Analysis of several flexibility options to improve wind power integration

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Abstract

Variable renewable electricity (VRE) such as wind power plays an important role in future energy scenarios. To efficiently integrate wind power into energy systems in large scale, effective flexibility measures are needed. In this study, we investigate to what extent flexibility could cost-effectively be used to integrate wind power in large scale. We use Finland as the case study with a Nordic coupling. The main flexibility options considered are sector-coupling such as power-to-heat and power-to-gas, energy storage in the form of thermal and electric storage, and electric vehicles. We employed a national energy system model with hourly resolution incorporating all sectors of an energy system. In addition to the flexibility options, we considered the possible lock-in effect of combined heat and power (CHP), important for Nordic countries with a cold climate.

Overall, wind production could be increased up to one third of total electricity production, while decreasing annual system costs (up to 10%) and carbon emissions (up to 28%) at the same time. The amount of wind power was mainly limited by the cross-border transmission capacity and the high amount of nuclear baseload. From the different flexibility options, power-to-heat and wind curtailment produced the most cost-effective cases with the lowest CO_2 emissions, whereas power-to-gas and stationary electricity storage were the least favoured flexibility measures. Furthermore, it would seem that combined heat and power might cause an obstacle to cost-effective wind power integration, as separate heat production and heat pumps are preferred to CHP in the cost-minimizing scenarios. Most of all, the results indicate that viewing the energy system as a whole rather than separate provides valuable insight for wind power integration, and wind power integration with sector coupling could even be done cost-effectively.

1 Introduction

To mitigate the global climate change, many future energy scenarios include high shares of variable renewable electricity (VRE) such as wind power [1]. However, the fluctuating nature of VRE will increase the mismatch between power supply and demand, imposing major challenges both for energy systems and markets. Without additional flexibility, large scale VRE generation cannot be fully utilized without compromising power system reliability and safety [2]. To efficiently integrate wind power in large scale into energy systems, effective flexibility measures are needed. There is a range of different approaches for increasing energy system flexibility, ranging from supply to demand side measures [3]. Furthermore, considering the energy system as a whole and integrating power, thermal and transport sectors together could considerably improve the integration of large-scale VRE [4].

Finland, subject to the case study of this paper, has ambitious climate targets, including increasing the share of renewables to 50% by 2030 [5]. Finland's decarbonization strategy is mainly based on nuclear power and forest biomass, but the share of wind power is also rapidly increasing [6]. In addition, like in many other Nordic countries, the share of combined heat and power (CHP) is high, approximately one third of all electricity production.

Wind integration to nuclear and CHP intensive energy systems has been discussed in literature. High shares of nuclear power, especially when beyond 50%, are shown to constrain the room for wind integration [7]. CHP with thermal storages could be an economical and technically easy option for balancing wind power [8], but many studies have shown that replacing CHP with a combination of power-to-heat (P2H) solutions (heat pumps and electric boilers) and heat storages could be economically feasible for wind power integration [7, 9–11]. A 100% renewable scenario for Finland relying on power-to-gas (P2G) has also been investigated [12]. In addition, electric vehicles [13] and load-shifting [14] could provide additional system flexibility, especially in combination with P2H solutions [10].

In this paper, we study the following research questions:

1. To what extent could different flexibility measures cost-effectively be used to integrate wind power in large scale in Finland?
2. Does CHP present an obstacle to cost-effective wind power integration?

To answer these questions, we employed a national energy system model incorporating all sectors of an energy system, in order to accurately model the couplings between sectors and to study sector-coupling flexibility measures. The methodology is presented in Section 2, the results are presented and discussed in Section 3, and Section 4 presents the conclusions.

2 Methodology

2.1 Analysis approach

To assess the impacts of several flexibility options on wind power integration, we employ a techno-economical energy system analysis approach, which is described in the next.

The model first forms an hourly energy balance over a whole year of the main final energy flows (electricity, heat, and fuel) covering the different sectors of the national energy system. The model then seeks for a cost-optimal solution of the energy system while keeping the supply-demand balance and meeting all given constraints. The model includes advanced conversion (P2X) between the final energy forms, enabling the analysis of large-scale variable renewable energy with flexibility measures, and combined heat and power (CHP). An hourly analysis is also important to correctly take into account the energy system dynamics, which is essential when considering intermittent energy sources and intersectoral couplings through the different energy carriers [3]. A schematic illustration of the model is presented in Fig. 1. Industrial CHP is considered here separately from district heating CHP.

In the energy balance part of the model, primary energy sources are converted into final energy in a 2-phase conversion process. First, primary energy is converted into fuel, electricity, and heat by conventional methods. Second, advanced conversion (e.g. P2X) is used to match the final energy amounts to the actual final demand. The hourly distribution of conventional conversion is scaled from historical production data, whereas the advanced conversion is based on rules. Scaling has been used e.g. by Olauson et al. [15]. The advanced conversion technologies and flexibility options included in this study are:

1. Power-to-heat (P2H)
2. Power-to-gas (P2G)
3. Smart charging of electric vehicles (EVs)
4. Vehicle-to-grid (V2G)
5. Biomass-to-biofuel conversion (B2B)
6. Thermal storage
7. Electricity storage
8. Wind power curtailment

