Impacts of large-scale solar and wind power production on the balance of the Swedish power system

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Abstract: Higher targets for renewable energy and current trends in wind power and photovoltaics (PV) suggest that future power systems will include large amounts of renewable and variable power generation. Integration of large-scale variable power generation changes the balance and operation of power systems, including scheduling of conventional generation units, transmission and use of balancing power. In this paper the Swedish power system is studied with the energy system optimisation model MODEST in a number of scenarios involving different combinations of large-scale solar and wind power. The model includes a representation of the Swedish district-heating systems to determine the effects on combined heat and power (CHP) operation. It is found that when renewable power generation is added to the present system, utilisation of investments in CHP plants is reduced due to an increased electricity surplus that favours use of heat pumps for district heating. At high penetration levels of both solar and wind power, water is spilled from hydropower reserves.

Keywords: *Solar power, Wind power, Power system, Optimisation*

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1. Introduction

According to the EU directive on renewable energy, 20 % of the energy use within the union is to be covered by renewable energy sources by 2020 [1]. An important part of this goal is to transform the power system to include more renewable electricity generation. The power source most likely to reach substantial integration levels within this time frame is wind power. Although wind power currently covers 4.8 % of the total electricity demand within the EU, penetration levels in some individual countries are higher, for example Denmark (19 %), Portugal (15 %), Spain (14 %) and Ireland (11 %) [2]. Solar power generation, mainly from grid-connected photovoltaics (PV), is also increasing worldwide, although the contribution is smaller than for wind power. In Germany, the country with the highest solar power penetration, PV electricity covers 1-2 % of the national electricity demand [3]. However, if current developments continue, combined with decreasing costs for solar cells, a future expansion of solar power does not seem unlikely. The EU directive on energy efficiency in buildings, which states that all new buildings must be nearly zero energy buildings by 2020, also suggests a future widespread integration of on-site solar technologies [4].

Solar and wind power are both *variable* power sources, which means that the output varies both systematically and randomly on different time scales. The power generation can be forecast to some extent, but not controlled. In the case of wind power, the variation is due to moving weather fronts. Solar power has a more predictable seasonal and diurnal pattern, although the output during daytime can be heavily fluctuating due to variations in cloudiness. Variable power sources have a number of impacts on the balance, operation and reliability of power systems. The hour-to-hour varying production pattern alters scheduling of other generation units in the system and affects transmission between geographic areas. Furthermore, power generation that deviates from the forecast must be handled by system reserves. Depending on the power system, an increase in the penetration level of variable power sources has to be met by some increase in reserve requirements. For large-scale wind power it has been estimated that an increased penetration that corresponds to 10 % of the total annual demand increases the reserve requirements by 2-8 % of rated wind power capacity [5].

An important aspect is how addition of volumes generated by wind and solar power affects scheduling of other generation units and the total system balance. In this paper, the impacts of a large-scale integration of solar and wind power on the balance of the Swedish power system, a high-latitude and hydro-dominated system, is investigated. For example, how is scheduling of other generation units affected and how do electricity exports and imports and CO_2 emissions change?

A model of the Swedish power system was built in the MODEST optimisation model [6]. The model encompasses and optimises the whole chain of energy flows from sources to end-uses. An aggregated but detailed representation of the total Swedish generation capacity, including nuclear power, hydropower, combined heat and power plants, *etc.*, is included and the time resolution captures important fluctuations in demands and renewable power generation. The Swedish district heating systems are also explicitly represented to capture the effects on CHP operation. Solar and wind power are integrated in different scenarios as additions to the existing system. In these scenarios, it is recognised that wind power will most likely be integrated on a large scale before solar power.

The rest of the paper is structured as follows. Section 2 presents an overview of the applied methodology, including the optimisation model and the parameters and data used. Section 3 presents the results from the different studied scenarios. These results are discussed in Section 4 and some conclusions are drawn in Section 5.

2. Methodology

Energy system modelling enables important properties of a real system to be varied in a controlled environment. Using a validated model with a realistic performance, the impact of future changes to the system can be estimated. With an optimisation model, the best performance of a system under certain conditions is found. This section describes the applied optimisation model of the Swedish power and district heating systems. It also presents the studied scenarios for solar and wind power integration.

