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Influence of wind power, plug-in electric vehicles, and heat storages on power system investments

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ABSTRACT

Due to rising fuel costs, the substantial price for CO_2 emissions and decreasing wind power costs, wind power might become the least expensive source of power for an increasing number of power systems. This poses the questions of how wind power might change optimal investments in other forms of power production and what kind of means could be used to increase power system flexibility in order to incorporate the variable power production from wind power in a cost-effective manner.

We have analysed possible effects using an investment model that combines heat and power production and simulates electric vehicles. The model runs in an hourly time scale in order to accommodate the impact of variable power production from wind power. Electric vehicles store electricity for later use and can thus serve to increase the flexibility of the power system. Flexibility can also be upgraded by using heat storages with heat from heat pumps, electric heat boilers and combined heat and power (CHP) plants. Results show that there is great potential for additional power system flexibility in the production and use of heat.

1. Introduction

Wind power is a variable and partly unpredictable power source that influences the rest of the energy system in ways that are different from conventional power plants. Wind power is also quickly becoming a major new source for power generation. As a result, new studies have been made to assess different aspects of integrating wind power into power systems.

One major aspect is the analysis of the additional costs and benefits that rise from power system operation with this variable and partly unpredictable power source. While this has been the dominant focus of research on wind power integration, increasing the share of wind power in the systems will also change the cost-optimal power production portfolio in the long-term. We analyse the investment and operational costs associated with this change. By changing assumptions about the relative costs of producing electricity and heat with different technologies, we arrive at different power system configurations and can demonstrate situations where wind power becomes the dominant source of power production. More flexible power systems enable the less costly integration of wind power. Therefore, we analyse the effect of two new forms of flexibility: plug-in electric vehicles and heat storages operated in tandem with heat pumps and electric heat boilers.

In general, wind power integration costs have been found to be relatively small, at least up to penetration levels of around 25%, as demonstrated by the several studies compared in the IEA collaboration (Holttinen [1]). The literature behind the article also establishes how to carry out wind integration studies (more detail and references in Holttinen et al. [2]). Wind power has influence on several different time scales. The main benefits of wind power result from fuel savings and lower CO_2 emissions as well as a decrease in conventional capacity requirements. Wind power also inflicts costs, mainly due to the variability of the resource and forecast errors. Costs are accrued especially from increases in the cycling of conventional power plants, partial load operation, non-spinning reserve capacity and transmission needs, as well as the relatively lower contribution to capacity than to electricity production.

Impact of wind power increases with penetration, but only a few attempts have been made to estimate the costs and benefits at higher penetrations (Meibom et al. [3], Karlsson & Meibom [4], Ea [5], Milborrow [6], Lund & Mathiesen [7] and earlier work with the same model [8,9], Ummels et al. [10]). One reason why such studies are more difficult to make is that wind power starts to affect the optimal portfolio of other power plants in the system by reducing their full load hours. With higher penetration levels, it becomes

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Nomenclature

Indices

i, I	Unit, set of units
I_a	Set of units in area a
$I^{HeatSto}$	Heat storage units
I_{PI}	Plug-in electric drive vehicles
r, $\bar{r}$, R	Region, neighbouring region, set of regions
a, A	Area, set of areas
t, T	Time steps, set of time steps
k, K	Country, set of countries

Variables

C	New capacity
P	Power generation
P^{Cur}	Wind curtailment
Q	Heat generation
S	Storage level
T	Electricity exchange between regions
U	Loading of electricity storage
Z	Loading of heat storage

Parameters

av	Availability of the unit
cc	Capacity credit
c^{Loss}	Transmission loss
C^{Ex}	Existing capacity
c^{Inv}	Annualized investment costs
c^{Fix}	Fixed operation and maintenance cost
$c^{Operation}(\cdot)$	Operation cost function of unit
d	Electricity demand
d^P	10-year peak demand
d_{PI}	Demand of plug-in vehicles
h	Heat demand
l	Round-trip storage loss
LC	Loading capacity of storage
SC	Storage capacity
W	Weight of time period

more and more unrealistic to assume that there would be no changes in the rest of the power system (Söder & Holttinen [11]). It is also unrealistic to implement such changes without proper investment optimization.

Karlsson & Meibom [4] use the same investment optimization model as in this article and consider high wind power penetration levels. However, their analysis concentrates on the cost competitiveness of hydrogen in road transport. In the All Island Grid Study, Meibom et al. [3] analyse wind power integration costs for six different power plant portfolios. Doherty [12] created these portfolios using a separate model, arriving at least-cost options according to varying input parameters. Furthermore, the influence of high wind power penetration on transmission systems was analysed by Nedic et al. [13] in the same study. While the study was comprehensive in many respects, it did not include the flexibility mechanisms studied in this article, namely plug-in electric vehicles and heat storages.

Ea [5] employed a similar approach and the same model as here, but again did not include the additional flexibility provided by heat storages and plug-in electric vehicles. Milborrow [6] quotes a tentative study by EnergiNet.DK, which indicates that there are no technical constraints for very large wind power penetrations and that the costs of variability should remain reasonable.

In work by Lund & Mathiesen [7], very large wind penetrations are achieved with power system flexibility from hydrogen generation and biomass CHP plants. Their model does not include endogenous investments and the investment decisions are based on expert opinions about energy system development. The results serve a somewhat different purpose than this article, as we have sought to focus on the merits of different ways of increasing power system flexibility. In another article [14], the same authors compare different ways of facilitating the integration of fluctuating power sources. Again their model does not include endogenous investments. As can be seen from this article, variable sources of power and different flexibility mechanisms change the optimal reference power plant portfolio, leading to deviation in the comparative results. Their analysis demonstrated that heat storages can have an important impact on power system flexibility, which also comes out strongly in our results. They also show that the use of electrolysers to produce hydrogen for fuel cell vehicles or combined heat and power plants does not appear to be cost competitive with the flexibility mechanisms provided by heat measures and battery electric vehicles.

Ummels et al. [10] analysed compressed air energy storage, pumped hydro storage and conventional heat boilers as means to increase flexibility. The model only analysed operational costs and did not make investment decisions. Of the three options, heat boilers were the most promising from the economical perspective, although their usefulness is limited to low load, high wind situations.

For a lower wind power penetration level of 20%, a large study was conducted by the US DoE [15]. The study used a generation expansion model and also incorporated a simple transmission system expansion. The assumptions about the relative costs of different technologies were such that wind power would not be cost competitive even in 2030 and would remain at the pre-ordained 20% minimum. In this study, wind power was more competitive and as a result higher penetration levels were cost-optimal. As there is no a priori knowledge about the relative competitiveness of different power production technologies in 20–30 years – and wind power cost is location dependant – it is prudent to also analyse situations where wind is the least-cost source of electricity. However, there will be a limit on the cost-optimal penetration level as integration costs keep increasing in step with penetration. This article analyses those situations and additionally takes into account the possibility of making use of new forms of flexibility to decrease integration costs.

The different time scales involved in investment optimization and operational optimization make the wind integration problem more complicated. A model that can analyse the operational costs of a power system is too detailed for analysing long-term investments. Therefore we use a model that optimizes the investments and somewhat simplifies the operational characteristics of power plants. This model, Balmorel, does not include start-up costs, part-load efficiencies or wind power forecast errors, all of which would increase the costs of integrating wind power into the system. The next step would be to feed the long-term investment results from Balmorel into a more complete power system model and analyse the missed costs. However, this step is not included in our analysis.