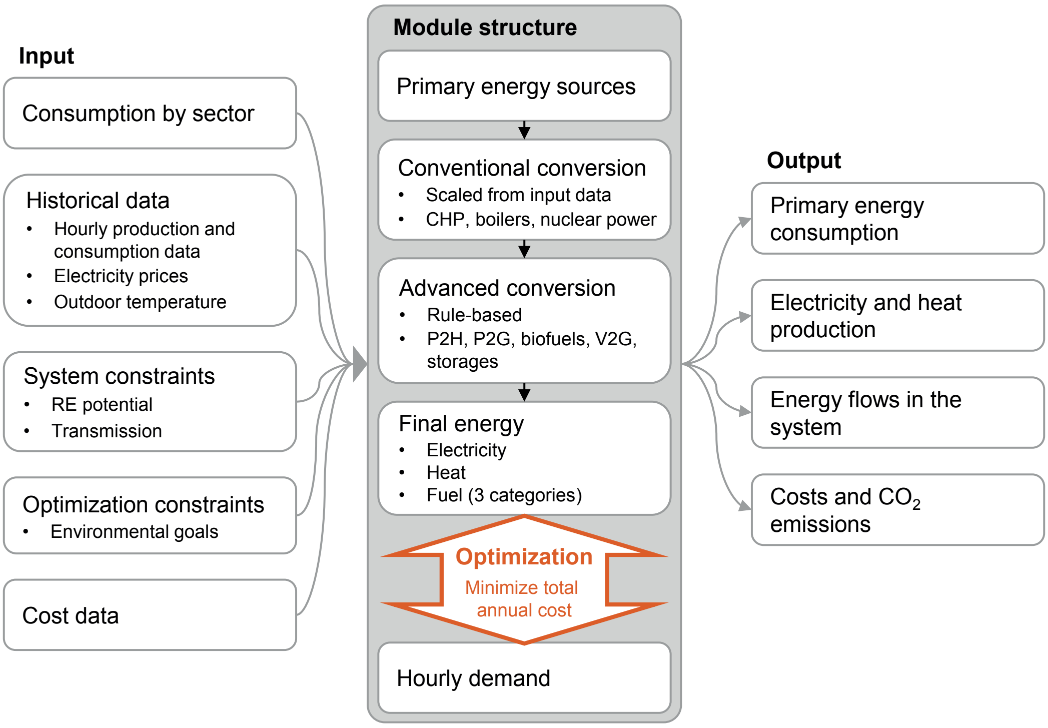

Figure 1: Schematic of the modelling approach.

The control rules for the flexibility options simply aim at balancing the unmet demands. For example, P2H operation is based on meeting the heat demand with excess electricity. Heat storage operation aims to minimize heat loss by filling any free capacity, and electricity storage aims to prevent unnecessary power import or export. Curtailment is used in case power export capacity is exceeded. Cross-border export and import are regarded as the final option for balancing electricity supply and demand.

The modelling of EVs and V2G is based on the work of Lund and Kempton [16], and it is assumed that 50% of the EV fleet participates in V2G. The batteries of the EV fleet are modelled as if there were one big battery for the entire EV fleet, and the battery's power connection to the grid depends on the driving patterns. It is assumed that 70% of EVs are grid-connected while parked. Smart charging implies that EVs may utilize excess electricity production if there is free capacity in the battery, while in V2G, two-way operation of the EV battery is allowed, limited only by the hourly power connections.

The cost optimization of the system problem is mathematically stated as

$$\min \text{Total Annual Cost} = \sum_{(t=1)}^{tech} (\text{Investment Cost}_t + \text{O\&M}_t) + \sum_{(f=1)}^{fuels} \text{Fuel Cost}_f$$
$$+ \text{Cost of imported electricity} - \text{Revenues of exported electricity} + \text{Emission costs}$$

subject to

a) balance of final energy supply and demand;
b) available renewable energy resources;
c) energy system constraints such as cross-border transmission capacities or amount of nuclear power and industrial CHP.

The annual investment cost is calculated as the total investment divided by lifetime. The hourly heat demand is calculated from outdoor temperature with a simple 2-component model, which includes a constant part for domestic hot water and a temperature-dependent space heating part. The whole country (here Finland) is modelled as a single node, without power and heat flow restrictions. However, overall transmission losses and cross-border power exchange capacities are considered. The total CO_2

emissions are calculated from the CO_2 content of the primary energy sources, considering that bioenergy is considered CO_2 neutral in statistics [17].

2.2 Input data

We use Finland's energy system in 2030 as our reference. The reference case is based on the Finnish government's National Energy and Climate Strategy 2030 [5]. The main aspects of the reference scenario are shown in Fig. 2 and Table 1. It can clearly be seen that Finland's energy strategy relies on nuclear power and biomass, composed mainly of wood and other forestry residues, as well as on combined heat and power (CHP). Primary energy (Fig. 2a) composes mostly of nuclear power, biomass and fossil fuels, one third each. The share of renewables is 40% in primary energy and 50% in final energy consumption. CHP, important in Nordic countries, produces 39% of total heat demand (Fig. 2b).

The cost and efficiency assumptions for the different technologies are given in Appendix A. Furthermore, we assume the carbon price to be 60 €/tCO_2 [1]. For the historical hourly data, we used 2013 as the reference year, for which supply and demand data was readily available [6, 18]. Wind power production data was modified [7] to reflect a higher wind integration level. To determine the hourly heat demand we used ambient temperature values from Central Finland [19]. For future market price of electricity, historical Nord Pool data for 2013 was used for the temporal price distribution [20], averaged to a projected electricity market price of 53 €/MWh [21]. Finally, the cross-border power transmission capacities are assumed to be 5460 MW for export and 5876 MW for import [22].

