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# Energy system impact of wind power with curtailment: national- and city-scale analysis

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## Abstract

With an increasing share of variable renewable energies in the power production, curtailment may become relevant to better manage the power system. Here, we explore the effects of wind power curtailment on the energy system composition and operation on two levels: national (Finland) and city level (Helsinki). For each level, optimization-based models were used. The results indicate that increasing the amount of wind power and curtailment and implementing power-to-heat conversion may not automatically lead to positive effects, such as emission reductions, but may need additional measures such as higher $CO_2$ emission pricing and more effective heat generation (heat pumps) to realize the full benefits.

*Keywords:* variable renewable energy; curtailment; power-to-heat; energy system flexibility

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## 1 INTRODUCTION

The Paris Climate Accord requires that carbon sources and sinks need to be in balance by the middle of this century [1]. This in turn will require massive investments in clean energy production and more efficient energy use. At the same time, the market penetration of new renewable technologies, notably wind power and solar photovoltaics, is accelerating [2, 3]. The International Energy Agency (IEA) estimates in its future energy scenarios that solar and wind power will be the most popular alternatives for new power generation investments till 2040 [4]. On a very long-term by year 2100, the global energy company Shell estimates that close to 40% of all energy could come from solar energy alone [5]. Clearly, the energy transition towards sustainability will rely on new energy technologies, such as variable renewable energy (VRE), whose characteristics differ quite much from the traditional fuel-based energy system.

According to Ref. [6], the overall challenge of large-scale VRE integration is to make the best use of a variable and uncertain power source while maintaining the continuous balance between consumption and generation and high level of reliability in the power system. Here, we focus on the challenge of matching the supply and demand of power, as the electricity system needs to be in balance at each point of time [7–11]. Existing balancing methods, e.g. the reserves of the power system, could manage some of the balancing need, but additional or new approaches may be necessary. Such include flexible supply, demand response, strengthening transmission cables, curtailment and power-to-x, among others [12, 13]. These methods also reduce the need for excessive electrical storage systems [14]. Most of the final energy in Europe is heat, e.g. in Finland around 80% of the final energy consumption of households is heat (space heating and domestic hot water [15]), increasing the interest in power-to-heat (P2H) conversion. This kind of sectoral coupling of power and heating has received increasing interest in the scientific literature as an energy system flexibility measure: P2H (heat pumps (HPs) or electric boilers) is shown to improve wind power integration for example in Denmark [16], Sweden [17], Finland [18], the Nordic countries [19, 20], the Netherlands [21] and Ireland [22]. Combined heat and power (CHP) is another heat-based option for wind power integration [23], in particular when combined with HPs [24–26]. On the other hand, curtailment is also shown to improve wind power integration cost-effectively [27, 28]. An interesting option would then be combining P2H with planned VRE curtailment, which could make use of the curtailed VRE instead of simply discarding it, while at the same time providing important power management aid to the electricity system,

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e.g. mitigating the problems related to wind power peaks or oversupply.

In this paper, we explore the idea of using curtailment and P2H for increasing the energy system flexibility with a high share of wind power. Here, we consider the term 'curtailment' to refer to any kind of reduction in wind power production: directing intentionally curtailed wind power to P2H could help to better integrate the wind power and prevent unnecessary wind power discard. The aim is firstly to assess the effects of three different curtailment strategies on the overall performance of the power system when increasing the amount of wind power, and secondly, quantify the role of linking P2H to curtailment. In particular, we assess the energy system composition and operation, as well as the overall indicators of an energy system: annual costs and $CO_2$ emissions. As the P2H technology, we selected HPs, because their higher efficiency allows higher delivery of heat when using curtailed wind power, leading to more noticeable effects in the energy system. For the analyses, we consider two levels of the energy system, a national (Finland) and a city (Helsinki), both in a northern cold climate with a considerable heating demand. The national case represents a macro-scale case with more inertia for smoothing out some transient effects (1-h time step), whereas the city model has a stronger dynamical resolution down to the power-plant level (10-min step). The analyses are therefore done with two different energy system models.

## 2 METHODOLOGY

The methodology employed in the study is based on techno-economic optimization of the energy system, seeking for a minimum cost solution under different constraints and boundary conditions. Two models are considered: a national model which aims to demonstrate the effects of wind power curtailment on the whole energy system, and a city-level model which focuses on optimal transient operation of the existing power plants under large wind schemes. The two models, one for the whole national energy system and one for the detailed operation of a city's energy system, focus on different aspects of the energy system, revealing a wider scope of results compared to a single model. Finland is used as the case study for the national analysis and Finland's capital Helsinki for the city-level analysis.