Our analysis seeks to fill a gap in the knowledge of wind power integration. We include long-term investment analysis with wind integration, enabling us to estimate the long-term total system costs of switching from conventional power production toward wind power. Portfolio planning has a long history and work has been done to include wind power (Doherty et al. [16]). Our extension also accounts for the effect of storages in heating and transport in the analysis. Doherty et al. [16] take fuel price volatility into account in their analysis. This would improve our study as well, but due to the hourly time series the complexity of the Balmorel model does not allow for the large number of model runs required to analyse the effect of fuel price volatility on the power plant portfolios.

The analysis made in our study is highly sensitive to the parameters put into the models and therefore the paper includes a detailed description of inputs and assumptions in order to increase transparency. It also means that a single study cannot take all the variables into account and only gives a partial view of the issue. To account for some of this, we have done a sensitivity analysis on a couple of influential variables.

Section 2 describes the Balmorel model. The data used and cases analysed are presented in chapter 3. Chapter 4 presents and analyses the model results. Conclusions are made in chapter 5.

2. Model

The Balmorel model is a linear optimization model of a power system including district heating systems. It calculates investments in storage, production and transmission capacity and the operation of the units in the system while satisfying the demand for power and district heating in every time period. Investments and operation will be optimal under the input data assumptions covering e.g. fuel prices, CO_2 emission permit prices, electricity and district heating demand, technology costs and technical characteristics. The model was developed by (Ravn et al. [17]) and has been extended in several projects, e.g. (Jensen & Meibom [18], Karlsson & Meibom [4]). The main equations of the model as used in this study are presented below with a focus on the contributions to the model in this paper, i.e. the capacity balance equation (eq. (4)) and inclusion of plug-in electric drive vehicles (eqs. 5–8).

The optimization period in the model is one year divided into time periods. This work uses 26 selected weeks, each divided into 168 h. The yearly optimization period implies that an investment is carried out if it reduces system costs including the annualized investment cost of the unit (eq. (1)).

The geographical resolution is countries divided into regions that are in turn subdivided into areas. Each region has time series of electricity demand and wind power production. Transmission lines connect the regions. Each country is divided into several regions to represent its main transmission grid constraints. The transmission grid within a region is only represented as an average transmission and distribution loss. Areas are used to represent district heating grids, with each area having a time series of heat demand. There is no exchange of heat between areas. In this article, Finland is used as the source for most of the input data.

The objective function (eq. (1)) minimizes system costs, which comprise the annualized investment costs of new investments, the fixed operation and maintenance costs of existing units and new investments, and the operational costs of units. The operational costs are fuel costs and costs of consuming CO_2 emission permits during model time periods. Each time period is weighted to represent a longer time span in order to cover full-year costs. Electricity demand in each region (eq. (2)) and district heating demand in each area (eq. (3)) have to be fulfilled in each time period. Wind power production is treated as production following a fixed production time series with the possibility of curtailing wind power if cost-optimal for the system.

Following Doherty et al. [16], a capacity balance equation (eq. (4)) was added to the model to ensure adequate production capacity and reserve margin in a country. The production capacity of each unit (either existing or new) is multiplied with the capacity credit. This is summed over all units and the result must be greater than the 10-year peak in demand. The peak demand for Finland was taken from Nordel [19] and corresponds to the peak demand caused by cold winter weather that is expected to happen once in ten years. It is approximately 5% higher than the peak demand in a normal winter [19]. It was scaled with the ratio between the estimated yearly electricity consumption in 2035 and the consumption in 2007 to get the peak demand in 2035. The capacity credit of conventional units is set to 0.99 (Doherty et al. [16]), and wind power is set to 0.14 (Holttinen [20], Petäjä & Peltola [21]). The capacity credits of conventional units are higher than the availability of these units, being in the order of 0.85–0.95, because the capacity credit is related to the average availability of all units during peak-load hours. More rigorously the capacity value of any generator is the amount of additional load that can be served at the target reliability level with the addition of the generator in question [2].

Equation (5) also influences the demand for capacity by ensuring that the power production from a unit either existing or new is lower than the capacity of the unit multiplied with an average availability. The equation simplifies the availability of power plants by assuming that a constant portion of each power plant type is unavailable due to scheduled maintenance or forced outage. Availability of wind power is included in the wind power production time series.

In the base scenario equations (4) and (5) results in installed capacity of power plants being 17% higher than the peak demand (i.e. a reserve margin of 17%) decreasing to 13%, if it is assumed that wind power has no capacity credit.

Plug-in electric drive vehicles are modelled as electricity storage with storage (eq. (6)), loading (eq. (7)) and unloading (eq. (8)) capacities depending on the number of vehicles connected to the grid in each time step. The balance equation for the electricity storage of plug-ins (eq. (9)) includes the electricity consumption of the plug-in vehicles. It is assumed that the investment costs of plug-in vehicles are covered by benefits in the transport sector, such that the model does not invest in plug-ins. The Balmorel model includes restrictions specifying the technical capabilities of CHP plants, heat pumps and electric boilers, heat and electricity storages, and hydropower with reservoir, although they are not shown here. The same applies to restrictions limiting the ramping up of units and the yearly usage of specific fuels.

$$\min\left(\sum_{i\in I} c_i^{\mathrm{Inv}} C_i + \sum_{i\in I} c_i^{\mathrm{Fix}}\left(C_i^{\mathrm{Ex}} + C_i\right) + \sum_{t\in T}\sum_{i\in I} w_t c_i^{\mathrm{Operation}}\left(P_{i,t}, Q_{i,t}\right)\right) \tag{1}$$

s.t.

$$\sum_{a\in A(r)}\sum_{i\in I_a} P_{i,t} - P_t^{Cur} + \sum_{\bar{r}\in R}\left(\left(1-c^{Loss}\right)\cdot T_{r,\bar{r},t}\right) = d_{r,t} + \sum_{\bar{r}\in R} T_{\bar{r},r,t} + \sum_{i\in I_a^{Pl}} U_{i,t} \quad \forall t\in T; r\in R \tag{2}$$

$$\sum_{i\in I_a} Q_{i,t} = h_{r,t} + \sum_{i\in I_a^{\mathrm{HeatSto}}} Z_{i,t} \quad \forall t\in T; a\in A \tag{3}$$

$$\sum_{a\in A(k)}\sum_{i\in I_a} cc_i\left(C_i^{Ex} + C_i\right) \geq d_k^p \quad \forall k\in K \tag{4}$$

$$P_{i,t} \leq \left(C_i^{\mathrm{Ex}} + C_i\right)\cdot av_i \quad \forall i\in I; t\in T \tag{5}$$

$$S_{i,t} \leq SC_{i,t} \quad \forall i\in I_{Pl}; t\in T \tag{6}$$

$$U_{i,t} \le LC_{i,t} \quad \forall i \in I_{PI}; t \in T \tag{7}$$

$$P_{i,t} \le C_{i,t} \quad \forall i \in I_{PI}; t \in T \tag{8}$$

$$S_{i,t+1} = S_{i,t} + U_{i,t} - P_{i,t}/l_i - d_{PI,t} \quad \forall i \in I_{PI}; t \in T \tag{9}$$

3. Cases

3.1. Description of the analysed system

The analysis is performed on the power system of Finland. The Finnish system gets about 10% of its production from hydropower and most of it is controllable to a smaller or larger extent. The share of global electricity production accounted for by hydropower was around 16% in 2004. Therefore we believe that the Finnish system is a good representative of a more general power system. Representativeness increases due to the long timeframe, since many of the power plants that are now in operation will be retired before the year of analysis and local historical decisions will have less influence. Our target year is 2035, which is far enough into the future that by then there will have been major turnover in the power plant fleet.