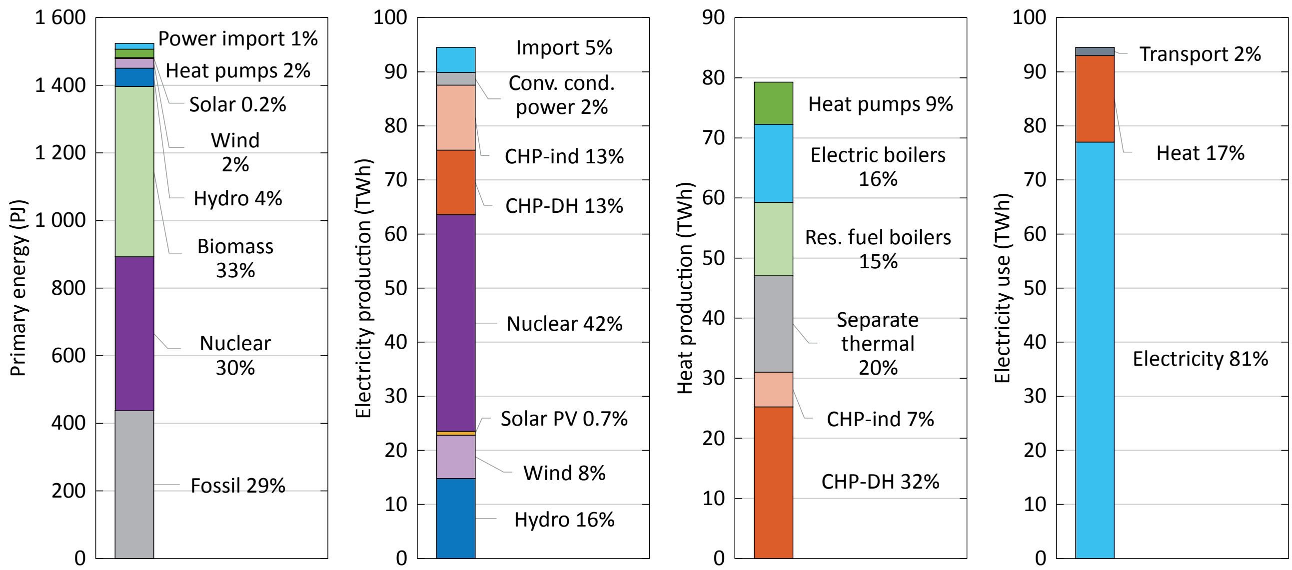

Figure 2: Reference scenario, Finland 2030, based on National Energy and Climate Strategy 2030 [5]. **(a)** Primary energy consumption **(b)** Electricity production **(c)** Heat production **(d)** Electricity use

Table 1: Consumption in Finland in 2030 based on National Energy and Climate Strategy 2030 [5].

	Fuel (PJ)	Electricity (TWh)	Heat (TWh)
Industry	380	44.0	17.7
Transport	175	1.5	-
Residential	-	11.3	41.2
Public sector	-	21.0	16.9
Transmission losses	-	3.0	3.4

2.3 Flexibility cases

The effect of different flexibility options on wind power integration is investigated through case studies, which are listed in Table 2. Each flexibility measure is considered as a separate case, and lastly as a combined case with all measures. In addition to the flexibility options, we investigate the possible lock-in effect of combined heat and power (CHP), important for Nordic countries. This is achieved by calculating all cases with both constant and variable CHP production. In the constant CHP case, CHP production stays the same as in the reference, whereas in the variable CHP case, CHP production is a variable in the optimization.

The variables in the optimization are the amount of wind power, fossil fuels, and conventional conversion (i.e. CHP and separate fuel-based power and heat production). However, the amount of fossil fuel could not be higher than in the reference scenario to avoid replacing wind power with fossil fuels.

Table 2: Cases in the study. Each flexibility option is limited by excess electricity production. Each case is run for both constant and variable CHP production (see explanation in text).

Case	Abbreviation	Notes
No flexibility measures	No P2X	
Power-to-heat	P2H	Both electric boilers (COP = 1) and heat pumps (COP = 3). Heat pumps max. 1/3 of the non-industrial heat demand.
Power-to-gas	P2G	
Smart charging of EVs	SC	
Vehicle-to-grid	V2G	Includes smart charging.
Biofuels		
Thermal storage	Heat storage	
Electricity storage	Elec storage	
Curtailment		Max. 5% of total annual wind production.
All, no P2G		All above flexibility measures except for P2G.
All, with P2G		All above flexibility measures.

3 Results and discussion

In this section, we analyse the effect of the different flexibility options described in Section 2.3.

3.1 Primary energy

Fig. 3 shows the change in primary energy consumption, compared to the reference (see Fig. 2). All cases exhibit replacement of fossil fuels with wind power and heat pumps, while the total primary energy consumption decreases by 2% at most. Primary energy replacement is higher (up to 40 PJ) in cases with variable CHP than with constant CHP. However, only 10% of total primary energy is at most replaced, due to the high amount of biomass and nuclear power, which were constant in the optimization.

Interestingly, a high number of the cases were almost identical in terms of outcomes (*No P2X*, *P2G*, *Smart charging*, *V2G*, *Biofuels*, *Heat storage* and *Elec storage*). We argue that in these cases, wind power could be added only up to a certain limit (+9 TWh), after which the export capacity (5460 MW) would exceed at peak times. In the 2013 dataset which we used as historical hourly data, this export peak occurs on Midsummer night, when overall electricity consumption is at its lowest, heat demand is low, but it is windy. During these peak hours, the difference between rigid electricity baseloads and electricity consumption can be as low as 200 MW (less than 10% of the prevailing wind power in the low-wind reference), so without demand side management high power export would be inevitable. Especially in times of low demand, the high share of nuclear baseload (26-83% of electricity demand, average 43%) poses a limit for effective wind power integration.

3.2 Electricity and heat production

Investigating the effects in final energy use is highly relevant in wind integration analysis, since wind production tends to be oversized in respect to the electricity consumption and the oversupply is often used in the other energy sectors.

Fig. 4 illustrates the differences in electricity production in the scenarios studied. Overall, 2-31 TWh of wind power could be added into the system in the different cases resulting in an 11-37% share of the electricity production. Variable CHP enabled higher amounts of wind power (8-31 TWh wind power added, resulting in an 18-37% share of the electricity production) than constant CHP (2-27 TWh and 11-31%, respectively). Taking into account cross-border power import and export, the self-use of wind power increases by 3-11 TWh (to 10-18% of total electricity use) with constant CHP and, respectively, 8-16 TWh (15-23%) with variable CHP. Curtailment seems to enable the highest wind power addition, as it can overcome the problematic peak export times discussed previously.

The dominant form of electricity defined by the policy preferences in Finland is nuclear power, but the share of wind power could be cost-effectively increased up to 37% of all electricity. This increase in wind power production is counterbalanced by increasing export and by decreasing conventional condensing power and especially CHP in the variable CHP case. The decrease in CHP and a distinct preference of separate heat production is well demonstrated in Fig. 5, as CHP heat production decreases by up to 25 TWh in all cases with variable CHP and, respectively, separate heat production increases by a similar amount. Furthermore, we find that heat pumps are employed to their maximum limit in all cases whenever included. Based on the changes in heat production in the different scenario cases (shown in Fig. 5), it seems that the order of preference in the heating solutions would be 1) heat pumps, 2) separate heat boilers, and 3) CHP, thus allowing efficient use of low-marginal-cost power sources (wind, solar, nuclear).