### 2.1 National-level model

The national-level analysis is conducted with a macro-scale energy system model described in detail in Ref. [29]. The model incorporates all aspects of an energy system, including electricity, heat and fuel. The model employs a 1-h time 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 balance. The cost optimization problem is defined as

$$\begin{aligned}\text{Minimize Total annual cost} &= \sum_{t=1}^{tech} (\text{Investment cost}_t + \text{O\&M}_t) \\ &+ \sum_{f=1}^{fuels} \text{Fuel cost}_f + \text{Net cost of power import} \\ &+ \text{Emissions costs} \end{aligned} \quad (1)$$

The variables in the optimization are the amounts of the fossil primary energy sources and the amounts of conventional conversion, i.e. CHP, separate production and heat pumps (HP). The energy system composition is thus endogenous to the model. 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, and a more detailed description of the input data can be found in [29]. The amounts of fossil fuels are not limited. The hourly distribution of the conventional production, such as CHP, is based on historical production data (2013) to mimic the hourly distribution, whereas the operation of P2H conversion is rule-based. The level of industrial CHP and residential heat production, which accounted for 43% of the heat demand in 2013, are assumed non-variable. The model also assumes 60 GWh thermal storage available through the existing Finnish district heating (DH) networks.

The national reference case is presented in more detail in Supplementary Information. Overall, the share of fossil resources in primary energy was 47% in 2013, while the share of renewables was 29% and the $CO_2$ emissions were 49.2 $MtCO_2$. Three levels of wind power penetration are assumed in the national-level analysis: 2013 level (0.8 TWh), 20 TWh and 40 TWh, corresponding to 0.9%, 24% and 48% of the yearly electricity use of Finland (84 TWh). The accompanying wind power curtailment strategies are described in detail in Section 2.3.

### 2.2 City-level model

The city-level analysis is conducted with a higher time resolution as 10-min time step described in detail in Ref. [26]. The model optimizes the operation of a given energy system using a mixed-integer linear programming. The objective function is given as

$$\text{Minimize Running costs} = \sum_{t} (\text{Production costs} - \text{Revenues from sales}) \quad (2)$$

The main optimization constraints reflect the technical properties of power plants and balancing methods, and the balance of energy demand and supply. The main optimization outputs are energy production, energy sold to consumers, and costs and profit from running the energy system. Unlike in the national case, the plant capacities are fixed to those existing in Helsinki.

The analyses are done for Helsinki (60°N) with an annual heat demand of 6.1 TWh and electrical demand of 4 TWh. In Helsinki, over 90% of the heat demand is covered through a DH system. The details of the present (2013) energy production plants in Helsinki are shown in Table 1.

## 2.3 Curtailment cases

Curtailment of wind power may be motivated during high supply of wind. Curtailing wind power may improve power system flexibility, but also feed surplus wind power into the heat production. In this paper, we explore the idea of using planned curtailment and P2H for increasing the energy system flexibility with a high share of wind power.

On both levels of analysis, we include three strategies for wind power curtailment 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 actual electrical load. We use two curtailment rates, 10% and 30%.

The curtailed wind power is used to strengthen the P2H strategy: all curtailed wind is directed to HPs (COP = 3). As wind power is a renewable and zero-marginal-cost resource, we argue that the heat produced by this 'forced' HP operation offers a renewable and low-cost, albeit non-dispatchable, source of heat, which in turn may decrease the marginal costs of energy production. In the national case, the HP capacity required by the curtailment strategy is added to the energy system. In the city-level case, this 'forced' HP operation limits the HP capacity available for the dispatch optimization. The reference case for the curtailment strategies does not include any 'forced' curtailment, and the HPs operate freely.

**Table 1.** *Nominal output of the energy plants in Helsinki (MW) [26].*

| | 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 |

The three strategies offer different ways to curtail wind power: 'Peak-shaving' focuses on mitigating wind power peaks, 'Wind-following' aims for a constant reduction of wind power and 'Load-following' focuses on mitigating hourly excess power production. However, it should be noted that this kind of 'forced' HP operation and wind power reduction might not be the optimal solution compared to fully market-based curtailment and HP operation. Our approach, however, provides insight into different wind curtailment strategies and the idea of pre-emptively directing part of wind power to the heat sector via P2H to improve wind power integration.

# 3 RESULTS

In this section, we analyse the effects of wind power curtailment on the national and city-level energy system. Both models aim to minimize annual system costs, and the main constraints of the models are the technical properties of power plants and balancing methods, in addition to securing the energy demand and supply balance.

## 3.1 National case (Finland)

In the national case, the three different wind power curtailment strategies, described in Section 2.3, produced very different levels of curtailed wind (Table 2). The temporal profile of the national wind power production led to very small curtailment with the 'Peak-shaving' case, suggesting a highly peaked profile, whereas in the 'Load-following' case, especially with the lower amount of wind power (20 TWh) the curtailment was negligible. The 'Wind-following' case produced the highest amount of curtailment (and heat). The curtailed wind power was used for heating through a P2H strategy with HPs. The reference case is Finland in 2013, based on historical data.