2.1. The MODEST power system and district-heating model

MODEST (Model for Optimisation of Dynamic Energy Systems with Time-dependent components and boundary conditions) uses linear programming to optimise the energy flows of a system to supply demands while minimising the total cost. In MODEST, an energy system is modelled as a set of nodes interconnected by energy flows. For each node and flow, a set of characteristics can be defined to relate, direct and constrain the flows. Typical such characteristics in a MODEST model are energy balances, dimensioning of maximum outputs for energy conversion and limitations of supplies. A cost can be associated with each flow and node, reflecting for example fuel costs.

Using MODEST, an energy system model of the Swedish power system was created. In the model, energy flows from resources (water and fuels) via generation units to distribution systems and finally to demand nodes representing the national electricity and district heating loads. For electricity, there is also an exchange with Nordic and continental European electricity markets. A flowchart showing the energy flows and nodes of the model is provided in Fig. 1. In the model, time is represented by a ‘quasi-dynamical’ time division, with a variable resolution that is more fine-grained for peak-load or peak-production periods. The time division is adapted to capture the relevant variability in solar and wind power generation.

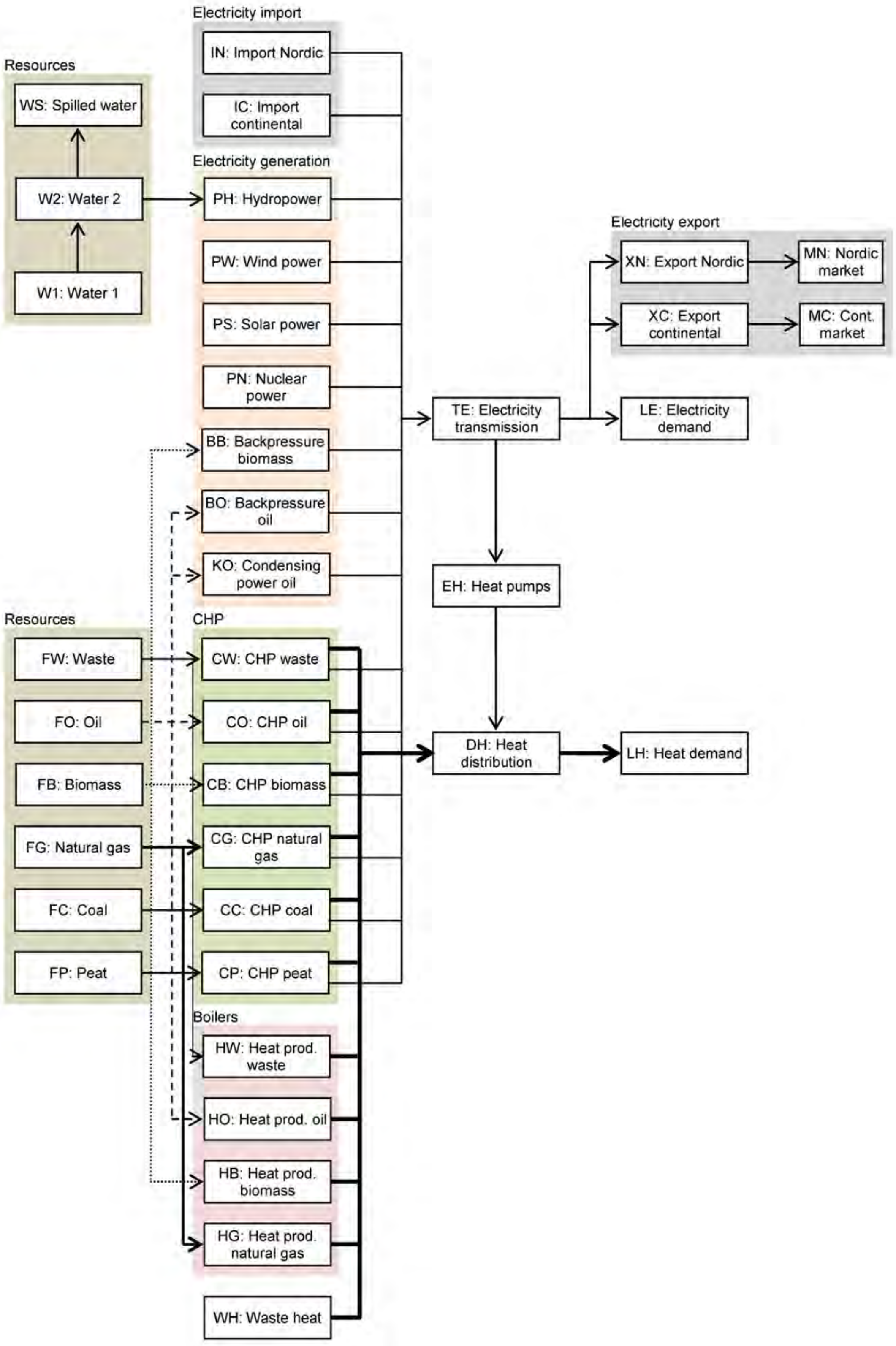


Fig. 1. Flowchart showing the nodes and energy flows in the MODEST model of the Swedish power and district-heating systems.

2.2. Studied scenarios

Two scenarios are studied. Scenario A represents today's system while Scenario B involves large-scale solar and wind power integration. In the latter scenario it is assumed that 30 TWh of wind power generation annually has been added to the existing system, which increases the total generation capacity of the system and turns the Swedish power system into a net producer of electricity. In three cases (B2-B4) besides the base case of today's solar power (B1), solar power is added to the system in 10 TWh steps, up to 30 TWh. In the most extreme scenario (B4), 60 TWh of renewable power generation are added, which is almost equal to the total current nuclear power generation. The main questions are how large volumes of electricity from plants with practically no running costs entering the system alter the scheduling of other power plants within the country, if the mix for heat production changes, how net exports and imports change and how CO_2 emissions are affected.

2.3. Input data