The intersectoral coupling of the different flexibility options is illustrated in Fig. 6. Cases with P2H exhibit directing excess wind power to heat (21-29% of electricity use), curtailment increases wind power export (14-23%), and P2G directs a small amount of excess electricity (1-3%), that would otherwise be exported, to synthetic gas. The small amount of P2G suggests that P2G might not yet be a cost-effective solution to wind integration compared to P2H and curtailment.

3.3 Further effects on the power system

Table B.1 presents the cost-optimal amounts of the various flexibility measures compared to the reference case. Most notably the results suggest that electricity storage might not be very cost-effective at this point, as the optimization did not prefer this option in any case. Furthermore, we find that the demand for heat storage decreases when CHP is replaced with more flexible separate heat production.

Even though the different flexibility cases may not differ much on the annual level, e.g. annual primary energy and electricity supply (Figs. 3 and 4), their effect on the power duration curve is well recognized. Fig. 7 illustrates the power duration curve of power import and export, which reflects the effect of the flexibility options on the hourly level. Firstly, it can be noticed that the curtailment cases exhibit much higher amount of export; curtailment allows wind power oversizing as export peaks can be avoided. Secondly, smart charging of electric vehicles and vehicle-to-grid mitigate small imbalances in demand, as there are significant periods of the year without any cross-border power exchange (1100-1400 h with SC, 2100-2900 h with V2G). This results in a 'zigzag' shape of the duration curve. Thirdly, P2G directs all potential export to gas synthesis, but this is due the operational rules.

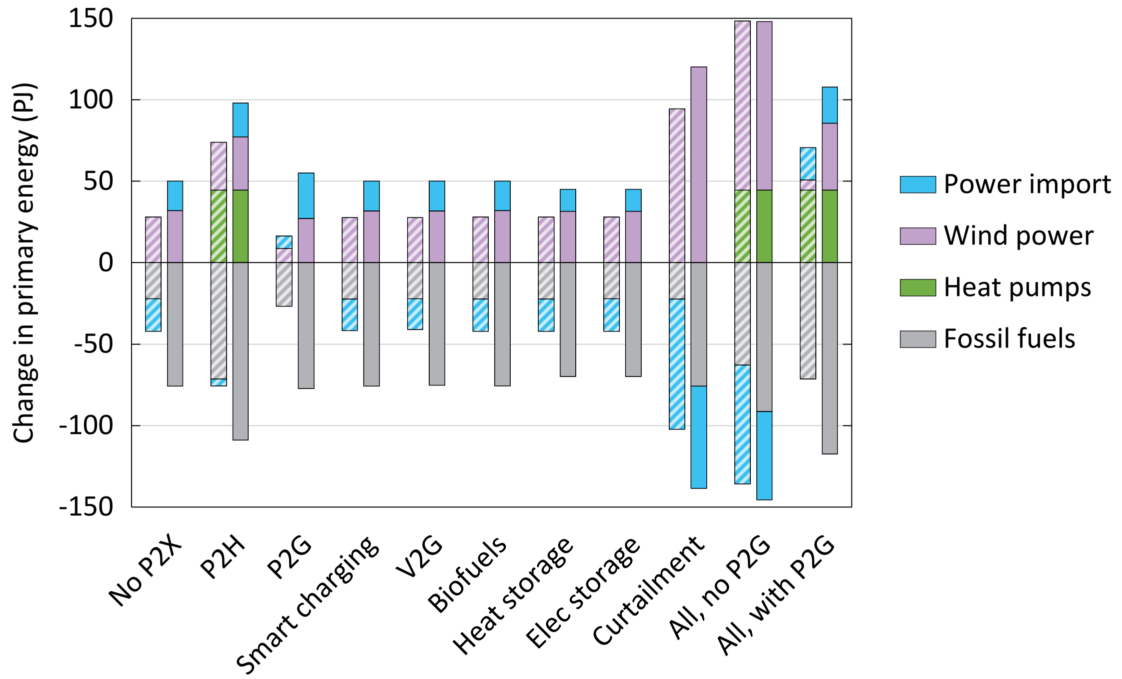

Figure 3: Change in primary energy, compared with the reference. The columns on the left (striped) refer to constant CHP, and on the right to variable CHP.