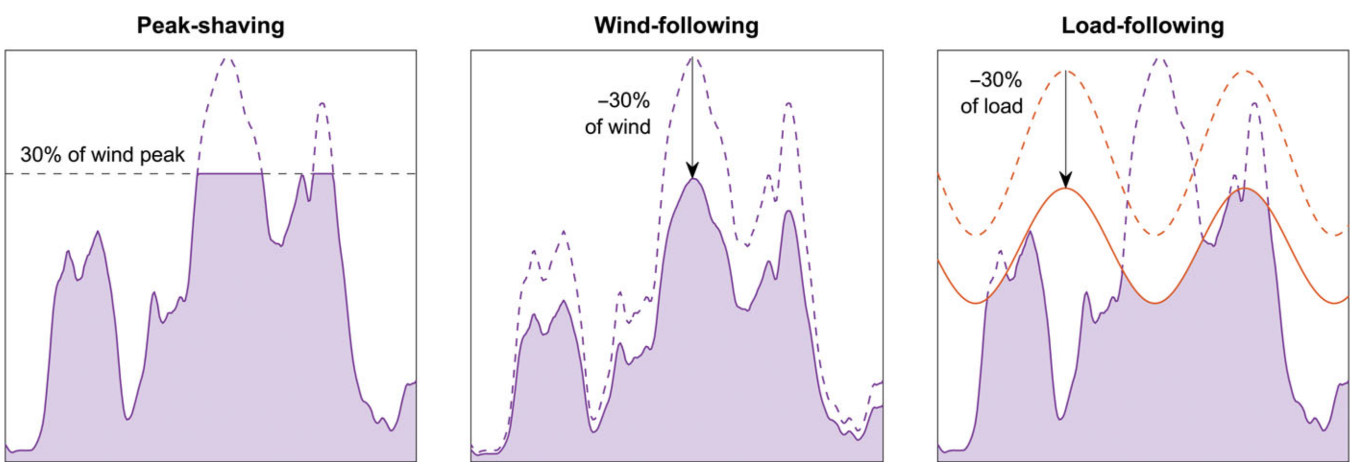


**Figure 1.** *Schematic illustration of the different wind power curtailment methods using a curtailment rate of 30% as an example.*

**Table 2.** *Effect of curtailment strategies on wind power production in the national case (% of initial wind power).*

| Wind power before curtailment | Curtailment rate (%) | Curtailment method | | |
|---|---|---|---|---|
| | | Peak-shaving (%) | Wind-following (%) | Load-following (%) |
| 20 TWh | 10 | 0.1 | 10 | 0 |
| | 30 | 4 | 30 | 0.05 |
| 40 TWh | 10 | 0.1 | 10 | 4 |
| | 30 | 4 | 30 | 12 |

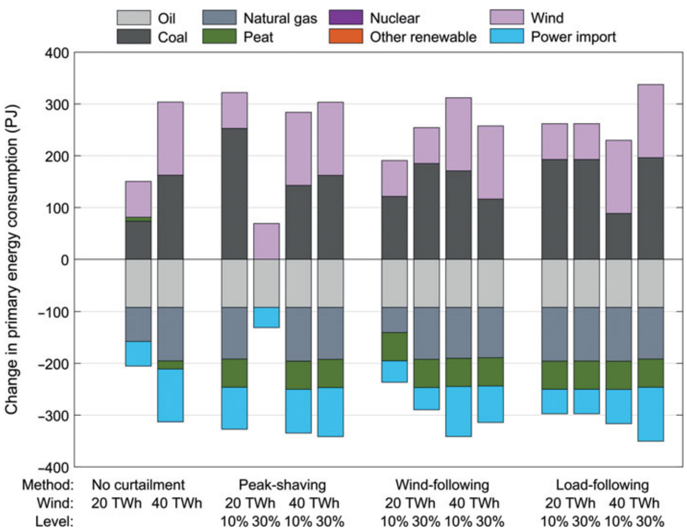


**Figure 2.** *Change in primary energy compared to the national reference case (Finland in 2013).*

Figure 2 shows the change in the overall primary energy consumption with the different curtailment strategies and wind power levels, compared to the national reference case (Finland 2013). All cases exhibit changes in fossil-fuel composition: the more expensive oil, gas and peat have been replaced by cheaper coal in particular in CHP plants (here, we used 2015 price level for coal, 2.3 €/GJ [30]). Furthermore, the $CO_2$ emissions had a positive correlation with the level of coal use, ranging from −10 to +6 $MtCO_2$ (−20% to +11% from reference). In addition, all cases showed a decrease in power import, and in the 40-TWh wind power case, even notable power export (3–13 TWh) resulted. This change from net importing to net exporting suggests that a high wind power addition may not always be cost-effectively utilized in the national scale due to the structure of fuel prices and system limitations, even with a P2H scheme for curtailed wind. There were no changes in nuclear power and other renewable resources in Figure 2 as these primary energy sources were not included as variables in this optimization.

