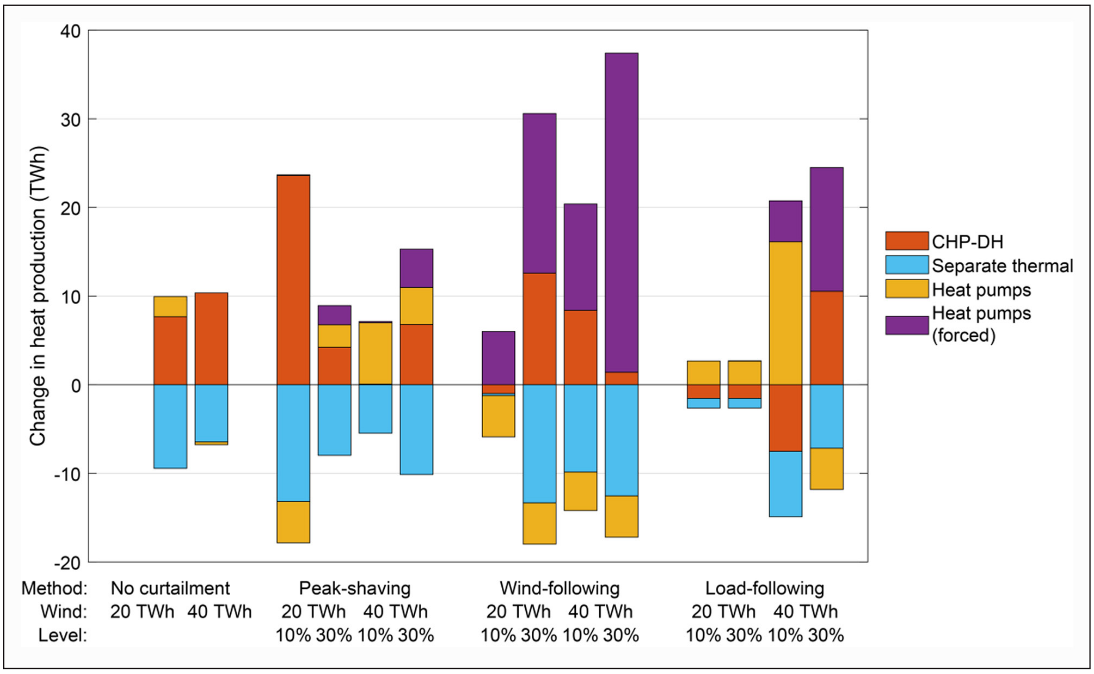

Figure 2: Change in the heat production compared to the national reference case (Finland 2013). "CHP-DH" refers to district heating CHP. Heat pump operation is divided into normal heat pump operation and "forced" heat pump operation using the curtailed wind power.

Table 4: Annual CO_2 emissions and fuel cost for different building energy efficiency improvements in the present energy system of Helsinki (Scenario 1).

Case	Heat demand reduction (%)	Wind (MW)	Fuel cost (M€/yr)	Emissions ($ktCO_2$/yr)
Present system	–	–	327	2271
1	–	750	296	2232
2	–	1500	288	2210
3	8	750	273	2137
4	8	1500	264	2112
5	16	750	250	2027
6	16	1500	239	2000

68%, respectively, when the "Load-following" curtailment method was used, though the difference to "Wind-following" curtailment was small. The heat production by coal was dramatically cut to less than 10% of the yearly heat production (–84%); the gas use dropped below 30% (–47%), respectively. The reduced coal and gas use lead to significantly reduced emissions (66-68% from the present). Heat pumps are the dominating heat production method in cases 4 and 6, which leads to a slight increase in electricity imports.