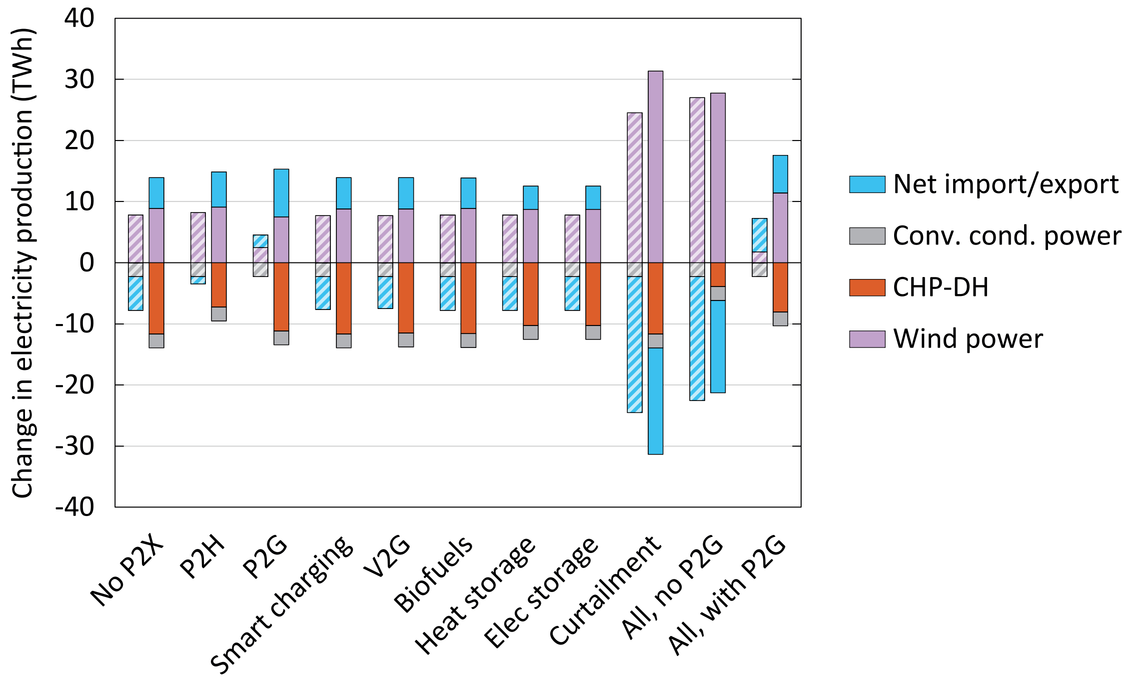

Figure 4: Change in electricity production, compared with the reference. The columns on the left (striped) refer to constant CHP, and on the right to variable CHP.

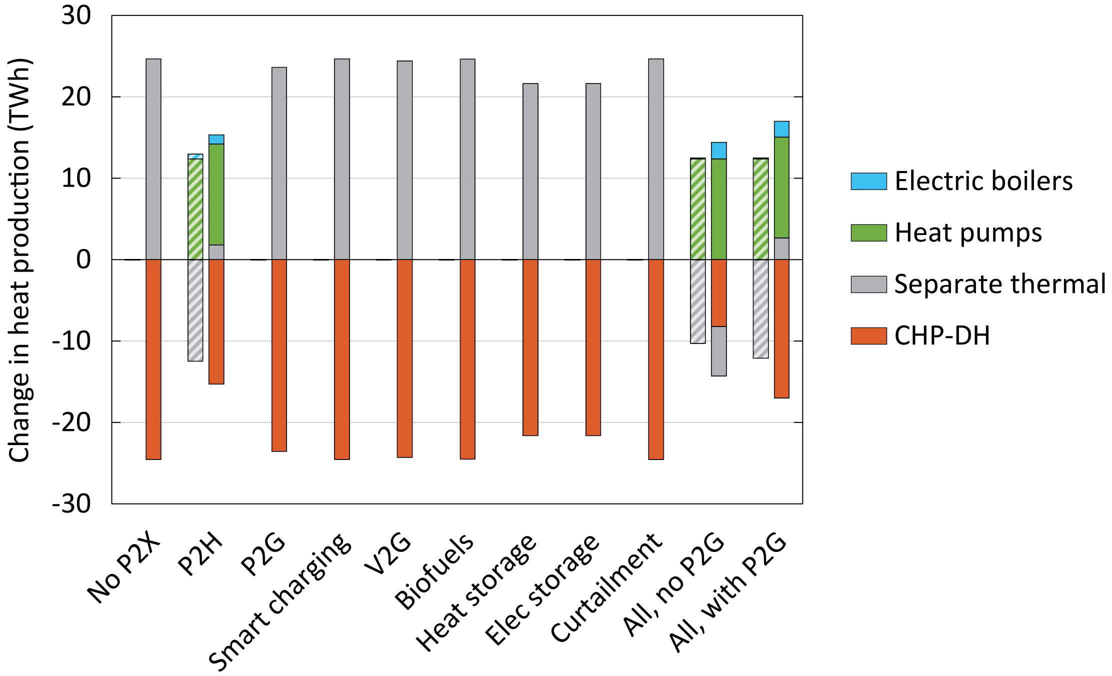

Figure 5: Change in heat production, compared with the reference. The columns on the left (striped) refer to constant CHP, and on the right to variable CHP.

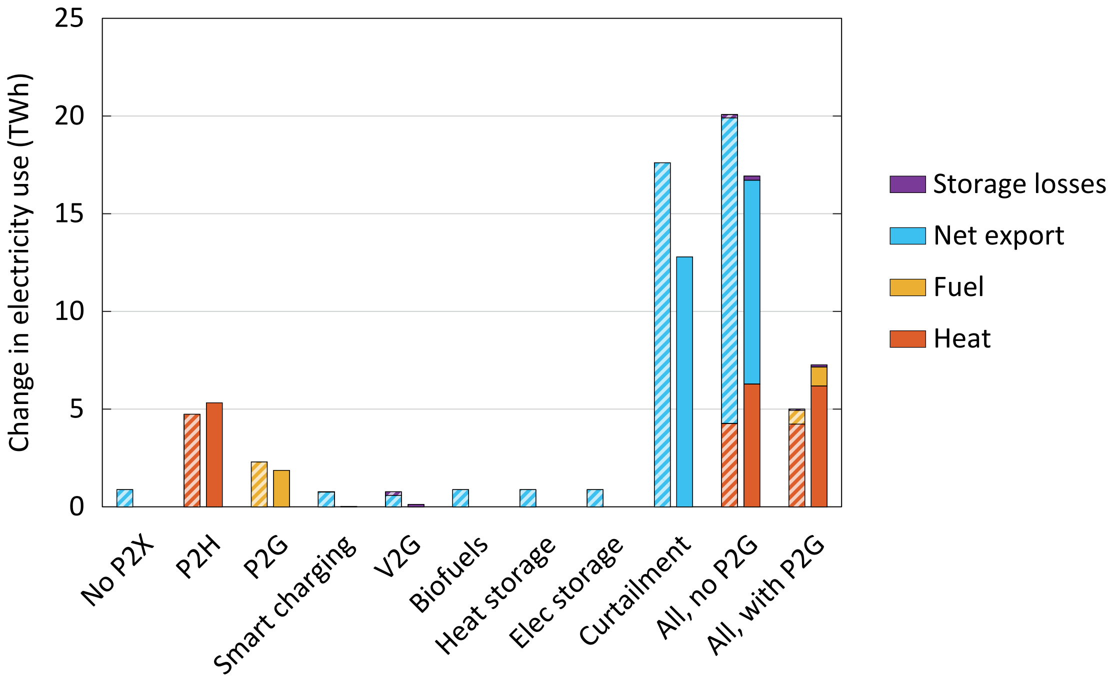

Figure 6: Change in electricity use, compared with the reference. The columns on the left (striped) refer to constant CHP, and on the right to variable CHP.

