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FLEXIBILITY FROM DISTRICT HEATING TO DECREASE WIND POWER INTEGRATION COSTS

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ABSTRACT

Variable power sources (e.g. wind, photovoltaics) increase the value of flexibility in the power system. This paper investigates the benefits of combining electric heat boilers, heat pumps, CHP plants and heat storages in a district heating network when the share of variable power increases considerably. The results are based on scenarios made with a generation planning model Balmorel [1]. Balmorel optimises investments and operation of heat and power plants, including heat storages. It uses hourly resolution and enforces temporal continuity in the use of the heat storages. Scenarios with high amount of wind power were investigated and the paper describes how the increase in variability changes the profitability and operation of different district heating options in more detail than was described in the article by Kiviluoma and Meibom [2]. Results show that district heating systems could offer significant and cost-effective flexibility to facilitate the integration of variable power. Furthermore, the combination of different technologies offers the largest advantage. The results imply that, if the share of variable power becomes large, heat storages should become an important part of district heating networks.

NOMENCLATURE

| Indices | |
|------------------------|---------------------------------------|
| i, I | Unit, set of units |
| I^{HeatSto} | Heat storage units |
| t, T | Time steps, set of time steps |
| a, A | Area, set of areas |
| Variables | |
| C | New capacity |
| P | Power generation |
| Q | Heat generation |
| Z | Charging of heat storage |
| Parameters | |
| c^{Inv} | Annualized investment cost |
| c^{Fix} | Fixed operation and maintenance costs |
| $c^{\text{Operation}}$ | Operation cost function of the unit |
| w | Weight of time period |
| h | Heat demand |

INTRODUCTION

Wind power is projected to be a large contributor to fulfill electricity demand in several countries. This could take place due to relatively low cost of wind power electricity or policy mechanisms promoting renewable energy. In any case, power systems with a large fraction of power coming from a variable power source will need to be flexible. Flexibility is used to cope with the increased variation in residual load (electricity demand minus variable power production) and with the increased forecast uncertainty in the residual load. On the other hand, lack of flexibility will cause larger costs from increased variability and forecast errors. Therefore, it is prudent to investigate the cost optimal configurations for the combined power and heat generation portfolios.

Heat generation could offer significant possibilities for increasing the flexibility of the power system. Currently, part of the inflexibility of the power system comes from CHP plants that are operated to serve the heat load while electricity is a side product. Installation of electric resistance heaters next to the CHP units or elsewhere in the heat network could break this forced connection. During periods of low power prices, which will become more common with high share of wind power, CHP plants could be shut down and heat would be produced with electricity. The dynamics can be made more economic with the use of heat storages. Further option is to have heat pumps in the DH network, but they will require large amount of full load hours to be profitable and will compete with CHP plants for the operating space.

In most countries heat demand is in the same order of magnitude as electricity demand. For example, in UK the demand for primary energy due to heat is around 40% of total primary energy demand [3]. About 25% of the primary energy demand is due to space and non-industrial water heating. In the US all kind of heat use accounts for about 30% of the primary energy consumption [estimated from 4].

Heat is inexpensive to store compared to electricity. Electricity storage has been seriously considered to alleviate the variability of wind power [5-6]. Therefore, it is apparent that the use of heat storages should also receive serious consideration in the current context. Some work has been done [7-9], but not considering

optimal investments in new power plants and heat storages.

The study has been restricted to residential and industrial district heating systems. Buildings not connected to district heating systems were not considered, although these also require heat. Cooling demand could also offer similar possibilities, but the problem was not addressed here. Industrial heat demand and water heating do not usually have strong seasonal variation and can therefore be more valuable towards the integration of variable power.

METHODS AND DATA

The model and assumptions used for the analysis are described in more detail in [2]. For convenience, most important sections are referenced below. The heat sector of the model is described more thoroughly here.