In Scenario 4, we added a heat source limitation to heat pumps by using a dynamic COP explained earlier to

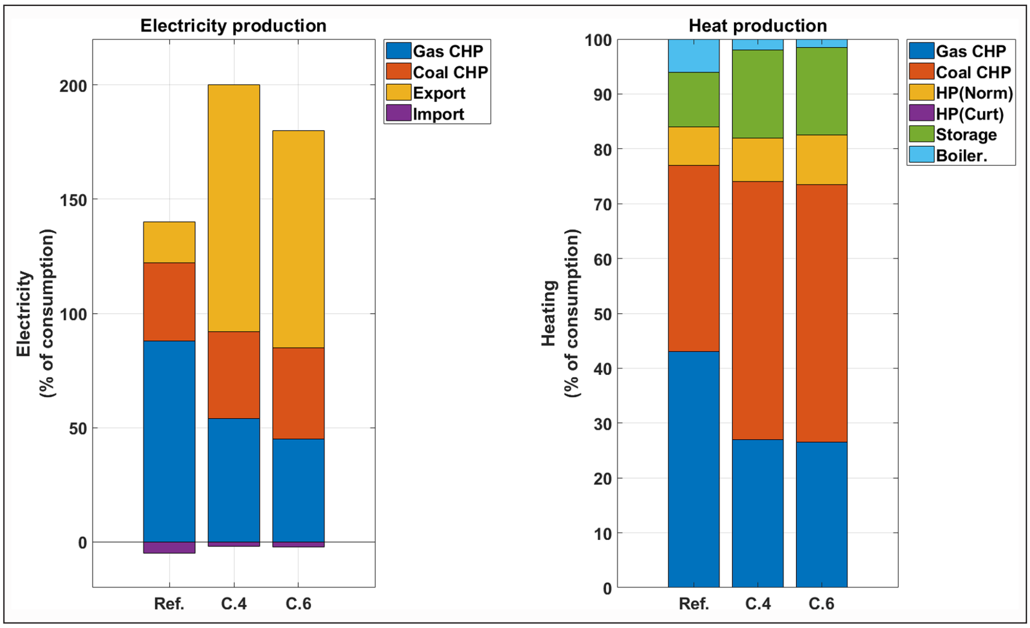

Figure 3: Electricity production and heat production of the power plants with different building energy saving levels for Scenario 1 (cases 4 and 6 in Table 4).

Table 5: Annual CO_2 emissions and fuel cost for building energy efficiency improvements and 1500 MW of heat pumps (Scenario 2).

Case	Heat demand reduction (%)	Wind (MW)	Fuel cost (M€/yr)	Emissions (ktCO$_2$/yr)
Present system	–	–	327	2271
1	–	750	204	1270
2	–	1500	162	1010
3	8	750	194	1234
4	8	1500	154	983
5	16	750	184	1201
6	16	1500	146	957

Table 6: Annual CO_2 emissions and fuel cost for the case with building energy efficiency improvements, 1500 MW of heat pumps, and 1500 MW of wind power with curtailment (Scenario 3).

Case	Heat demand reduction (%)	Curtailment method	Curtail-ment (%)	Fuel cost (M€/yr)	Emissions (ktCO$_2$/yr)
Present system	–	–	–	327	2271
1	–	Peak-shaving	10	145	950
2	–	Peak-shaving	30	142	925
3	8	Wind-following	10	140	752
4	8	Wind-following	30	118	727
5	16	Load-following	10	111	727
6	16	Load-following	30	110	710

reflect the changes in the heat source availability for the heat pumps. An electric boiler with a maximum output of 1500 MW (equal to COP = 1) was therefore added to the energy production system. **Table 7** presents the results for Scenario 4.