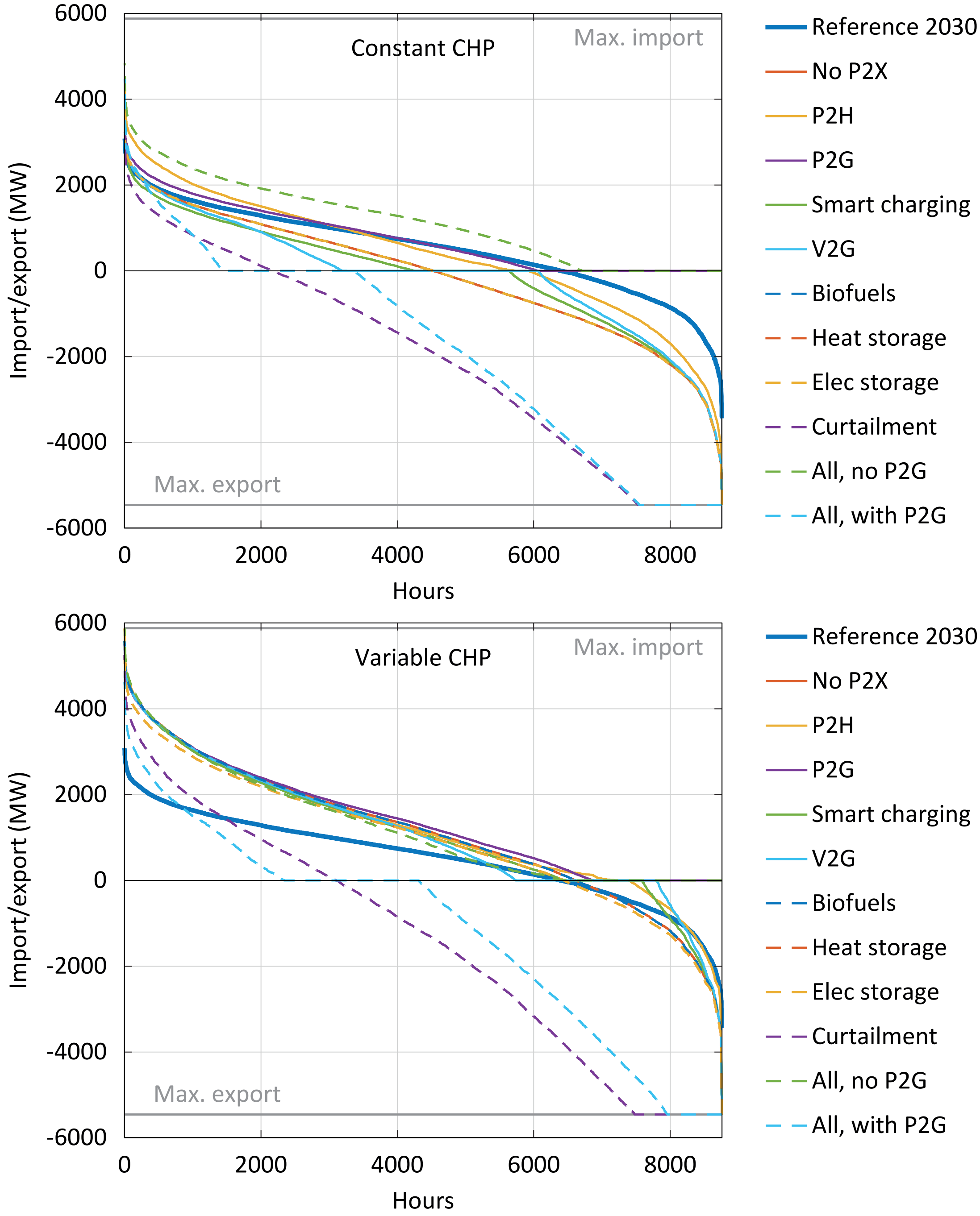

Figure 7: Duration curve of power import (positive) and export (negative) with the different flexibility measures, with **(a)** constant CHP and **(b)** variable CHP.

3.4 Costs and CO_2 emissions

Finally, we analysed the annual costs and CO_2 emissions of the scenario cases. The overall results are shown in Fig. 8, while the numerical values can be found in Table B.1.

All cases had lower annual costs (-1-10%) and CO_2 emissions (-5-28%) than the reference case. The lowest cost was in the case *All, no P2G* (-10%/-10%, constant CHP/variable CHP), followed by *P2H* (-8%/-9%) and *Curtailment* (-7%/-10%) respectively. The cases with constant CHP had on average 2% higher costs than variable CHP. On the other hand, cases *Smart charging*, *Biofuels*, *Heat storage* and *Elec storage* had exactly the same costs than the case with no P2X, further highlighting the apparent ineffectiveness of these particular technologies for cost-effective wind power integration as they were not able to decrease system costs. However, this may have been caused by the limited power export capacity discussed in Section 3.1.

As for the CO_2 emissions, the lowest emissions were in the *P2H* case (-15%/28% from the reference), followed by *All, with P2G* (-15%/23%) and *All, no P2G* (-14%/20%). All the other cases had similar emissions than the No P2X case. The cases with constant CHP had on average 11% higher emissions than variable CHP, explained by the higher fossil fuel demand in CHP.

Overall, adding wind power seems to decrease annual costs and CO_2 emissions, also illustrated in Fig. 9. Overall system cost exhibits a clear downward trend with increasing wind power. Based on this observation, it seems that wind power could be cost-effective up to a certain limit, but after this limit increasing wind power would increase costs. Unusable excess wind power may be more expensive to integrate to the system, for example with P2G or electrical storage, than the cost benefit of fossil fuel replacement. Furthermore, large-scale wind power integration may imply major energy system changes, such as extension of infrastructures, the analysis of which were beyond the scope of this study.