Finland is a northern country where heating is required during the winter. The country has many combined heat and power units for district heating. The model includes three heating areas for Finland, all of which have to fulfil their heating requirements separately. The first of these areas is the capital region, the second aggregates industrial heat demand, and the last aggregates district heat demand for space heating in other population centres with district heating.

The model can invest in electric heat boilers, heat pumps, and heat storages. This enables the model to further increase the flexibility of the power system to accommodate larger amounts of variable power (Meibom et al. [22]). Although more southern countries do not have similar heating needs, they could use district cooling in the summertime and have similar connections between cooling and power in the future, especially when climate change leads to warmer summers. Some district cooling networks are already operational in the Nordic countries. Similar operational benefits can also be achieved without district heating or cooling networks using local hot water tanks or ice storage. Many local water heat tanks already exist in Finland, but the heat demand fulfilled by these devices is not covered by this analysis. Industrial heat demand uses a large fraction of global primary energy and could serve as a source of flexibility for the power system, especially in countries where space heating and cooling has a lesser role. Although heat demand in Finland is comparatively high in principle, only part of it was available for the model: types of heating other than district heating were not included and a large fraction of industrial heat was served by cost-free wood waste from industrial processes.

Other options for increased flexibility may emerge in the future, such as electric vehicles or cost competitive electricity storages. We analyse the effect of plug-in electric vehicles by approximating them as electricity storages with capacity limitations that vary according to plug-in availability. The time series for plug-in availability have been derived from the National Travel Survey conducted during 2004–2005 in Finland (WSP LP Consultants [23]). It gave information on the purpose, timing, and distance of personal travel. The information was processed to give estimates of the times when people driving cars might arrive at their workplaces and home as well as of the distances they travelled to get there. The Balmorel model does not do investment optimization for plug-in vehicles, as the transport sector is not covered by the model. Instead, it is assumed that the investment costs of the plug-in electric vehicles are covered by fuel savings and other benefits (e.g. reduction of local pollutants) in the transport sector.

Table 1
Definitions of words used in scenario names.

Base	Wind at 800 €/kW, no flexibility, nuclear allowed, high fuel prices
700	Wind at 700 €/kW
900	Wind at 900 €/kW
OnlyPlug	One million plug-in vehicles with flexible charging/discharging
OnlyHeat	Heat storages, heat pumps and electric heat boilers allowed
HeatPlug	Both plug-in vehicles and heat measures
NoNuc	No new nuclear plants allowed
LowFuel	Lower fuel price scenarios as indicated in Table 2

3.2. Input data for investments

Assumptions made for the model runs are crucial for the results and the results should not be interpreted without taking the assumptions into account. The paper does not try to assume the most likely future costs for investments, fuels, and CO_2 emissions. Rather, it seeks to chart how large penetration of wind power could affect the rest of the power system and identify the situations where this might happen. Cost assumptions therefore intentionally set up situations where wind power is a very large contributor to electricity production.

To create different scenarios, we varied the cost of fuels and the cost of wind power as well as allowed and disallowed different technologies. The scenario names are described in Table 1. Most scenarios use the high fuel prices indicated in Table 2. The number of plug-in vehicles is exogenously set at one million, which is about half of the personal car fleet of Finland.

What is important about the cost assumptions is the relative cost between the different technologies rather than the absolute cost level. The costs do not reflect the recent price hikes of building all kinds of power plants due to scarcity in commodity markets. There are two reasons for this choice: first, costs should come down when the markets are once again well supplied; second, the relative costs between capital-intensive forms of power production have not changed much due to the price increases. Simultaneously, fuel dependant power production has seen cost increases in the form of higher fuel prices.

The fuel costs are for 2035 and it is impossible to predict costs so far into the future. Natural gas prices are assumed to be higher than coal, since natural gas should have more resource constraints [26]. The costs of biomass and peat-based fuels are slightly higher than at present, since the resource base should stay similar, but higher natural gas prices should give some leeway for price increases. In

Table 2
Assumptions in high and low fuel price scenarios and average 2007 prices in Finland for comparison.

	HighFuel	LowFuel	2007	
Interest rate	9.0	9.0		%
CO_2 cost	45	20		€/tCO_2
Coal (CO)	3	2.1	2.2	€/GJ
Natural gas (NG)	11	6	5.8	€/GJ
Light oil (LO)	16	13	12.9	€/GJ
Fuel oil (FO)	13	10	7.5	€/GJ
Peat (PE)	2.8	2.8	2.3	€/GJ
Industrial wood waste (WW)	0	0		€/GJ
Forest residues (WR)	4.2	3.5	3.4	€/GJ
Wood and straw (WO)	7.5	5.3		€/GJ
Municipal waste (MW)	0	0		€/GJ
Nuclear fuel (NU)	0.4	0.4		€/GJ

Table 3
Power plants available for investment [24], [25]. For wind power the investment cost is for the base scenario and for heat storage the investment cost unit is €/MWh of storage capacity.[a]

Unit	Comments	Source	Type	Fuel	Avg Eff	CHP CB	Ext CV	Availability	Invest. costs [€/kW]	Variable O&M [€/MWh]	Annual O&M [€/kW]	Life time
NG_CC_EX	Large combined cycle CHP	DEA et al., 2005	Extraction	Natural gas	0.62	1.7	0.13	0.94	550	1.5	12.5	25
WW_EX	Large scale biomass plant	DEA et al., 2005	Extraction	Ind. wood waste	0.49	0.84	0.15	0.9	1300	2.7	25	30
WR_EX	Large scale biomass plant	DEA et al., 2005	Extraction	Forest residues	0.49	0.84	0.15	0.9	1300	2.7	25	30
WO_EX	Large scale biomass plant	DEA et al., 2005	Extraction	Wood and straw	0.49	0.84	0.15	0.9	1300	2.7	25	30
CO_EX	Advanced coal plant	DEA et al., 2005, 2010–15 data	Extraction	Coal	0.53	0.95	0.15	0.91	1200	1.8	16	35
EL_HP	Very large heat pumps	DEA et al., 2005; eff. down 10%	Heat pump	Electricity	4.5			1	900	0	2	40
WO_HB	District heating boiler	DEA et al., 2005; eff. estimated	Heat boiler	Wood and straw	0.91			0.97	250	2	15	35
NG_HB	District heating boiler	DEA et al., 2005; eff. estimated	Heat boiler	Natural gas	0.93			0.96	50	1	2	40
EL_HB	Electric boiler	Estimates; Eloverløbsrapport	Heat boiler	Electricity	1			1	40	0	1	40
CO_HB	District heating boiler	Estimates	Heat boiler	Coal	0.9			0.95	100	1	7	40
FO_HB	District heating boiler	Estimates	Heat boiler	Fuel oil	0.9			0.97	55	1	2	40
NU_CON	Nuclear	IEA 2007, improved effic.	Condensing	Uranium	0.37			0.92	2625	7.2	52	40
NG_CC_CON	Combined cycle, condensing	IEA 2007	Condensing	Natural gas	0.58			0.95	553	3.2	20	25
NG_OC_CON	Open cycle, condensing	IEA 2007	Condensing	Natural gas	0.37			0.95	320	2.4	16	25
CO_CON	Pulverised coal, condensing	IEA 2007	Condensing	Coal	0.46			0.93	1260	5.6	40	35
WIND	Wind	Estimate	Wind	–	1			0.32	800	0	20	20
HEATSTO	Heat storage (inv.: €/MWh)	Estimate	Storage	–				1	1840			20

[a] Average efficiency is defined as power output divided by fuel input for condensing and extraction plants, and heat output divided by fuel input for heat boilers. Heat pump efficiency is heat output divided by electricity consumption, i.e. the low temperature heat input extracted from the surroundings is not included when calculating heat pump efficiency. Investment cost is €/kW_{elec} for electricity producing plants and €/kW_{heat} for plants producing only heat.