The reference case in this scenario is a modified system since the nominal maximum HP output is set as 1500 MW. For each curtailment method, the lowest fuel cost and emission were achieved with the highest heat demand improvement of 16% (case 3, 6 and 9). The details of the

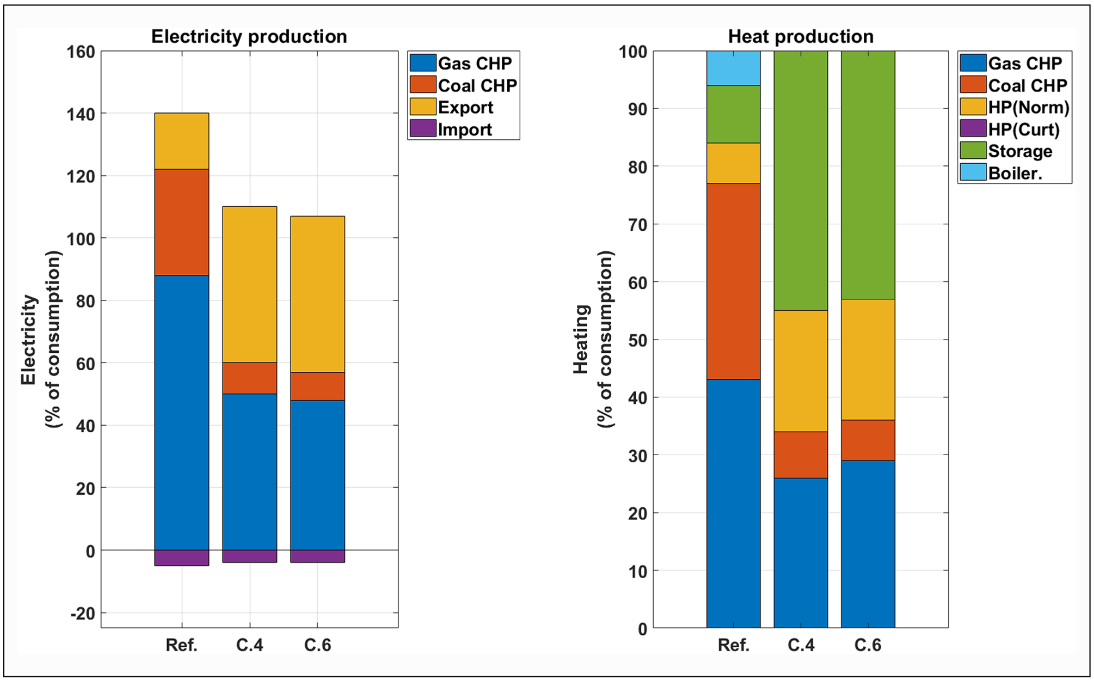

Figure 4: Electricity production and heat production of the power plants with different building energy saving levels and 1500 MW of heat pumps for Scenario 2 (cases 4 and 6 in Table 5).