Model parameter values were chosen to make the model correspond to today's power system, with the year 2008 chosen as a representative year. All data were collected with the aim of reproducing the system performance of this year. Data for system parameters such as capacities, conversion efficiencies, resource limitations, prices, emission factors, *etc.*, were collected from a variety of sources, including different statistics sources, authorities' reports and business reports. Some data, which were still considered sufficiently up-to-date were collected from a previous national-level MODEST study. Data for estimating the variable components in the system were obtained from empirical time series with an hourly resolution. Some variable components are electricity and heat loads, solar and wind power generation and electricity market prices. Electricity prices were collected from NordPool and EEX spot market data, solar power data from a previous study of large-scale solar power variability in Sweden, wind power data from a database with modelled wind power data based on a scenario for widespread wind power in Sweden, electricity demand from NordPool's power system data and heat demand data scaled up from heat load data for a local district-heating system. All data series are from 2008 except the wind power and solar power data, which are from 1999, a representative year in terms of annual availability of solar irradiation and wind energy. All of these data are reported in detail in [7].

3. Results

The results of the energy system optimisations for the studied scenarios are shown in Fig. 2 and Fig. 3. Fig. 2 shows the energy balances for scenarios A and B. The impacts on the electricity and district heating production and the fuel use are visualised, as well as occasionally spilled energy, electricity imports and exports and CO_2 emissions. Fig. 3 shows duration graphs for district heating in scenario A and in the extreme case B4. The bold lines in the latter figure represent the district heating demand and show the different demand levels sorted in decreasing order. The step length corresponds to the length of each individual time period in the model. The other curves show plant outputs in the time periods.

As can be seen in Fig. 2 for the electricity production, the total production increases gradually in scenario B due to integration of wind and solar (B2-B4) power. This has no significant effect on the other parts of the electricity mix, apart from in case B4, where there is a small decrease in hydropower production. This is because some water has to be spilled as the capacity for electricity export is reached. This can also be seen in the graph for spilled energy. In the heat production mix, there is an incrementally larger contribution from heat pumps. This is because it is occasionally feasible to use excess electricity in the system for heating, compared to other more costly alternatives. This is generally on the expense of heat-only production, but in B4 also of CHP. As seen in the graph for fuel use, the total use of fuels decreases accordingly, mainly biofuel but in all cases also oil as compared to scenario A. From the heat duration curve in Fig. 3 (case B4) it can be seen that the heat pumps, which in scenario A are exclusively used at high loads, are now feasible to use even at lower loads.