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, CO2 emission permit prices, electricity and district heating demand, technology costs and technical characteristics (eq. 1). The model was developed by (Ravn et al. [1]) and has been extended in several projects, e.g. (Jensen & Meibom [10], Karlsson & Meibom [11], Kiviluoma & Meibom [2]).

$$\min \left(\sum_{i \in I} c_i^{inv} C_i + \sum_{i \in I} c_i^{fix} (C_i^{Ex} + C_i) + \sum_{i \in I} \sum_{t \in T} w_i c_i^{Operation} (P_{i,t}, Q_{i,t}) \right) \quad (1)$$

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

The geographical resolution is countries divided into regions that are in turn subdivided into areas. Each country is divided into several regions to represent its main transmission grid constraints. Each region has time series of electricity demand and wind power production. 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 hourly heat demand has to be fulfilled with the heat generation units, including heat storages (eq. 2). Loading of heat storage adds to the heat demand. Loss during the heat storage process is not considered. The

dynamics of heat networks were not taken into account.

$$\sum_{i \in I} Q_{i,t} = h_{r,t} + \sum_{i \in I} Z_{i,t} \quad \forall t \in T; a \in A \quad (2)$$

Analysis is done for the year 2035. By this time, large portion of the existing power plants are retired. Three district heating areas were considered. These have a rather different existing heat generation portfolio by 2035. This helps to uncover some interesting dynamics in the results section.

In this paper, scenarios without new nuclear power are compared (scenarios 'Base NoNuc' and 'OnlyHeat NoNuc' in article [2]). This meant that wind power had a very high share of electricity production. Accordingly, there was more demand for flexibility in the system.

'Urban' area presents the heat demand in the capital region of Finland. The existing power plants in 2035 cover over half of the required heat capacity. Largest share comes from natural gas, which is a relatively expensive fuel in these model runs. The annual heat demand is smallest of the considered areas: 6.2 TWh.

'Industry' area aggregates the known industrial district heating demand from several different locations. This is a necessary simplification, since Finland has over hundred separate DH areas and the model would not be able to optimise all of these simultaneously. The industrial heat demand in Finland is driven by paper and pulp industry, which produces waste that can be used as energy input. This capacity is assumed to be available in 2035 and as a consequence the model does not need more industrial heat capacity. The annual heat demand is 46.8 TWh.

'Rural' area aggregates non-industrial heat demand excluding the capital region considered in 'Urban'. This is probably the most interesting example, as the existing capacity covers only 20% of the heat capacity demand. Therefore, the model has to optimise almost the whole heat generation portfolio. There are wood resources (limited amount of forest residues and more expensive solid wood) available unlike in the urban area. The annual heat demand is 21.0 TWh.

RESULTS

Figures 1-3 give an example how heat production meets demand in the different areas during the same 4.5 days in January. Negative production indicates charging of heat storage. Electricity price is on separate axis together with the cumulative content of heat storage. When electricity price is low, storage is loaded with electricity using heat boilers and heat pumps. When electricity price is high, CHP units produce heat and electricity. Fluctuations in electricity price are mainly driven by changes in wind power production, since these are larger than changes in electricity demand (Fig. 4).

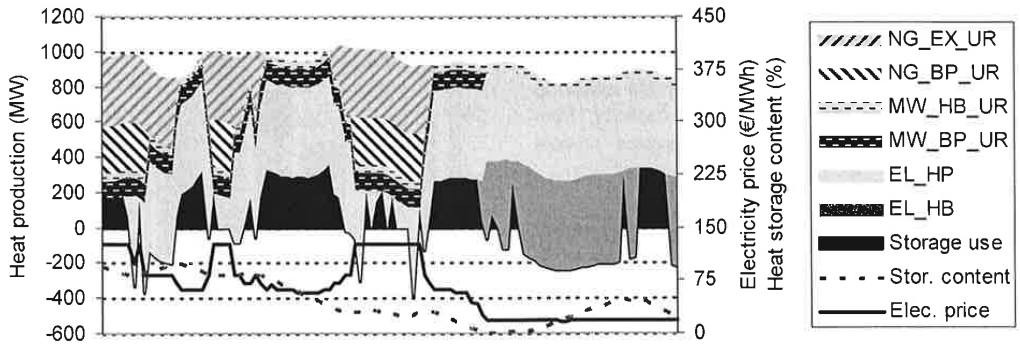


Fig. 1. Example of operation in 'Urban' heat area. Negative production indicates charging of heat storage.