As for the energy system composition, the results show increased heat production from HPs, mostly due to the P2H scheme, which in turn decreased the heat from heat-only boilers. The influx of wind power also eliminated power production from power-only plants. Interestingly, almost all cases exhibited increased CHP production, despite the large wind power additions. This CHP increase was most likely caused by the availability of low-cost coal and the comparably high electricity export prices, i.e. coal-CHP production was economically motivated by export, rather than only local electricity demand, leading to oversupply of electricity. We also found out oversupply of heat [31]. The P2H scheme with curtailed wind power led to an increased share of HPs, but it seemed to have only a minor effect in mitigating excess electricity production: increasing the curtailment share from 0% to 10% to 30% did not systematically decrease power export, which may be used as a measure of unsuccessful wind power integration. The failure of the P2H scheme to mitigate wind power excess may have partly been caused by the fact that the wind power curtailment sometimes coincided with times of low heat demand.

Table 3 shows the change of the annualized system cost compared with the reference case (Finland 2013). Overall, all optimized scenarios had lower annual system costs than the reference case, suggesting that integrating wind power into the Finnish energy system may be cost-effective. However, there is no clear trend whether wind power curtailment systematically decreases costs. Furthermore, the cost effect of different curtailment methods remains ambiguous: only in the 'Wind-following' method, the annual costs decreased for both levels of wind power.

### 3.1.1 *Sensitivity analyses*

As the carbon emission price has a significant effect on the overall system costs and mutual competitiveness of fossil-based generation, we also conducted a sensitivity analysis with a varying $CO_2$ price. The basic case described previously used 8 €/$tCO_2$ as the emission price, which is quite low and may have contributed to the increased coal use. In the sensitivity analysis, we used additional emission prices of 20 and 60 €/$tCO_2$. Secondly, we tested sensitivity of the results against the optimization variables by including nuclear power and bioenergy as optimization variables. In this case, nuclear power addition is limited to the upcoming Olkiluoto 1600 MW nuclear power plant, while the bioenergy potential is assumed to be +20% of the current use. The sensitivity studies used the 'Wind-following' curtailment method as it resulted in most curtailment (and heat).

The detailed results of the sensitivity studies are presented in Supplementary Information. In conclusion, a higher $CO_2$ price indeed resulted in lower coal use: the power production from coal-CHP plants decreased and the heat production shifted to

**Table 3.** *Change in the annual system cost from wind curtailment strategies compared to the national reference case.*

| Wind power before curtailment | Curtailment rate (%) | Curtailment method | | | |
|---|---|---|---|---|---|
| | | None (%) | Peak-shaving (%) | Wind-following (%) | Load-following (%) |
| 20 TWh | 0 | −13 | | | |
| | 10 | | −18 | −13 | −15 |
| | 30 | | −9 | −17 | −14 |
| 40 TWh | 0 | −14 | | | |
| | 10 | | −15 | −15 | −10 |
| | 30 | | −15 | −15 | −13 |

HPs, using either curtailed wind power or power import. The annual costs increased with increasing $CO_2$ price, even higher than the reference case (up to +17%), indicating that the decrease in $CO_2$ emissions due to decreased coal (up to −39%) was not enough to compensate the effect of the higher $CO_2$ price in overall annual costs.

Secondly, including nuclear power and biomass in the optimization resulted in increased nuclear power, while biomass use slightly decreased. The increase in nuclear production consequently decreased the power production from CHP plants, which in turn shifted the heat production from CHP plants to HPs, using curtailed wind power. However, in the case without wind curtailment, nuclear power did not increase, suggesting that the uncurtailed wind power was enough to provide the country's power demand cost-effectively. Including nuclear power and bioenergy in the optimization also decreased the annual cost (up to −23%), as well as emissions (up to −25%), implying that adding nuclear power might be cost-effective, especially if combined with the P2H scheme utilizing curtailed wind power. However, this depends on the actual construction cost of nuclear power which has a large spread (here we used 4000 €/kW for nuclear investments).

## 3.2 City case (Helsinki)

For the sub-national level, three scenarios explore the system operation with wind power integration (750 or 1500 MW) and curtailment management. These scenarios, which use extensively HPs for P2H, are defined as:

- Current (90 MW HP) and modified energy systems (1500 MW HP, no curtailment);
- Existing energy system (90 MW HP with curtailment and P2H);
- Modified energy system (1500 MW HP with curtailment and P2H).