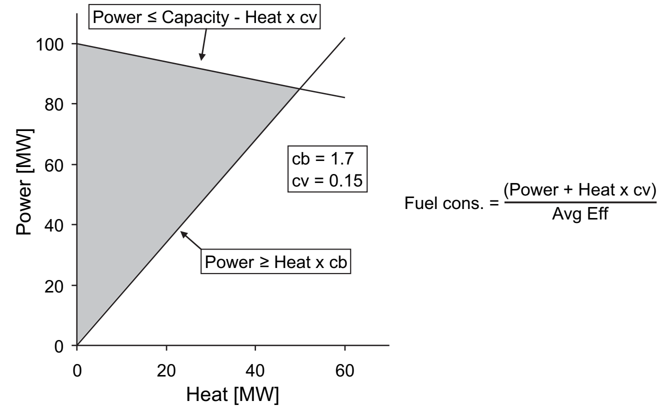

Fig. 1. Operating area of extraction CHP plants. Model decides the capacity to be invested.

the case of CO_2 prices, the high fuel price scenarios assume that marginal CO_2 reductions in the global emissions market are from coal power plants with carbon capture and storage (CCS). In the low fuel price scenarios, we assume that enough low carbon energy sources will replace a large amount of coal and natural gas at the global level, resulting in lower fuel prices and eliminating the need to use CCS as the marginal CO_2 reduction source. A similar effect would be achieved if the global CO_2 quota were to be set higher.

The characteristics and costs of power plants that are available for investment are presented in Table 3. The number of options has been kept as small as possible, since additional options increase the size of the model, making it insolvably large. Therefore some power plants where investments were not made in the initial model runs were removed from further model runs. These include oil-based heat or power plants.

One of the sources for economic data, IEA [24], did not include construction-phase financing costs. These were estimated and are included in the investment costs of Table 3.

The assumed investment cost for wind power in the base scenario is on a par with or slightly lower than what was realized in some of the larger onshore projects in 2003–2004. Since then, higher commodity prices and the tight supply of wind turbines have increased the costs considerably (BTM [27]). This situation masks any cost reductions due to advances in technology, which should be more rapid in the relatively immature field of wind power technology than for conventional power plants. Once the wind turbine markets are well supplied and commodity prices lower, technological advances will push down costs over several years, which should be reflected in the cost of wind power. Further advances should be made by 2035. Therefore, the cost assumptions for wind power in comparison with other technologies should be reasonable, if not pessimistic. In all scenarios, wind power is the cheapest source of electricity per MWh when comparing other plants operating at maximum availability and the assumed 2823 full load hours for wind power. This is probably a rather high figure for Finnish onshore wind power in 2035, but a lower number would

Table 4
Energy sources with resource limitations in primary energy TWh due to domestic resource constraints.

Resource limitations	TWh
Peat	30
Industrial wood waste	65
Forest residues	20
Wood and straw	33
Energy waste	5

Table 5
Electricity and heat demand in model regions. The model has one region for electricity and three regions for heat demand. Only heat demand in district heating systems is considered.

	Region	TWh	Assumption
Elec demand	FI_R	113.0	20% over projected 2010 consumption
Heat demand	FI_R_Urban	6.2	projected 2010 consumption
	FI_R_Rural	21.0	30% over projected 2010 consumption
	FI_R_Industry	46.8	projected 2010 consumption

have resulted in smaller wind penetration and the purpose of the article is to analyse high penetrations instead of focusing on the specifics of Finland.

Wind resources at different onshore sites are not equal and this means that while the best wind power sites might be competitive, sites with lower wind speeds might not be. This increases the costs of building more and more wind power in certain areas. An increasing cost curve is difficult to implement in a linear investment model without making the model too large to solve. As a simplification, the whole resource was assumed to have the same wind power production potential and the same investment cost. In the results, this can be interpreted as an average cost for wind power. It was also assumed that the hourly variation in wind power production remains unchanged regardless of the amount built.

CHP power plants available for investment are extraction-type plants. Their operating area in the model is described in Fig. 1. The figure also explains some of the parameters in Table 3.

The investment model does not take into account the need to improve the transmission system as the share of wind power increases. Since wind power production is variable, the transmission requirements per produced MWh are larger than for conventional power production. This is not a problem when penetration levels are low, since wind power can use existing transmission lines and probably only changes the utilization rate of the lines. In the study by US DoE [15], the costs of new transmission lines caused by 20% wind power penetration represented about 7% of the total wind power costs. Greater penetration increases the need to strengthen existing transmission lines or build completely new ones. One of the two studies carried out thus far addressing transmission limitations at high wind penetration levels indicated that in the case of Ireland, the transmission system would need to be redesigned somewhere between wind power energy penetration levels of 34% and 47% (Nedic et al. [13]). The cost of a redesign was not estimated. However, Ireland has a relatively small and isolated power system. In larger systems with more transmission links, the need for a redesign would arise later, although internal weak links and the relative location of wind resources and load centres can also force it earlier. Ea [5] estimated that the Danish grid would be able to handle wind power at a 50% energy penetration level with quite reasonable onshore network reinforcements. The Danish system is strongly interconnected and can use the reservoir hydropower resources of other Nordic countries.

3.3. Resource limitations and existing power plants

Renewable energy resources have resource limitations. Our model has hard limits on resources in order to simplify the problem. In real life, higher cost could make additional resources available. The same limitations apply in all of the scenarios. These limitations are presented in Table 4. As in most other countries, wind power resources in Finland are much larger than the consumption and do not need hard limits.

Electricity and heat demand were estimated for 2035 and are presented in Table 5. FI_R_Urban represents the capital region and it is assumed that any increase in the heating area by 2035 will be compensated by efficiency gains from better insulation. In FI_R_Rural, there are more cities and towns installing district heating networks, leading to increased demand. The industrial base might change by 2035, but in FI_R_Industry it is assumed that the total heat consumption will remain at the same level.

The current power plants that are expected to still be in operation in 2035 include all hydropower plants, most nuclear units and some CHP capacity (Table 6). They have been aggregated from a database of actual units in Finland (unpublished). Except for some light oil capacity, the current condensing fossil fuel power plants will be retired. The only heat boilers in the system are for municipal waste. It is assumed that these boilers are primarily meant for

Table 6
Existing power plants. NG_CHP_UR includes 2 units in the model, one back pressure and one extraction unit and is presented here as one back pressure unit. For back pressure units power = heat * CHP cb.