As the final note, we also tested how much wind power could be integrated at maximum, not considering cost-effectiveness. With all the available technologies (similar to *All, with P2G*), wind power production could be increased up to 70% of electricity production, which would decrease the CO_2 emissions by 50-81% from the reference case, but this would result in 46-58% higher costs. Without P2G, the respective numbers would be up to 50% wind power, 18-35% higher costs, and 16-19% lower emissions. These results illustrate that allowing up to 35% higher costs, the amount of wind power could be increased up to one half of all production, compared with the 9% wind share in the reference case.

4 Conclusions

The purpose of this paper was to assess the viability and effects of different flexibility options to improve wind power integration in a national energy system using Finland as the case study. The main flexibility options considered were sector-coupling such as power-to-heat and power-to-gas, energy storage in the form of thermal and electric storage, and electric vehicles. As the reference case we used Finland's energy strategy for year 2030, which heavily relies on forest biomass and nuclear power as low-carbon energy sources with less focus on VRE. We investigated here to what extent flexibility could cost-effectively be used to integrate wind power in large scale.

Overall, wind production could be increased up to one third of the total electricity production, while decreasing annual system costs (up to 10%) and carbon emissions (up to 28%) at the same time. The amount of wind power was mainly limited by the cross-border transmission capacity and the high amount of nuclear baseload. From the different flexibility options, power-to-heat (P2H), wind curtailment, and the combination case *All, without P2G* produced the most cost-effective scenarios with the lowest CO_2 emissions. On the other hand, the other simulated flexibility options (P2G, Smart charging, V2G, biofuels, heat and electricity storages) appeared to be quite similar to the situation without additional flexibility measures. Furthermore, the power-to-gas (P2G) case showed the lowest level of cost-effective

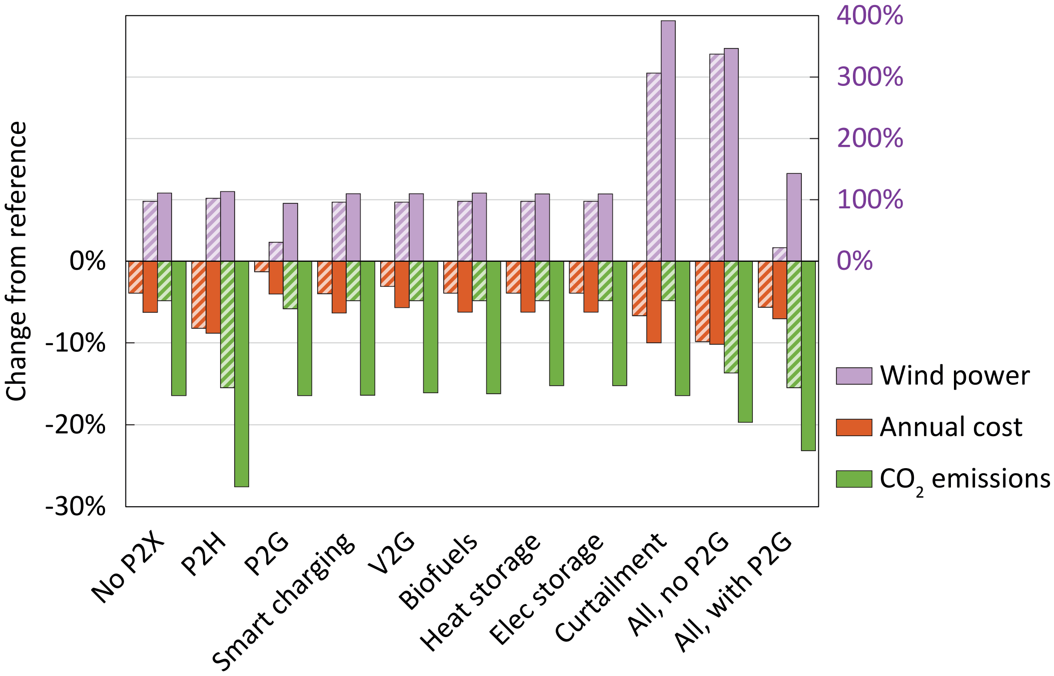

Figure 8: Effect of the different flexibility measures. Power-to-heat (P2H) and curtailment are the most cost-effective, though the cost differences are quite small, max. 10% from the reference case. The columns on the left (striped) refer to constant CHP, and on the right to variable CHP.

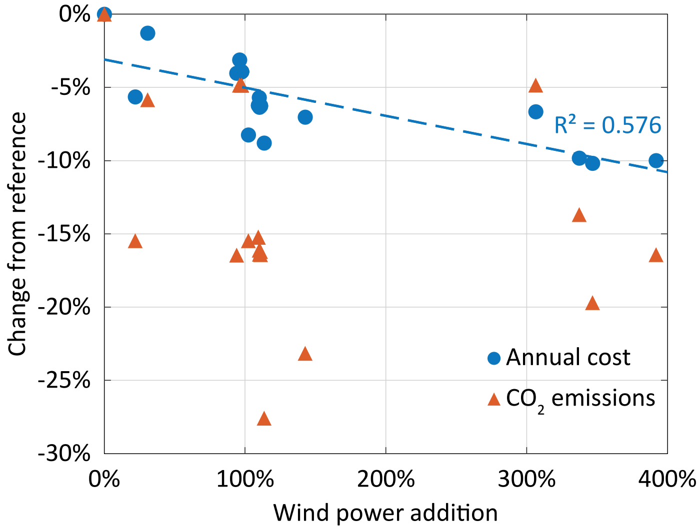

Figure 9: Effect of the different flexibility measures. Power-to-heat (P2H) and curtailment are the most cost-effective, though the cost differences are quite small, max. 10% from the reference case. The columns on the left (striped) refer to constant CHP, and on the right to variable CHP.

wind power integration, and stationary electricity storage was not added in any of the cases, implying low cost-effectiveness.