The $CO_2$ emissions and fuel costs are the main indicators used for evaluating the energy system operation. The system cases are presented in Table 4. In the modified cases, the HP output is increased to 1500 MW to cover nearly 50% of Helsinki's peak heat demand. The wind power schemes of 750 MW and 1500 MW stand for 43% and 86% of the annual electricity demand in Helsinki, respectively. In each scenario, the highlighted cases are discussed in more detail as presented in Figures 3–5. Moreover, in this section the results are presented as percentage of Helsinki's annual power and heat consumption. In the figures, the term 'Ref.' stands for the reference system, 'Mod.' refers to the modified system, 'Curt' describes the heat production by curtailed wind power and 'Norm' means heat production by the HP via electricity. The reference case in Scenarios 1 and 2 uses a 90-MW HP, while in Scenario 3 the modified base case uses a 1500-MW heat pump.

**Table 4.** *$CO_2$ emissions and fuel costs for the existing system with two heat pump outputs (90 MW and 1500 MW). The cases with the lowest emissions and costs are highlighted in bold.*

| Case | HP output (MW) | Wind (MW) | Emissions ($ktCO_2$/year) | Cost (M€/year) |
|---|---|---|---|---|
| Ref. | 90 | 0 | 3227 | 298 |
| 1 | 90 | 750 | 3079 | 286 |
| **2** | **90** | **1500** | **3013** | **282** |
| 3 | 1500 | 0 | 2181 | 191 |
| 4 | 1500 | 750 | 1441 | 126 |
| **5** | **1500** | **1500** | **1122** | **102** |

### 3.2.1 *Scenario 1: No curtailment*

Scenario 1 focuses on wind power integration and P2H on the operation of Helsinki's existing energy system. The reference case in this scenario has no wind power integration. The Cases 1 and 2 in Table 4 present the effect of the wind power integration on the current energy system. The last three include the effect of the higher P2H scheme.

For the existing system, increasing the wind power up to 1500 MW (Case 2) led to 7% and 5% reductions in $CO_2$ emissions and fuel costs, respectively. However, by only expanding the HP capacity up to 1500 MW (Case 3) without wind power, significant reductions occurred in emissions (32%) and fuel costs (36%), because the HPs can match the heat demand temporally better than the power-considering CHP plants, leading to reduced fossil-fuel-based CHP production. When the maximum amount of wind power is introduced to the modified system (Case 5), the emissions are cut by 65% and fuel costs by 66%, respectively.

Figure 3 shows the electricity and heat production breakdown for the selected cases highlighted in Table 4. The gas-CHP power and heat production are dropped to 20% and 12%

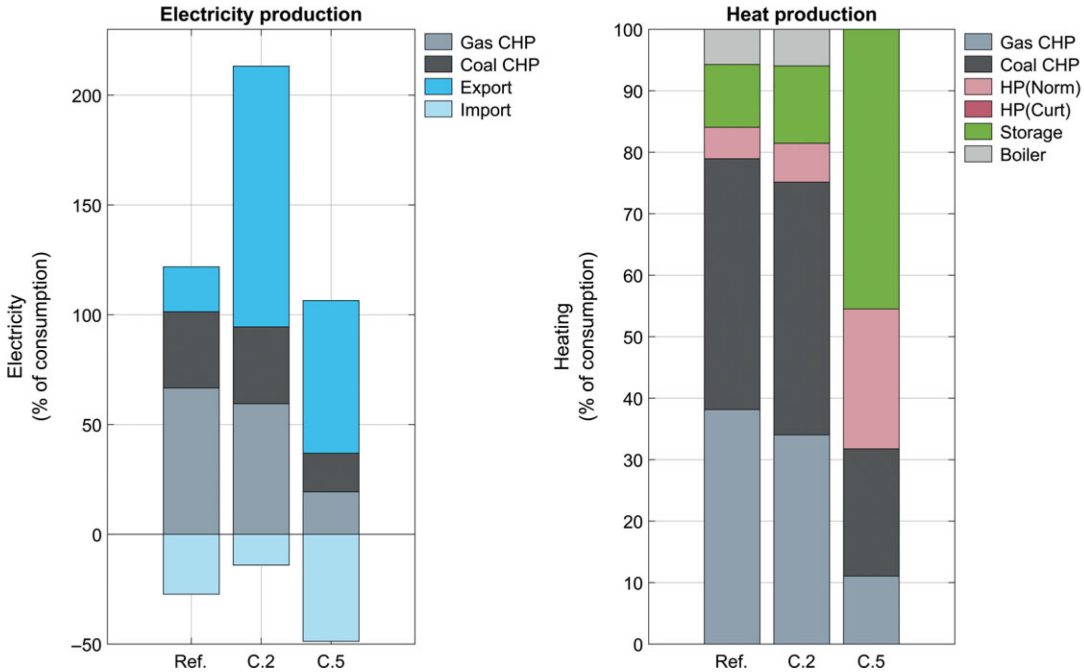


**Figure 3.** *Energy production breakdown for Scenario 1. ('Ref.' is Reference, 'C.2' is Case 2 and 'C.5' is Case 5 in Table 4.)*