Unit	Fuel	Capacity, elec [MW]	Capacity, heat [MW]	CHP cb	Variable O&M [€/MWh]	Avg Eff	Availability
FO_BP_IN	Fuel oil	36	185.7	0.19	1.6	0.9	0.94
HY_01	Hydro	133.6			−2.8	1	0.9
HY_02	Hydro	883.1			2	1	0.9
HY_03	Hydro	239.3			3	1	0.9
HY_04	Hydro	93.1			4.7	1	0.9
HY_05	Hydro	215.7			5	1	0.9
HY_06	Hydro	183.6			5.9	1	0.9
HY_07	Hydro	224.1			6.2	1	0.9
HY_08	Hydro	274			6.7	1	0.9
HY_09	Hydro	181.7			6.8	1	0.9
HY_10	Hydro	705.7			7	1	0.9
LO_CON	Light oil	180.6			1.3	0.33	0.95
MW_BP_UR	Municipal waste	40.7	110	0.37	19	0.9	0.93
MW_HB_RU	Municipal waste	500			10	0.91	0.9
MW_HB_UR	Municipal waste	50			10	0.91	0.9
NG_BP_IN	Natural gas	249.3	530.4	0.47	1.3	0.9	0.94
NG_BP_RU	Natural gas	192.1	195.5	0.98	1	0.9	0.94
NG_CHP_UR	Nat. gas, 2 units	785	707	1.07	1.4	0.91	0.93
NG_CON	Natural gas	80.3			1.3	0.3	0.95
NU_CON	Uranium	2440		0	7.2	0.35	0.92
PE_BP_IN	Peat	386.5	546.1	0.71	2	0.9	0.92
PE_BP_RU	Peat	139	290	0.48	2.7	0.88	0.92
WO_BP_RU	Wood and straw	246.8	264.8	0.93	1.8	0.91	0.91
WR_BP_IN	Forest residues	44.7	180	0.25	1.8	0.91	0.9
WW_BP_IN	Ind. wood waste	2031	7120.4	0.29	2.8	0.88	0.9

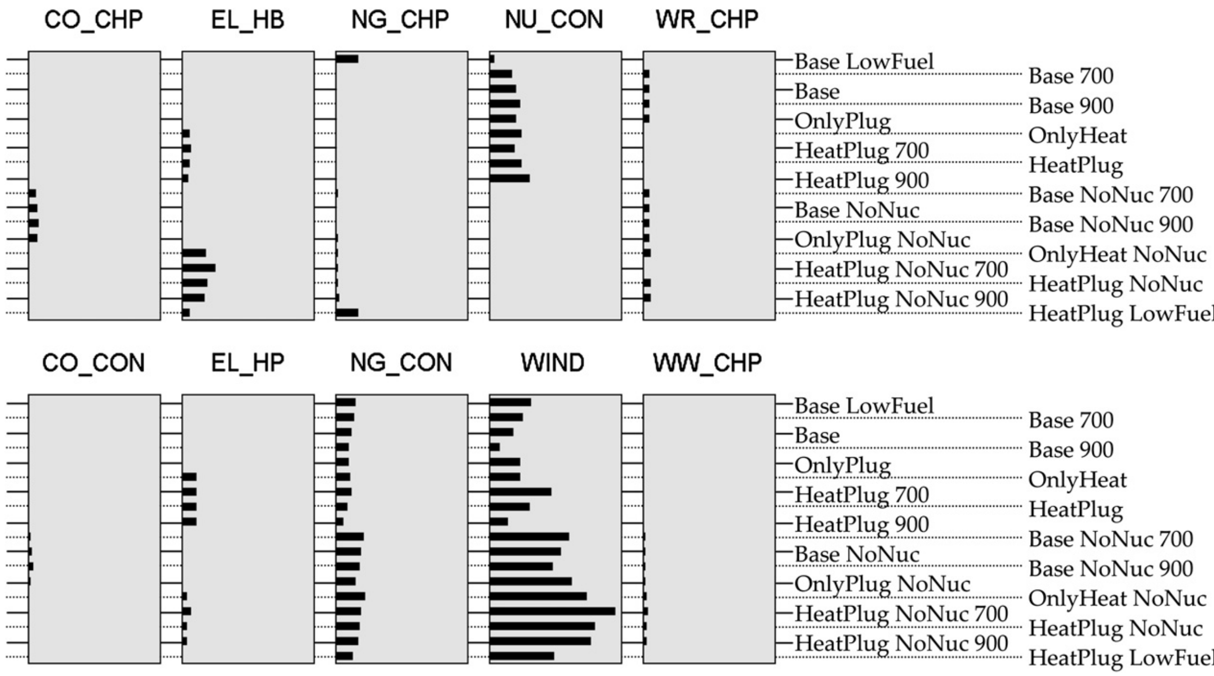

Fig. 2. Investments in new production capacity. Electrical capacity given for all plants except EL_HB and EL_HP (electric heat boilers and heat pumps), which have capacity defined on heat production. The *x*-axis scale is from 0 to 27 GW.

getting rid of waste and that heat production is a side-benefit. Other heat boilers are relatively cheap to build or retrofit for new fuels and for this reason full flexibility of choice was left to the investment model.

The model runs in one-hour time steps. Non-nuclear units are considered to be capable of full ramp up or ramp down inside the hour. Ramp rate for old nuclear units is set to 20% of capacity per hour and for new units to 50%. When ignoring industrial biomass with zero-cost fuel and wind power, nuclear is the least-cost source of electricity for high full load hours.

Hydropower capacity is divided into ten blocks with variable O&M costs. This simulates the fact that different water reservoirs end up with different water values and have different reservoir sizes in comparison with production capacity and inflow. This division is based on an analysis of Finnish river systems (Kiviluoma et al. [28]).

The industrial CHP has quite a large amount of heat production capacity using zero-cost wood waste as fuel. This strongly restricts new investment in industrial heat production.

4. Results

The results from the model runs are naturally sensitive to the assumptions in the input data. However, clear trends emerge in the different scenarios when the assumptions are modified. Fig. 2 shows the general trends in the investments in power and heat production capacity.

The base scenario was selected to have a reasonable but not excessive amount of wind power (12% of produced electricity). Any changes that are made will thus be reflected in the wind power penetration level. In the scenarios with higher fuel prices, the new capacity is mainly nuclear and wind power as shown in Table 7 and Fig. 2. In the scenarios with lower fuel prices, new nuclear power is for the most part replaced with fossil fuels, mainly natural gas. Also, wind power increased penetration as it is more economical to have lower utilization of fossil fuel power plants than nuclear power plants. As the base scenario, we selected a scenario with high fuel prices and 800 €/kW investment cost for wind power. Finland has greater opportunities for combined heat and power production than most other countries and it seems likelier that the strongest competitor to wind power will be nuclear power if CO_2 emissions have to be cut dramatically and fossil fuel prices stay at a relatively high level.

While nuclear or wind power take the dominant position in new capacity, their relative share depends on the assumptions about their relative cost and the fuel costs of other production types.

4.1. Increasing the flexibility of the power system

Flexibility in the power system will make it easier and less costly to integrate energy forms with variable or otherwise inflexible production. Allowing the model to use new forms of energy system flexibility increases investments in inflexible forms of power production. The scenarios include two kinds of flexibility: plug-in electric vehicles and heat measures.

Charging of plug-in electric vehicles offers some flexibility as it takes only a few hours to charge a vehicle after typical daily use. The timing of the charging can be optimized in line with the requirements of the power system. Furthermore, plugged in vehicles can provide ancillary services for the system, thereby decreasing the need for power plant capacity dedicated to ancillary services. It is assumed that when power prices are very high, it can also be profitable to discharge the batteries in order to shave demand

Table 7
Electricity production [TWh] from new power plants in some of the scenarios. The first three scenarios used the higher fuel price assumptions and the last one used the lower fuel price assumptions. The number refers to the assumed wind power cost [€/kW].