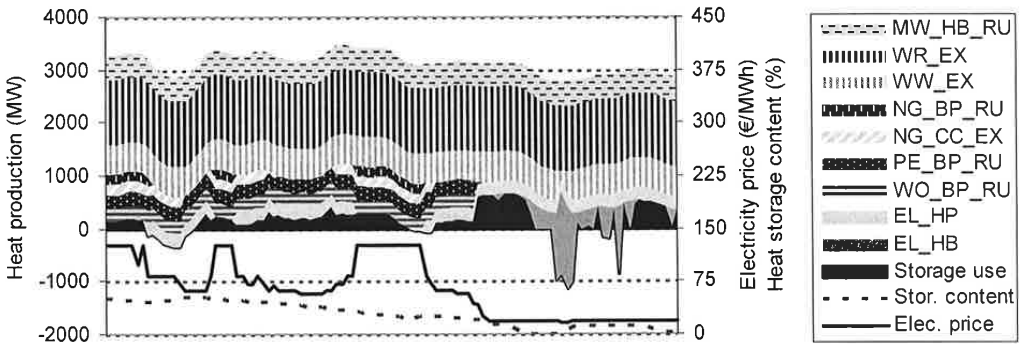


Fig. 2. Example of operation in 'Rural' heat area. Negative production indicates charging of heat storage.

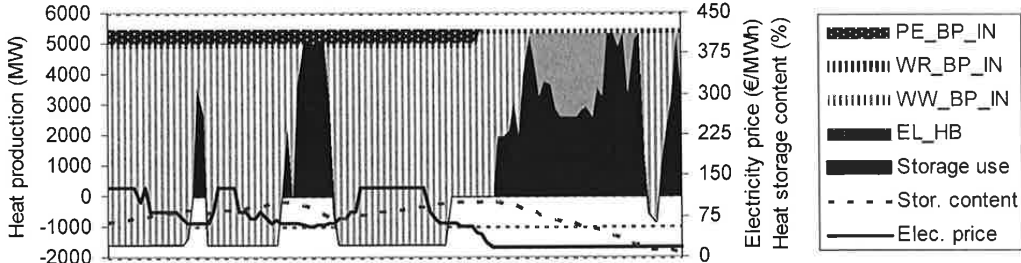


Fig. 3. Example of operation in 'Industrial' heat area. Negative production indicates charging of heat storage.

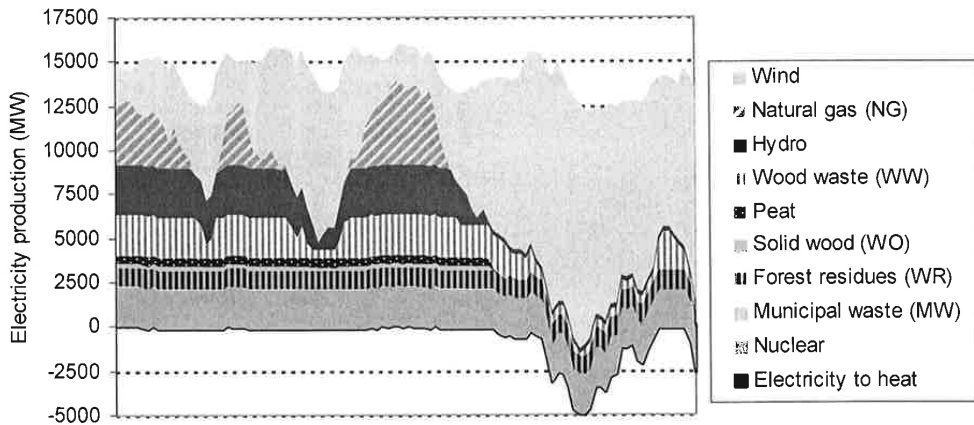


Fig. 4. Electricity production. Negative production indicates the use of electric heat boilers and/or heat pumps.