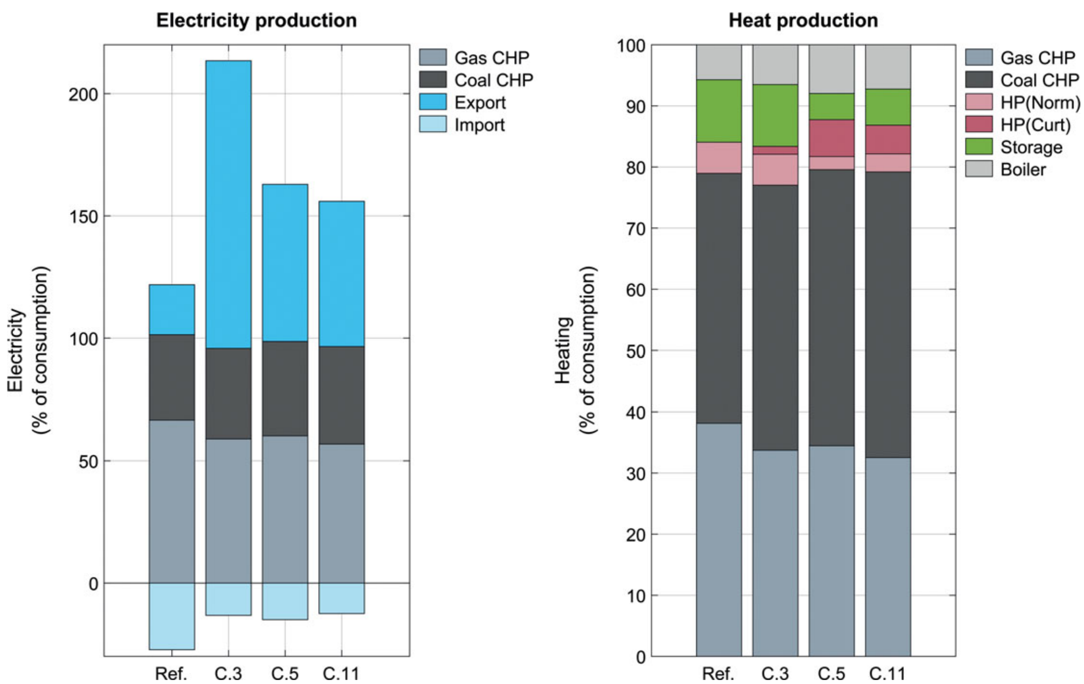


**Figure 4.** *Energy production breakdown for Scenario 2. ('Ref.' is Reference, 'C.3' is Case 3, 'C.5' is case 5 and 'C.11' is Case 11 in Table 5.)*

in Case 5 compared to 68% and 38% in the reference case. Furthermore, in comparison with the reference system, the coal-CHP power and heat production are cut to 20% and 22% in Case 5, respectively. Moreover, in Case 5, the imported power and heat storage increased to 40% and 46%, respectively, compared to the reference case. The use of boilers for heat production was eliminated because of significant increase in HP use. The major effect of the wind power integration is on the gas-CHP production due to a higher gas price (56 €/MWh) used compared to the coal price (43 €/MWh). Moreover, expanding the HP output up to 1500 MW improved the use of the surplus power production and emphasizes the role of heat storage.

### *Scenario 2: Existing energy system with curtailment*

The focus in the second scenario is to explore the effect of different curtailment methods on current energy system operation. The curtailment methods were explained in Section 2.3. For each curtailment method, the case with the maximum emission and fuel cost reductions is selected to be discussed further in Figure 4.

In the Case 3, the emissions and fuel costs are reduced to 5% and 3% compared with the reference case. The 'Peak-shaving' method cut the emissions and fuel costs up to 5% and 3% respectively (Case 3). 'Wind-following' yields the lowest performance in the main measures and can even increase the fuel costs. In addition, for 'Load-following' method, the maximum emission reduction is 4% and fuel cost reduction is only 1% (Case 11). The breakdown of the energy production for highlighted cases (Table 5) are shown in Figure 4.