	CHP	Cond.	Nuclear	Wind
700	7.9	0.9	36.9	19.5
800 (Base)	8	0.7	42.6	13.3
900	8	0.5	50.2	5.6
800 LowFuel	27.9	1	6	24.1

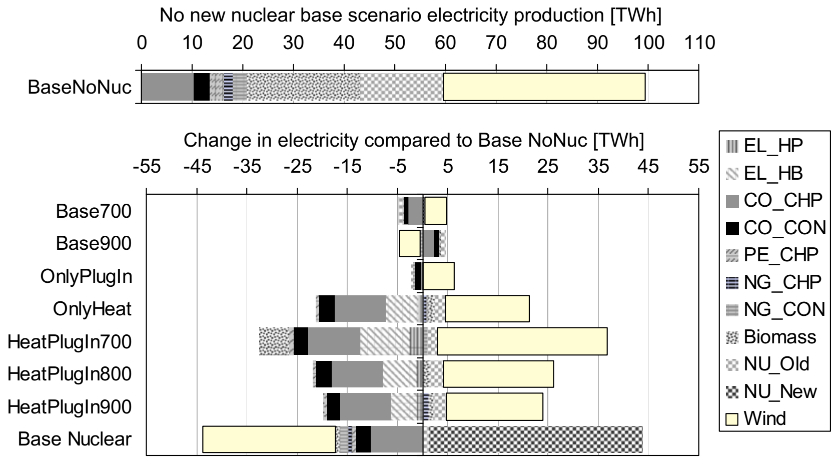

Fig. 3. Electricity production in the scenario runs without new nuclear power. First the production from different sources in the base scenario without new nuclear is shown. Changes compared to this are then shown in the lower part of the figure. Heat pumps (EL_HP) and electric heat boilers (EL_HB) will increase electricity consumption and are therefore negative changes in the graphs. Hydropower is not shown, as electricity production from hydropower does not change between scenarios.

peaks. Thereby plug-in vehicles can contribute 500 MW to the capacity balance restriction in the model (eq. (4)), reducing investments in peak-load capacity in some cases.

Electric heat boilers use electricity to produce heat. Heat pumps also use electricity, but they are more efficient since they refine ambient heat to a higher temperature with the help of high exergy electricity. Efficiency increases come with a higher investment cost. When any kind of electric heater is connected to heat storage, heat can be produced from the electricity at the times when it suits the power system most and the heat can be used when there is demand for it. These options are enabled in the scenarios with the heat measures.

First we look at results without nuclear power. This makes it easier to see the effects of heat measures and plug-in electric vehicles on the integration of wind power.

In scenarios with plug-in electric vehicles, electricity consumption is higher due to the consumption of the vehicles. Wind power is the cost-effective source of electricity for new consumption, as can be seen from Fig. 3. In addition, the flexibility provided by the plug-in electric vehicles helps wind power to increase its market share a little bit in the long-term. Flexibility from the heat measures increases the market share of wind power much more than the flexibility provided by plug-in electric vehicles. The reason is that the energy storage capacity of heat storages is much larger than the electricity storage capacity of plug-in electric vehicles. This can be seen in the scenario 'OnlyHeat' where a great deal of heat production is switched away from coal CHP to electric heat boilers running with wind electricity. Furthermore, the additional flexibility makes wind power more competitive with condensing coal electricity. When the price of wind power is decreased (scenario 'HeatPlug 700'), biomass based on forest residues is also forced out by wind. The additional wind power production in 'HeatPlug 800' compared to the base scenario is larger than the sum of the additional wind power production in 'OnlyHeat' and 'OnlyPlug-In', showing that combining the flexibility measures does not reduce their value with regard to wind power integration.

When nuclear is allowed, it pushes out a large amount of wind and is competitive enough to push out coal CHP without using flexibility mechanisms (see Fig. 4). In these scenarios, the additional flexibility from heat measures forces biomass and natural gas out and increases the share of nuclear and wind. On the other hand, lower fuel prices make natural gas CHP combined with wind power competitive with nuclear, and the result is very little or no new nuclear (Base_LowFuel & HeatPlug_LowFuel).

Fig. 5 displays heat production in the scenarios. The figure also shows the aggregated size of the heat storages the model decides to

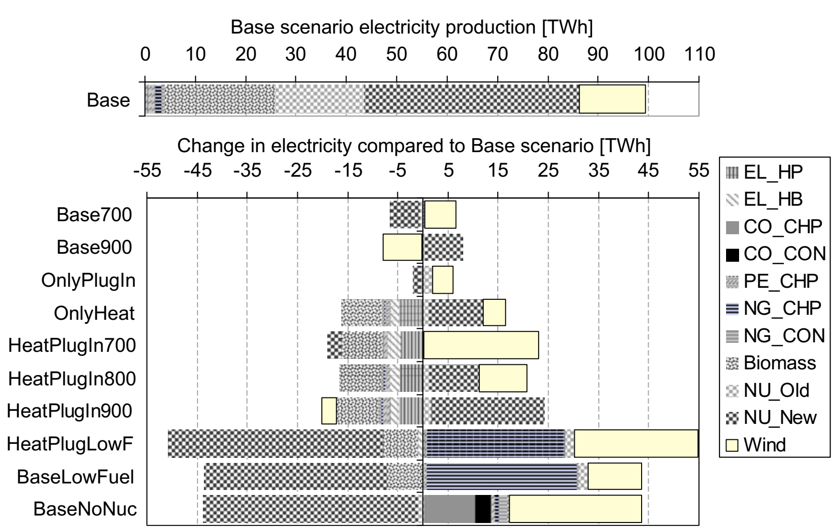

Fig. 4. Same as Fig. 3 except with new nuclear allowed.

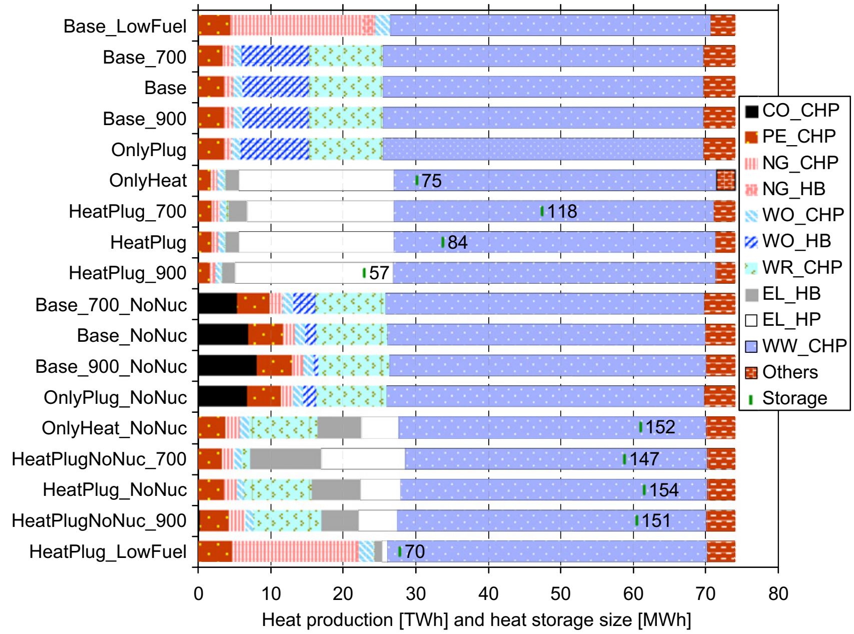

Fig. 5. Heat production [TWh] and the size of heat storages [GWh] in different scenarios.

invest in, when those are allowed. When the heat measures were allowed, the model switched a large part of the heat production to heat pumps and electric heat boilers. The exception was the scenario with low fuel prices, in which natural gas CHP-based heat production remained competitive. The large block of heat production based on wood waste comprises the industrial use of waste material from pulp and paper industry. As the fuel is practically free and the power plants are in operation, the share accounted for by this type of heat production hardly changed between scenarios.