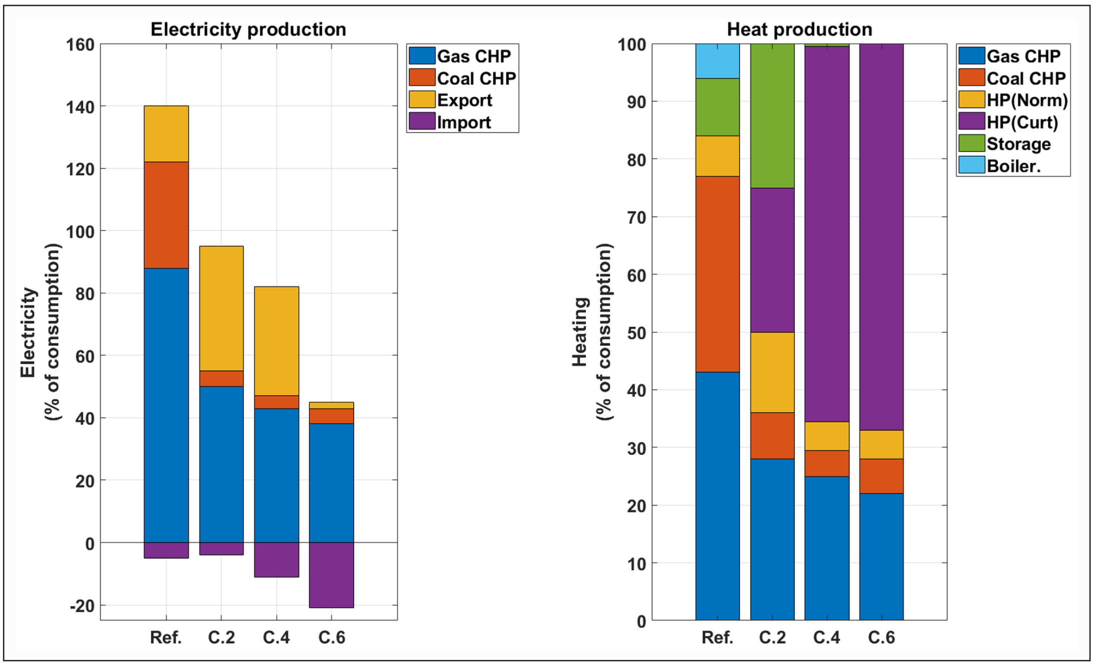

Figure 5: Electricity production and heat production of the power plants with different building energy savings, 1500 MW of heat pumps, and wind curtailment for Scenario 3 (cases 2, 4 and 6 in Table 6).

energy production for Scenario 4 are shown in **Figure 6**. The base system in this scenario is the modification of the present system (1500 MW heat pumps), but electric boilers are used in cases 6 and 9 due to heat source limitations. In case 9 with the "Load-following" curtailment scheme, there is no heat storage use at all. It seems that increasing the wind energy share would reduce the contribution of the heat storage in this case. Both the share of gas and coal in heat production is halved compared to the base system; the share of gas comes down to 25% and coal to 5% of the yearly heat consumption. In power production, we see the similar trend: the share of gas power production is halved compared to the base system to 43% of power consumption and coal 5%, respectively. Due to the heat resource limitation, a part of the heat consumption from curtailed wind power is supplied by the electric boiler. For the "Load-following" curtailment (case 9), the electric boiler contribution is 18%. In **Figure 6**, the term "curt" and "norm" for the electrical boiler deal with heat production by electrical power and produced heat with curtailed wind power.

Table 7: Annual CO_2 emissions and fuel cost for energy system with a HP with capacity as function of the heat demand (wind energy = 1500 MW and curtailment = 30%) (Scenario 4).

Case	Heat demand reduction (%)	Curtailment method	Fuel cost M€/yr	Emissions ($ktCO_2/yr$)
Modified system	0	–	298	1843
1	0	Peak-shaving	159	994
2	8	Peak-shaving	150	955
3	16	Peak-shaving	141	922
4	0	Wind-following	139	855
5	8	Wind-following	128	802
6	16	Wind-following	117	750
7	0	Load-following	136	841
8	8	Load-following	127	805
9	16	Load-following	119	769