As illustrated in Figure 4, the gas-CHP electricity and heat production are decreased to 60% and 34% (Case 3), respectively. The coal-CHP and boiler production in all highlighted cases remain almost the same compared to the reference case. In Case 5, the maximum HP production using curtailed wind

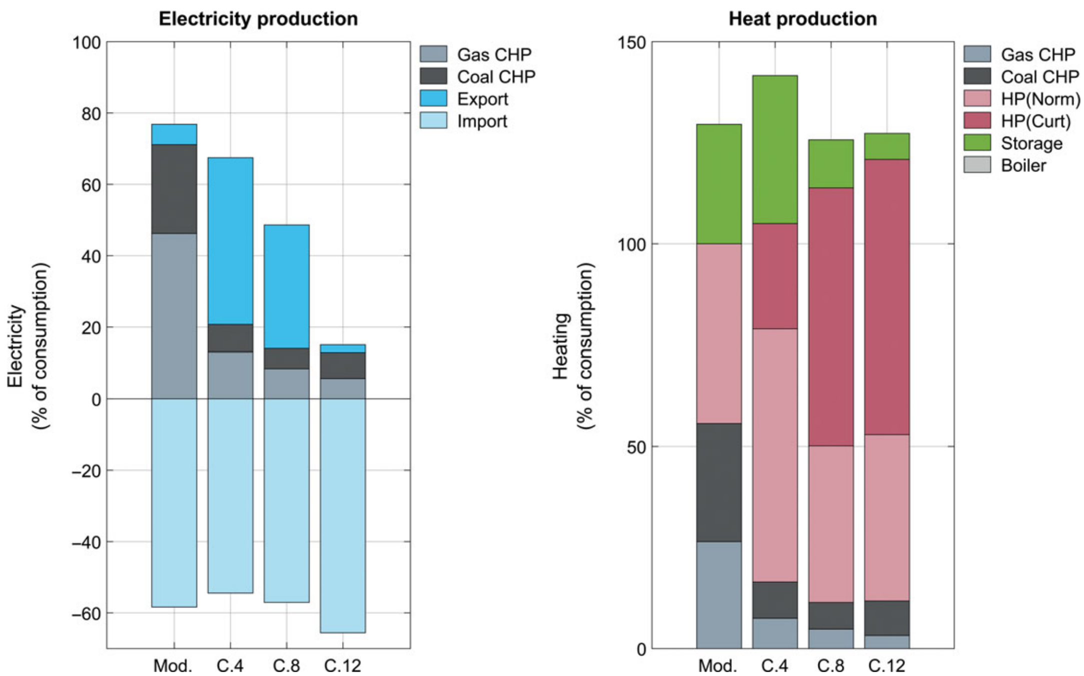


**Figure 5.** *Energy production breakdown for Scenario 3. ('Ref.' is Reference, 'C.4' is Case 4, 'C.8' is Case 8 and 'C.12' is Case 12 in Table 6.)*

**Table 5.** *$CO_2$ emissions and fuel costs for the existing energy system with wind power curtailment (HP output = 90 MW). The cases with the lowest emissions and costs are highlighted in bold for each curtailment method.*

| Case | HP output (MW) | Curtailment method | Curtailment | Wind (MW) | Emissions (kt$CO_2$/year) | Cost (M€/year) |
|---|---|---|---|---|---|---|
| Ref. | 90 | | | | 3227 | 298 |
| 1 | 90 | Peak-shaving | 10 | 750 | 3100 | 292 |
| 2 | 90 | Peak-shaving | 30 | 750 | 3102 | 293 |
| **3** | **90** | **Peak-shaving** | **10** | **1500** | **3061** | **288** |
| 4 | 90 | Peak-shaving | 30 | 1500 | 3094 | 292 |
| **5** | **90** | **Wind-following** | **10** | **750** | **3175** | **303** |
| 6 | 90 | Wind-following | 30 | 750 | 3230 | 310 |
| 7 | 90 | Wind-following | 10 | 1500 | 3184 | 305 |
| 8 | 90 | Wind-following | 30 | 1500 | 3208 | 309 |
| 9 | 90 | Load-following | 10 | 750 | 3137 | 296 |
| 10 | 90 | Load-following | 30 | 750 | 3145 | 298 |
| **11** | **90** | **Load-following** | **10** | **1500** | **3093** | **296** |
| 12 | 90 | Load-following | 30 | 1500 | 3123 | 299 |