Heat storage size was largest in the scenarios where nuclear power was not allowed. In these scenarios, the share of wind power was larger and heat storages were a cost-effective source of flexibility. However, heat storage size appears to have a limit. One might assume that when wind power production goes up, heat storages would be charged with electric boilers. However, this happens only during periods of very high wind power production. Usually heat storages *discharge* during good wind power production. The reason behind this is that CHP plants shut down to save on fuel costs and to make room for wind power electricity. During periods of lower wind power production, CHP plants and heat pumps charge heat storages slowly. The rate of charge is limited by the heat production capacity available after heat demand has been served. Heat production capacity is set by the periods of highest heat demand and it is not cost-effective to overbuild heat production capacity. The length of the low wind power production period multiplied with the spare heat production capacity limits the optimal size of the heat storage. As a complicating factor, the model has a large amount of old CHP capacity that cannot be replaced by heat pumps.

One of the heat areas, FI_R_Rural, includes less old CHP capacity and the results show that heat storage size actually decreases as wind power production increases (no new nuclear scenarios). A combination of heat pumps and electric heat boilers out-competes CHP production, which means that CHP plants provide less cheap heat during low wind power production. With less CHP, there is no excess heat from CHP during these periods, and a smaller heat storage capacity is enough to take care of shorter time scale fluctuations.

Fig. 6 shows how the flexibility mechanisms facilitate wind power integration in practise. The time scale is two weeks in March. The period was chosen to show very high wind power production and very low wind power production. The chosen scenario (HeatPlug NoNuc 700) has the highest wind power penetration out of all the scenarios. Wind power electricity production in the scenario corresponds to 65% of electricity demand, without taking into

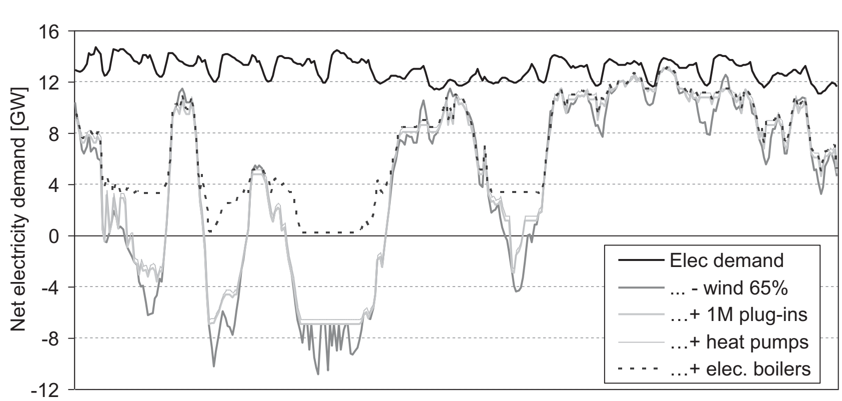

Fig. 6. Changes in net electricity demand when flexibility mechanisms are overlaid on top of each other. Two weeks in 'HeatPlug NoNuc 700' scenario in March.

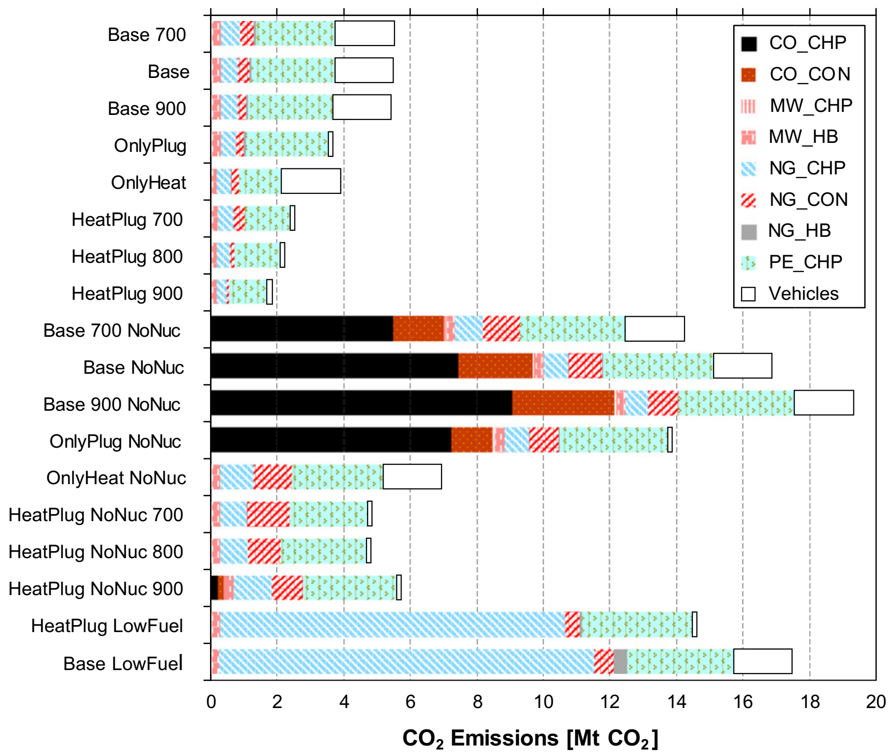

Fig. 7. CO_2 emissions in different scenarios. Vehicles refers to emissions from gasoline and diesel light vehicles, which were assumed to be replaced by electric vehicles in the scenarios where that emission source is not present.

account new demand from heating and plug-in vehicles. In the figure, different flexibility mechanisms are overlaid on top of each other and cumulative changes are shown. Wind power production is first subtracted from electricity demand to show the remaining demand and what the flexibility mechanisms and conventional power plants have to cope with. The electricity consumed during the smart charging and discharging of one million electric vehicles is then added to the remaining electricity consumption. The next steps are to add consumption from heat pumps and electric heat boilers. The dotted line after all the changes shows what the conventional power plants have to produce. The flexibility mechanisms are meaningful: wind power production does not need to be curtailed and the full load hours of conventional plants are reasonable. For example, the 2440 MW of old nuclear capacity still gets 8250 full load hours in a year even though wind power makes such a large contribution to the system.

4.2. CO_2 emissions

Finnish CO_2 emissions from the sources covered in this analysis were in the order of 45 Mt of CO_2 in 2006. This includes all power production, most of heat production and about one third of road transport emissions. Fig. 7 shows that emissions in the different modelled scenarios are much lower than historical values; the new range is 2–20 Mt of CO_2. This is a direct result of the assumed CO_2 price, fuel costs, and the new power plant investment costs. The emissions from the one million gasoline and diesel vehicles that the electric vehicles would replace are calculated at 90 g of CO_2 per kilometre and an average annual driving distance of 20 000 km. Newly registered vehicles in Finland currently average around 160 g/km. In the scenarios where plug-in vehicles are present, the emissions in the figure are generated by fuel use in plug-in hybrids. The CO_2 emissions from vehicle electricity consumption are included in the electricity production emissions.

4.3. Costs of different scenarios

The cost of serving electricity consumption varied between 33 and 43 €/MWh in the different scenarios, if old power plants were assumed to have been fully amortized and the value of heat was 10 € per produced MWh. The cheapest scenarios were those with low fuel costs and low wind power costs and the most expensive were those where the construction of new nuclear was not allowed, additional flexibility was not available and wind power costs were higher. Table 8 shows the cost differences between scenarios. The cost refers to the average cost for produced electricity including annualized investment costs.