Effects of heat measures in the three heat areas

In the 'Industry' heat area availability of heat measures (electric heat boilers, heat pumps, and heat storages) had relatively little effect (Fig. 2). The main reason is that the existing heat production capacity from industrial wood waste and the associated no-cost

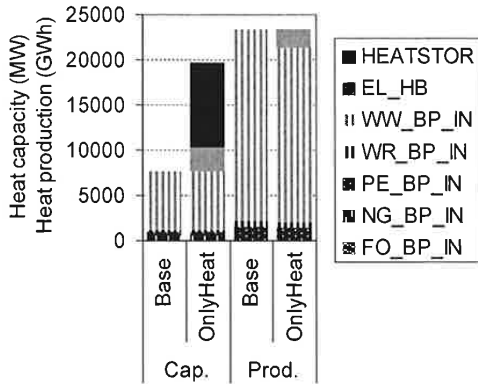


Fig. 2. Heat capacity and production¹ in the 'Industrial' heat area.

waste wood were not easily replaced. However, there were some high wind situations with low power prices where it was beneficial to use electric heat boilers to produce heat and decrease heat production from wood waste in the 'Industry' area. There was an annual resource limit on wood waste on the country level and the wood waste use was transferred to the 'Rural' heat area. It was also profitable to install some heat storage capacity. This enabled the full shut down of wood waste back pressure power plants for the duration of low electricity prices. This decreased electricity production and gave more room for the upsurge in wind power production.

In the 'Urban' heat area heat measures enabled the replacement of CHP coal units with production from heat pumps and to smaller extent from electric heat boilers (Fig. 3). Also wood based heat boilers were replaced. Investment in heat storage was relatively smaller. However, they were cycled more due to faster charging rate.

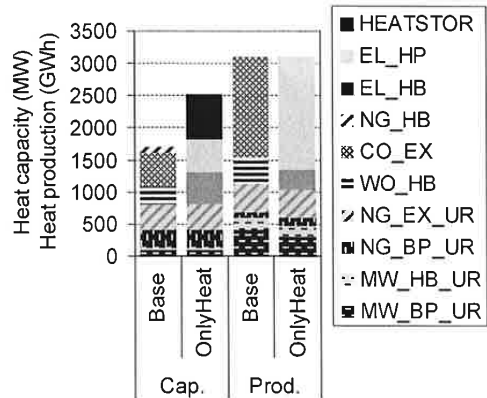


Fig. 3. Heat capacity and production¹ in the 'Urban' heat area.

The combined utilization of the heat measures was used to shut down existing natural gas based CHP power plants during hours of average or lower electricity prices. During low electricity prices electric heat boilers were used to charge heat storage. Accordingly, during average electricity prices heat was used from heat storage to prevent the use of electric heat boilers. During the highest electricity prices electric heat pumps were also shut down with the help of heat from the heat storages.

The most important difference between 'Urban' and 'Rural' heat areas is the availability of wood residues in the 'Rural' heat area (Fig. 4). For the most part this resource was able to outcompete heat pumps as means to produce heat. Heat measures still helped to replace coal CHP. The combination of electric heat boilers and heat storages was again a large source of additional flexibility to the system.

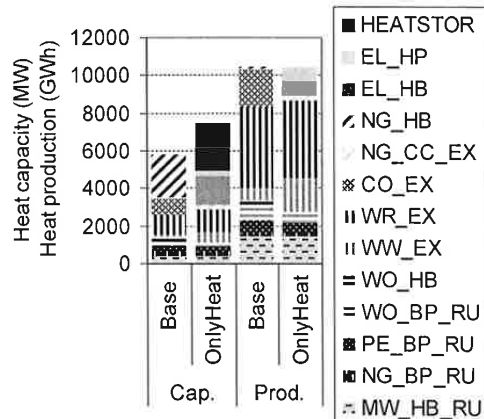


Fig. 4. Heat capacity and production¹ in the 'Rural' heat area.

¹ Heat production is from the modelled 26 weeks and should be multiplied by 2 to get an estimate on annual production.

Dynamics of heat storage

Most of the daily fluctuation in heat demand was smoothed with heat storages and electric heat boilers in all heat areas. If CHP units were operated, they were usually operated at maximum heat output.