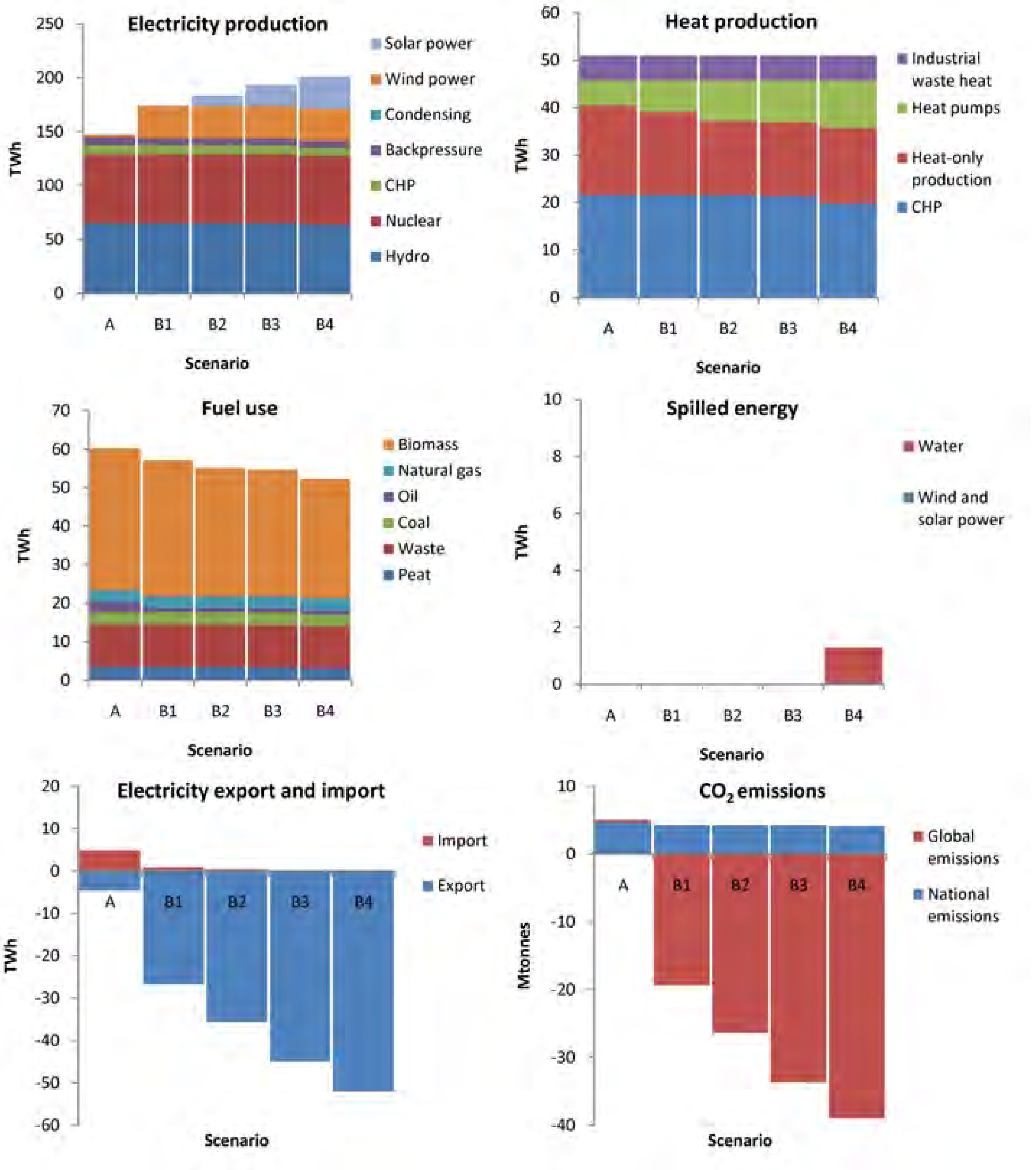
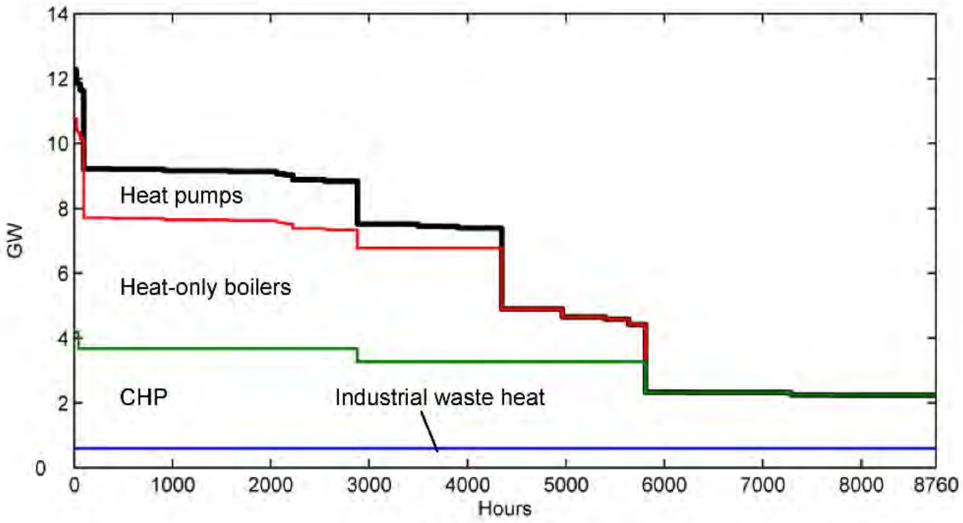