The scenarios implied that the cost of not allowing new nuclear to be built is 0–4.1 €/MWh. The cost rises as wind power cost increases. However, the low fuel price scenarios have the cheapest costs and in the 'HeatPlug LowFuel' scenario no new nuclear is built although it is allowed. Accordingly, banning nuclear would not have increased costs in this scenario. Table 8 also shows that electricity gets cheaper when the flexibility mechanisms are available. Heat measures have a greater cost impact than plug-in electric vehicles. Even though plug-in electric vehicles increase electricity consumption, their flexibility allows changes in power

Table 8
Average cost of producing electricity [€/MWh] in different scenarios. 700, 800, and 900 in the scenario name refer to wind power investment cost [€/kW].

	Base	OnlyHeat	OnlyPlug	HeatPlug
700 Nuclear	37.9	–	–	34.7
800 Nuclear	38.4	36.0	37.3	35.6
900 Nuclear	38.8	–	–	36.2
700 No nuclear	40.0	–	–	36.0
800 No nuclear	41.5	39.1	39.8	37.7
900 No nuclear	42.8	–	–	40.3
800 Low fuel prices Nuclear	33.6	–	–	32.5

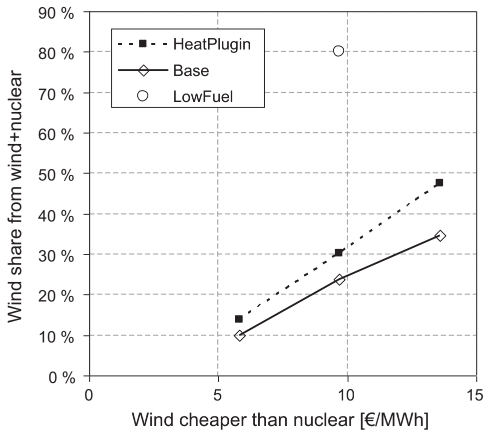

Fig. 8. Optimal share of wind power as a function of the cost difference between wind and nuclear. Only production from new nuclear plants is included.

plant investment patterns, which outweigh the cost of the additional electricity consumption. From the system point of view, it would be practically free to provide the energy required by the plug-in vehicles in exchange for flexibility services – at least when power system investments are factored in and with the caveat that the plug-ins are likely to be more flexible in the model than in real life due to consumer preferences and modelling simplifications.

Since wind power production is variable and nuclear serves the base load, wind power is less valuable to the power system than base load power. Therefore wind power must be less costly than nuclear in terms of €/MWh in order to compete in an optimized system, at least if environmental and social concerns apart from CO_2 emissions are not factored in. The wind power cost varies between 34.2 and 42.0 €/MWh and the nuclear cost is 47.8 €/MWh assuming 92% utilization. Fig. 8 shows how much wind power the model decides to build at different cost difference levels. There is a shift from nuclear toward wind power when the cost of wind power is decreased from 900 €/kW to 700 €/kW and everything else remains the same. Lower fuel prices mean that natural gas largely out-competes nuclear, and wind stays competitive as it saves fuel costs.

The cost-optimal share of wind and nuclear capacity is in reality dependant on several factors. These results only highlight the precariousness of the balance. Uncertainties concerning the future costs and societal acceptance of wind and nuclear power are large in comparison with the cost area where they would both be large contributors in a power system.

The analysis did not consider several factors that would influence the societal decision on permitting new power plants to be built. These include environmental concerns about nuclear waste disposal, the risk of major accidents and nuclear proliferation. Furthermore, using current nuclear technology would cause constraints on uranium resources, if nuclear power were to be used as a major global source of electricity production in the future. Other nuclear fuel cycles still have to demonstrate economical or even technical feasibility.

Wind power has an increasing cost curve, since the best sites are used up first, and further wind farms have to be built on less attractive sites,. The very best sites might be competitive, but these sites often have limited resource potential. Furthermore, higher wind penetration increases transmission costs disproportionately. At very high penetrations it might not be enough to merely reinforce the grid; a complete redesign might be required (Nedic et al. [13]). Costs related to ancillary services and power plant cycling are not as binding as in conventional wind integration studies, since heat measures and plug-in electric vehicles provide more new flexibility in the system to cope with variation and prediction errors.

5. Conclusion

In the scenarios where it was assumed that future fossil fuel prices are high and CO_2 emissions have a substantial cost, the model assumptions caused wind and nuclear to dominate the new power capacity. In the case of wind power, the variability of the production has to be compensated by lower production costs. Costs due to the variability are more influential at higher wind power penetration levels. The conclusions are sensitive towards the price assumptions in the input data, e.g. wind power penetration increased from 8% to 29% when wind power investment cost decreased from 900 €/kW to 700 €/kW in the scenarios with flexibility from heat measures and electric vehicles.

In the low fuel price scenario, nuclear was replaced by natural gas combined cycle power plants together with wind power, although the use of wind will be dependant on the uncertain investment costs of the future. The price of natural gas changed from 11 €/GJ to 6 €/GJ between the high and low fuel price scenarios. No social, environmental or resource constraints for nuclear power were assumed in the scenarios where the construction of nuclear power plants was allowed. However, these constraints could be binding in real life. In addition, wind power resources or permitting and grid integration were assumed to pose no constraints on wind power penetration. However, new flexibility mechanisms, especially heat measures, displayed a large capacity to balance out fluctuations in wind power production. It is conceivable that energy systems with a very high share of electricity from variable power sources can be created without the use of dedicated electricity storage, which is known to be expensive. Systems relying heavily on wind power and flexibility from heating, cooling and transport could be more economical than the alternatives, if the assumptions in the study turn out to be realistic.

When introducing new flexibility into the system, the share of wind power increased against other types of power production in all scenarios. The effect was larger when wind power was less costly i.e. at higher wind power penetration levels, because the variability of wind power induces more costs at higher penetration levels. Hence making the flexibility measures more beneficial for wind power. Nuclear also gained from the additional flexibility, although not quite as much as wind power. Heat storages with heat pumps benefit base load power relatively more than variable power, while plug-in electric vehicles and heat storages with electric boilers are more helpful for variable power. Heat pumps are capital-intensive and require more operating hours during the year to be economical than electric heat boilers, i.e. a high number of hours during the year with low power prices, which can be better provided by base load power plants. In absolute terms the increase in wind was much larger with the heat measures than with plug-in electric vehicles. It was evident from the results that heat measures can offer large amounts of flexibility to the system, while plug-in electric vehicles would have a more limited, although important effect. Combining the flexibility measures did not reduce their value with regard to wind power integration.

If the fuel and CO_2 cost assumptions in the article are realized in the future, then a large reduction in CO_2 emissions will not pose an economic problem, because it will be cost-effective to do so. This would happen at least in the electricity and district heating sector. In the transport sector, investments in electric vehicle fleets were assumed to be covered by benefits in the transport sector, and the results only show that those vehicles would be powered with electricity from new low emission power plants, at least in the context of the study assumptions. The introduction of flexibility to the power system with the integration of heating and transport can actually induce cost-effective emission reductions in power production while simultaneously producing electricity for transport and heating with near-zero CO_2 emission sources. The flexibility benefits from plug-in electric vehicles could be larger than the costs of producing the electricity consumed by the vehicles, when power production investments are optimized to take full advantage of the flexibility.

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