The investment cost for heat storage was assumed to be 1840 €/kWh. With the assumed ratio of 12 between storage capacity and heat capacity this translates to 153 €/kW. In comparison the capacity cost of electric heat boilers was assumed to be 40 €/kW and 50 €/kW for natural gas heat boiler. This means that investment into heat storage capacity was not driven by need for new capacity since heat boilers were cheaper. There had to be operational benefits from the use of heat storage to cover the additional investment costs.

Heat storages create operational benefits by moving consumption from more expensive sources of heat to less expensive by shifting demand in time. In all heating areas whole operating ranges of heat storages were extensively utilized. During most 168 hour periods heat storage reached both the minimum and maximum storage capacities. In the 'Rural' area heat storage was 2.1% of the time either full or empty. With a larger storage capacity this could have been reduced, but it was not worth the investment.

The size of the heat storage in 'Industry' area was larger than in other areas in relation to daily heat demand (Fig. 5). In 'Industry' area charging of heat storages took place over several days during higher power prices, when wood waste CHP units were producing extra electricity. Storing the extra heat required larger heat storage capacity. On the contrary, in 'Rural' and 'Urban' charging and discharging was more balanced and smaller heat storage was enough.

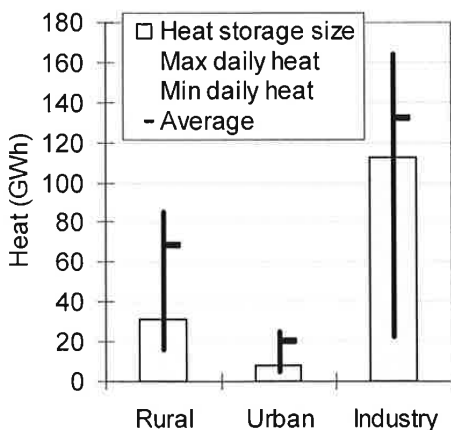


Fig. 5. Heat storage size compared to maximum, minimum and average daily heat demands.

In the 'Rural' area during winter time, charging of heat storages is mostly based on the use of electric heat

boilers. They create large amount of heat in relatively short time during periods of low power prices. During summer time, heat storages are charged by turning on wood waste and forest residue CHP units. During spring and fall CHP units operate more often, since the heat load is larger, but still the heat storage helps to shut them down for periods of some hours.

'Urban' area has similar dynamics, but during summer time the adjustment is made by heat pumps instead of CHP. In the winter during high power prices old natural gas CHP units are less expensive to operate than the heat pumps.

CONCLUSIONS

District heating systems offer good possibilities for increasing the flexibility of the power system, if the penetration of variable power like wind power increases greatly in the future. According to the results, main vessels to increase flexibility are the use of heat storages, electric heat boilers and flexible operation of CHP units.

Investment in electric heat boilers in district heating systems is driven mainly by periods of very high wind power production. The resulting cheap electricity is converted to heat and to some extent stored in heat storages for later use. Investments in heat storage in turn are driven by the same mechanisms, but also to create flexibility in the electricity production when prices are higher. To enable this, the operation of CHP units and heat pumps is altered with the help of heat storages. Heat pumps mainly compete against CHP as a source of heat. They succeed in replacing coal CHP, but are not very competitive against wood residues. This is naturally due to assumed costs where coal has a considerably penalty due to CO₂ cost. Heat pumps are not very important as a source of flexibility, since they require lot of full load hours due to their investment cost.

While the research has been conducted on district heating, similar dynamics could be achieved in household heating not connected to district heating networks. However, the costs are likely to be larger unless there is an existing hot water tank. Flexibility could also be gained from district cooling or a air-conditioning units with the addition of a cold storage.

Further research should also address some of the shortcomings of current study. Sensitivity analysis would be important, especially concerning the cost estimates of the analysed heat measures. Heat storage model was very simple and this should be improved. Heat grade, especially in the industrial environment, can vary and the model should take this into account. Heat pumps were assumed to work at constant COP and this is a crude approximation even if the heat source is groundwater or sea water.

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