**Table 6.** *$CO_2$ emissions and fuel costs for the modified energy system with wind power curtailment (HP output = 90 MW). The cases with the lowest emissions and costs are highlighted in bold for each curtailment method.*

| Case | HP output (MW) | Curtailment method | Curtailment | Wind (MW) | Emissions (kt$CO_2$/year) | Cost (M€/year) |
|---|---|---|---|---|---|---|
| Mod. | 1500 | | | | 2181 | 191 |
| 1 | 1500 | Peak-shaving | 10 | 750 | 1249 | 107 |
| 2 | 1500 | Peak-shaving | 30 | 750 | 796 | 67 |
| 3 | 1500 | Peak-shaving | 10 | 1500 | 791 | 69 |
| **4** | **1500** | **Peak-shaving** | **30** | **1500** | **637** | **56** |
| 5 | 1500 | Wind-following | 10 | 750 | 1193 | 100 |
| 6 | 1500 | Wind-following | 30 | 750 | 716 | 59 |
| 7 | 1500 | Wind-following | 10 | 1500 | 690 | 58 |
| **8** | **1500** | **Wind-following** | **30** | **1500** | **431** | **39** |
| 9 | 1500 | Load-following | 10 | 750 | 633 | 57 |
| 10 | 1500 | Load-following | 30 | 750 | 573 | 53 |
| 11 | 1500 | Load-following | 10 | 1500 | 383 | 36 |
| **12** | **1500** | **Load-following** | **30** | **1500** | **392** | **37** |

power covered 6% of the yearly heat production. The 'Peak-shaving' method had the highest electricity export and the lowest curtailed heat production (Case 3), while the 'Load-following' method reduced the amount of exported power (Cases 5 and 11). Even introducing higher wind power failed in providing remarkable benefits compared to the last scenario due to the limited P2H scheme (HP output capacity covering only 3% of Helsinki's peak heat demand) and mismatch between the heat demand and heat production using curtailed wind power.

### 3.2.2 *Scenario 3: Modified energy system with curtailment*

The last scenario takes advantages from increasing P2H capacity and curtailment management. The base case in this scenario is the modified system (HP with output as 1500 MW) without wind power. The results are listed in Table 6. The highest impact was found in Case 12 with 'Load-following': 82% reduction in emissions and 81% in fuel cost. This strategy provided the highest curtailed heat for the energy system (see Figure 5).

The gas-CHP electricity and heat production are decreased from 52% and 26% in the modified base case to 10% and 5% in Case 12. In addition, the coal-CHP electricity and heat production are reduced to 6% and 8% in Case 12 (20% and 28% in base case). The lowest exported electricity is 2% while the highest curtailed heat is almost 70% (Case 12). Consequently, the thermal boiler production is eliminated in all curtailment methods. In this scenario, for the heating sector there is surplus curtailed heat production with the defined P2H scheme, which cannot participate in the modified system because of mismatching between heat demand and curtailed heat.

## 4 CONCLUSIONS

Here, we have investigated the effects of different curtailment strategies of wind power and P2H conversion on the energy system in terms of energy system composition, operation, and annual costs and emissions. We explored the idea of pre-emptively curtailing wind power and directing it to P2H to improve wind power integration. Two energy system topologies were considered, namely a national (Finland) and city (Helsinki) case. We used dynamic energy system models and optimizations as the method of the study, exploring the interaction between wind power, curtailment, and P2H.

One of the main conclusions from the analyses is that integration of wind power involves very complex energy system interactions, meaning that the impacts of wind and curtailment need to be analysed case by case. Fuel prices, market conditions and energy system limitations among others may significantly affect the outcomes from introducing large wind power and curtailment schemes. On the national level, we found that wind power was not always effectively used even if planned curtailment and P2H were considered, but it rather led to increased export of power, partly caused by the mismatch between heat demand and forced wind power curtailment. To avoid such as a situation and revert the curtailed wind power to heating could require increasing the price of carbon emissions (€/t$CO_2$), making fossil-based production less attractive. Increasing wind power decreased the annual system costs, but the cost effect of curtailment remained ambiguous.

For the city level, integrating wind power to the existing system only marginally decreased the fuel costs and $CO_2$ emissions, in line with Ref. [26]. Wind power caused CHP electricity production to decrease by providing a more low-cost power alternative, while due the sectoral coupling of heat and power, the heating sector is affected as well. Incorporating a curtailment strategy with P2H and HPs could provide an effective solution to replace fossil-fuel-based CHP and thermal boilers and result in major emission reductions. A straightforward integration of wind without such a strategy may lead to marginal impact only. The optimal system composition may also be affected by fuel prices and other market conditions.

As the final note, in a fully market-based situation, this kind of 'forced' HP operation and wind power curtailment might not yield the optimal solution. Nevertheless, our approach of using pre-determined curtailment strategies provides insight into different wind curtailment strategies and the idea of combining planned wind power curtailment with P2H to mitigate the challenges related to wind power integration.

## SUPPLEMENTARY DATA

Supplementary data is available at *International Journal of Low Carbon Technologies* online.

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