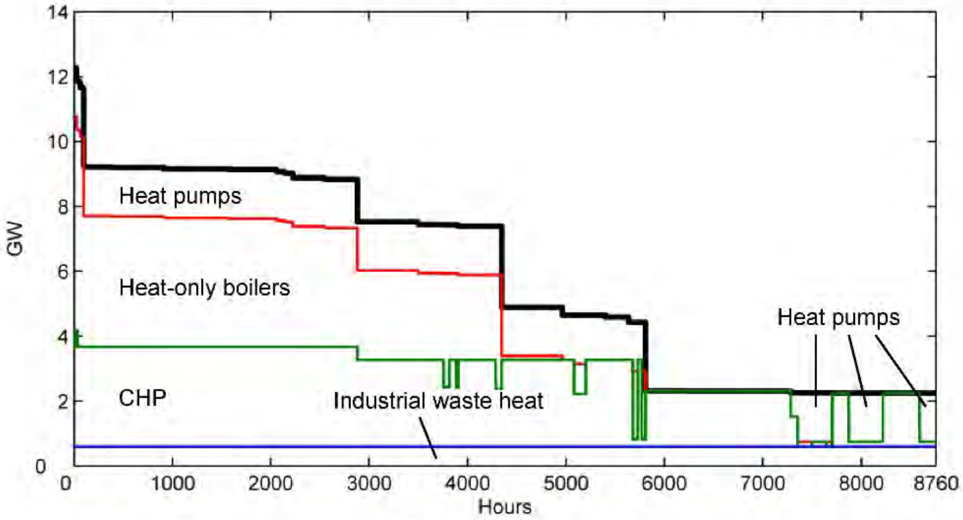