In addition, it would seem that combined heat and power (CHP) might limit the use of cost-effective wind power integration, as separate heat production and heat pumps are preferred to CHP in the cost-minimizing simulation. The cases with less CHP had higher amounts of wind power (avg. 20%), as well as lower annual costs (avg. 2%) and lower emissions (avg. 11%), than the cases with the reference level of CHP. The replacement of CHP by heat pumps is in line with several previous studies [7, 9].

The results suggest that wind power integration with sector coupling could be done cost-effectively up to a certain limit, as the system cost decreases with increasing wind power production at least up to 37% of the electricity production in the Finnish case. The amount of wind power could technically be increased even higher, up to 70% of electricity production, but this would result in 60% higher costs. Most of all, the results indicate that viewing the energy system as a whole rather than separately provides valuable insight for wind power integration.

Acknowledgements

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Appendix

A Input data for the cases

Table A.1: Fuel costs (excluding taxes) and carbon contents. The costs are based on [23] if not mentioned otherwise. The CO_2 emission factors are based on [17]. Fuels not listed are assumed to have zero cost and emissions. Emissions from biomass are written in brackets, but here they are considered zero-emission energy sources.

Fuel type	**Cost (€/GJ)**	**CO_2 emission factor ($kgCO_2/GJ$)**	**Notes on costs**
Oil	9.1	73.0	
Coal	2.3	93.3	
Natural gas	7.6	55.0	
Peat	3.8	105.9	
Nuclear	1.1	0	[24]
Industrial wood residue	0	(109.6)	Own assumption
Other wood	6.0	(109.6)	
Agro-biomass	3.0	(100.0)	Assumed half of the cost of energy wood
Waste	0	31.8	Own assumption
Biogas	7.6	(56.1)	Cost assumed same as natural gas

Table A.2: Costs of different technologies used in study. The costs are based on [10, 24, 25], otherwise mentioned.

Technology	Invest. cost (€/kW)	Fixed O&M (€/kW)	Variable O&M (€/MWh)	Lifetime (years)	Notes
Hydropower	1 500	8	0	50	
Wind power	1 200	37	11.0	25	
Nuclear power	4 000	40	0	50	
Solar PV	800	17	8.2	25	
CHP-DH	1 300	25	2.7	30	
CHP-industrial	1 300	25	2.7	30	
Condensing power	1 300	52	0	35	
Heat-only boiler	150	9	1.5	35	
Residential boiler	200	2	0	20	
Electric boiler	40	1	0	40	
Heat pumps	900	2	0	40	
P2G	800	32	-	30	[12]
G2L	300	12	-	20	[12]
Biofuel conversion (unit €/PJout)	17.5	1.9	-	20	[26]
	Invest. cost (€/MWh)	**Fixed O&M (% of invest.)**		**Lifetime (years)**	
Heat storage	900	1%		25	
Electricity storage	100 000	3%		15	
V2G	Cost of vehicle-to-grid calculated from the number of extra cycles to car batteries due to V2G activity, based on 1000 cycles during normal lifetime.				

Table A.3: Conversion efficiencies of advanced conversion (P2X). The efficiencies are based on own assumptions if not mentioned otherwise. The conversion efficiencies of conventional technologies, such as CHP, are assumed to be the same as in 2013 [6].

Technology	Conversion efficiency		Notes
P2H – Electric boiler	0.95		
P2H – Heat pump	3		
P2G	0.55		[27]
Gas-to-liquid (G2L)	0.8		[12]
Biofuel conversion	0.8		
	Charging efficiency	**Constant loss**	
Heat storage	1	0.06% / hour	[28]
Electricity storage	0.9	3% / month	[29]

B Flexibility additions

Table B.1 is presented here due to its horizontal width.

Table B.1: Flexibility additions in the different cases. The colors visualize positive (green) and negative (red) additions within a category, compared with the reference (shown in a separate column).

P2X additions	Reference	No P2X		P2H		P2G		Smart charging		V2G		Biofuels		Heat storage		Elec storage		Curtail-ment		All, no P2G		All, with P2G	
		consCHP	varCHP	consCHP	varCHP	consCHP	varCHP	consCHP	varCHP	consCHP	varCHP	consCHP	varCHP	consCHP	varCHP	consCHP	varCHP	consCHP	varCHP	consCHP	varCHP	consCHP	varCHP
P2H - electric heating (TWh of heat)	13	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	2
P2H - heat pumps (TWh of heat)	7	0	0	12	12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	12	12	12	12
P2G (PJ of gas)	0	0	0	0	0	5	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2
Biofuel from biomass (PJ)	40	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	21	0	3
Heat storage (GWh)	36	0	0	0	0	0	0	0	0	0	0	0	0	0	-15	0	-14	0	0	5	86	42	-29
Elec storage (GWh)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
V2G output (TWh)	0	0	0	0	0	0	0	0	0	0.7	0.5	0	0	0	0	0	0	0	0	0.7	0.8	0.2	0.4
Heat storage output (TWh)	0.6	0	-0.4	0.6	-0.4	0	-0.4	0	-0.4	0	-0.4	0	-0.4	0	-0.5	0	-0.5	0	-0.4	0.1	-0.1	0.7	-0.5
Elec storage output (TWh)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Wind curtailment (TWh)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.7	2.1	1.8	1.0	0	0
CHP heat (TWh)	25	0	-25	0	-15	0	-24	0	-25	0	-24	0	-25	0	-22	0	-22	0	-25	0	-8	0	-17
Wind production (TWh)	8	8	9	8	9	2	8	8	9	8	9	8	9	8	9	8	9	25	31	27	28	2	11
Annual cost (100 = reference)	100	-4%	-6%	-8%	-9%	-1%	-4%	-4%	-6%	-3%	-6%	-4%	-6%	-4%	-6%	-4%	-6%	-7%	-10%	-10%	-10%	-6%	-7%
CO_2 emissions ($MtCO_2$)	33.5	-5%	-16%	-15%	-28%	-6%	-16%	-5%	-16%	-5%	-16%	-5%	-16%	-5%	-15%	-5%	-15%	-5%	-16%	-14%	-20%	-15%	-23%

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