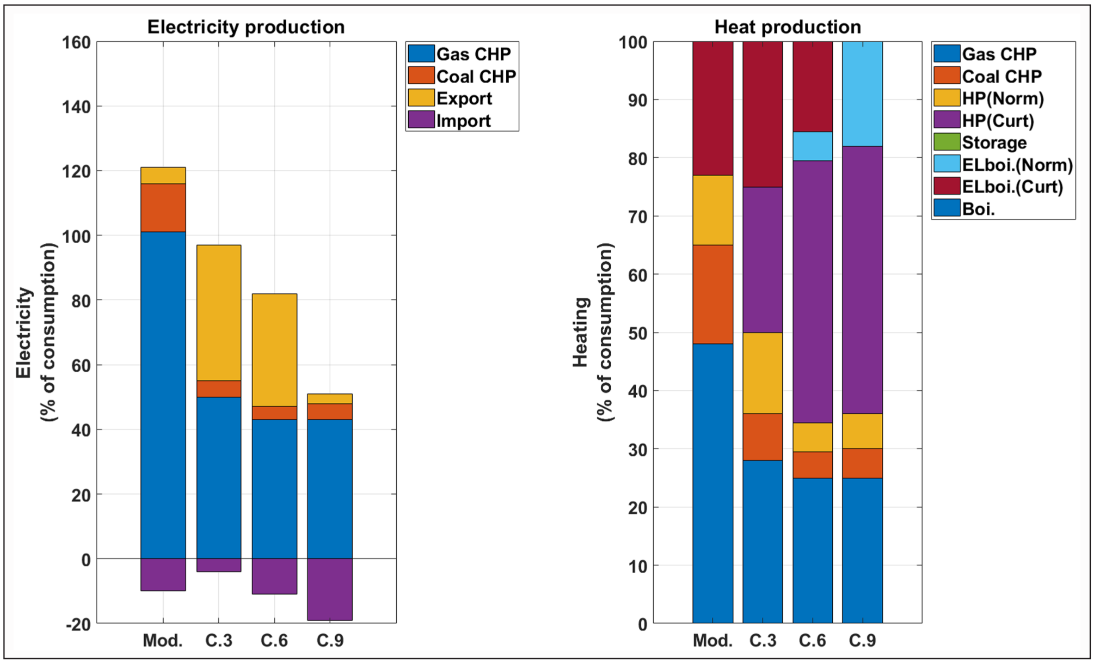

Figure 6: Electricity production and heat production of the power plants with different building energy savings, 1500 MW of heat pumps, wind curtailment, and dynamic heat pump COP for Scenario 4 (cases 6 and 9 in Table 7). The base system is here a modification of the present system.

Conclusions

In this paper, we have studied the sectoral coupling of variable renewable energy (VRE) to the heating sector on a national (Finland) and city (Helsinki) level. For VRE, we used a large wind power scheme to which different curtailment & P2H strategies, building energy efficiency measures, and heat pump schemes were added. The effects to the existing energy system were analysed with dynamic energy system models. On the city level, four basic scenarios with a total of 27 cases were analyzed to reveal the system effects from the above strategies, while on the national level 14 cases were analyzed. The main findings of the analyses are the following:

- On the national scale, the system inertia is typically larger than on a city level, leading to more ideal spatiotemporal integration of VRE, i.e. stronger smoothing effects of VRE. Therefore, the sectoral coupling of VRE to the heating sector produced larger impacts on the national scale. On a city-level, the simulations better considered the dynamics of individual power plants and the consequent limitations, which is most likely the reason why the impacts were smaller than on a national scale, where all plants were handled in a lumped way.
- The amount of VRE-based heat strongly depends on the type of curtailment strategy chosen, e.g. mere

'Peak-shaving' would typically produce the least heat and 'Wind-following' the most.

- On the national level, the most effective curtailment strategy ('Wind-following', 30%) with P2H conversion and 40 TWh of wind power was able to cover up to 40% of the yearly heat demand (the initial wind power production corresponding to 48% of the yearly electricity consumption). The P2H strategy with wind power also replaced separate heat boilers.
- On the city level, with a 1500 MW wind power scheme (corresponding to 86% of the yearly electricity use in Helsinki) and the 'best' curtailment strategy (Scenario 3 and 4), wind power and wind-power derived heat were able to radically modify the existing use of the fossil-based CHP plants, which led to close to 70% emission reductions.
- In the city-level analyses, adding wind power to the Helsinki case with a CHP dominated energy system would actually increase the export of electricity. Wind power would replace more gas-CHP than coal-CHP, the latter being more important to the heat production.
- On the city-level, improving the building energy efficiency 10%–20% of the yearly heat demand did only marginally reduce the annual fuel costs and emissions, which is a result of the energy system dynamics.

The heat pumps played a major role in the sectoral coupling of VRE to the heating sector. On a national level the heat pumps were assumed to work at a constant COP, but on the city level we employed a dynamic COP which considers heat source limitations. The assumption of a constant COP may lead to too optimistic values of heat production, but as this also caused oversupply of heat which couldn't be utilized, the error to the energy balance is probably minor.

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Competing Interests

The authors have no competing interests to declare.

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