Fig. 2. Energy system characteristics in Scenarios A (base scenario) and B (addition of wind power) with cases 1-4 (different solar power integration levels).

Electricity exports increase due to the excess generation (Fig. 2), while imports decrease due to wind and solar electricity replacing imported electricity. This is reflected in the CO_2 emissions: emissions are reduced in power systems abroad due to export of electricity, which is assumed to replace coal-fired marginal electricity production. National emissions, resulting from fuel combustion in the studied system, and global emissions, being emissions caused or replaced by electricity exchange with continental Europe, are shown separately in Fig. 2. The reduction of global emissions vastly exceeds the local emissions.



(a) Case A



(b) Case B4

Fig. 3. Duration curves for the district heating demand (solid bold staircase line) and contribution of different types of heat production meeting this demand.

4. Discussion

The major impact on the district heating system in scenario B is biomass-fuelled CHP being replaced by heat pumps. This is perhaps a questionable system solution because investments in CHP plants are utilised to a lesser degree. From an overall systems perspective it may seem more reasonable to use CHP in Sweden where the heat can be utilised in district heating systems and to install solar cells in countries with less district heating and a higher and less seasonally fluctuating insolation. However, on a liberalised electricity market, if solar cells become cost-effective, a large-scale integration is possible and would be something that district heating utilities would have to adapt to. With a large surplus generation from renewables, the electricity prices would occasionally be very low, which would make it reasonable to decrease CHP production because of the low revenues from sold electricity. At the same time the low electricity prices would make electric heating, at least with heat pumps, cost-effective. It is important to note that neither competition with CHP, nor other impacts such as water spillage, pose any definitive limits to the integration of solar and wind power. In general, integration of variable power generation is not primarily restricted by any fundamental technological limits but is rather determined by economic trade-offs, depending on the balance between demand and generation locally and in neighbouring areas, transmission capacities, hydropower control and spillage [8].

Some limitations of the studied scenarios, which are based on today's power and district heating systems, have impacts on the results. For example, the increased use of heat pumps occurs when transmission capacities restrict the possibilities for electricity export. Therefore, increased transmission capacity to neighbouring countries would make it possible to export the electricity instead of using it for electric heating. An increased transmission capacity would probably accompany an extensive integration of renewable power generation. However, if solar and wind power penetration levels increase in other countries, its variability will to some extent be correlated to the variability of the Swedish plants. A production surplus in neighbouring countries would therefore reduce the possibilities for exports, despite a higher transmission capacity. Additional scenarios that take this into account would be needed for further studies.

Another possibility that should be included in future scenarios is load management, which could help absorbing solar and wind power variability. Increased use of heat pumps could be seen as one type of load management, as it occasionally increases the electricity demand. Other types of demand response should be included as well. Another possible feature of the future power system is a changed electricity demand due to a large-scale introduction of electric vehicles. These could also introduce additional storage capacity to the system. A large-scale change to the district heating load is also possible, following energy efficiency measures in the built environment, which could possibly change the basis for the CHP production. But district heating may, on the other hand, also serve new purposes, such as industrial heat demand, absorption cooling and washing machines, which reduce seasonal demand variations and improve conditions for CHP production. Global warming and its effects on the climate could also be taken into account. For example, precipitation will probably increase in Sweden [9], which improves the hydropower ability to balance variable power generation. All of these possibilities should be included in further research.

Some more fundamental limitations of the applied model should also be mentioned. The variability of combined solar and wind power is described in detail, but not the short time-scale fluctuations that determine the instantaneous utilisation of reserve capacity. Moreover, hydropower control is modelled in an aggregated form and does not consider individual rivers where the flows between hydropower plants may be coupled. Another simplification is that bottlenecks in transmission capacity within the Swedish power system are not included. Combined, these simplifications may overestimate the flexibility of the power system. In reality, it would be possible e.g. for water spillage to occur for lower penetration levels of renewable power generation than the ones in case B4.

5. Conclusions

The energy system optimisation model MODEST has been used to study the Swedish power and district-heating systems with large-scale renewable power integration. It was found that incremental amounts of solar and wind power added to the existing system do not cause any spilled energy until they reach the levels in the most extreme case where solar and wind power each produce 30 TWh annually. However, the large-scale renewable power integration reduces utilisation of investments in CHP plants due to an increased use of heat pumps and, as a consequence, leads to reduced use of biofuels for district heating. A major proportion of the added generation capacity produces a surplus that is exported. Further research should include scenarios for the major influential system components and parameters, such as domestic and foreign transmission capacity.

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