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Heat pumps in district heating networks

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Abstract:

In the current Danish energy system, the majority of electricity and heat is produced in combined heat and power plants. With increasing shares of intermittent renewable power production, it becomes a challenging task to match power and heat production, as heat demand and production capacity constraints limit the power plants. Efficient heat pumps can be used to decouple the constraints of electricity and heat production, while maintaining the high energy efficiency needed to match the politically agreed carbon emission goals. The requirements in terms of COP, location, capacity and economy are calculated using an energy system model which includes power plants, heat pumps and district heating consumption profiles. The model is developed with focus on accurate representation of the performance of the units in different locations and operating modes. The model can assist in investment decisions and strategic planning in the energy sector. The paper presents a case study of optimal implementation of heat pumps in the present energy system of the Copenhagen area. By introduction of the correct capacity of heat pumps, a 1,6 % reduction in fuel consumption for electricity and heat production can be obtained at present conditions in a month with high heating demand.

Keywords:

Combined heat and power, Heat pumps, District heating, Energy systems analysis, Optimisation.

1. Introduction

In areas with large shares of Combined Heat and Power (CHP) production, a significant introduction of intermittent power production may influence the operation management of both heat and electricity production. CHP plants may be needed to operate in hours where the electricity price is not favourable, as demand for heat production exceeds supply. Methods to decouple the production constraints of both utility products, while maintaining high energy efficiency, are investigated as they may prove highly valuable. Integration of heat pumps in district heating may pose this ability [ⁱ].

In the liberalized, Nordic electricity market, the operation pattern of each plant is determined by optimization of economics. In order to evaluate the feasibility of installation of heat pumps, the numerical models used in the optimization should include the complete characteristics of the operation of both CHP plants and heat pumps utility optimisation of utilities. Today, the Danish energy system consists mainly of CHP plants, peak production boilers and wind turbines. In the coming years an increased number of wind turbines will be installed, and the intermittent power production may assign further constraints to the remaining utility units.

A number of energy system models have been developed during the last decade both in Denmark and worldwide [ⁱⁱ], and many of these models are continuously expanded and maintained. Some of the system models will require a training period up to several months, “depending on the level of complexity required”. The majority of the models are using linear optimisation [ⁱⁱⁱ].

In the linear programming (LP) models, the outlines of thermal units such as CHP-plants appear to be simplified to an extent where the representation of the plant does not characterise the physical unit satisfactory at the full operating range. Two alternative methods, i.e., Non-linear programming (NLP) and Mixed Integer Linear Programming (MIP) are increasingly used, as they both provide a possibility to increase the detail of the constraints.

The influence of using the three different optimisation approaches has been investigated in a recent paper [iii]. This study shows that the operation of heat pumps is highly affected by the representation of CHP-plants in the model. Both alternative approaches estimate increased supply of heat from heat pump operation, but the results differ to some extent. The increase is respectively 23 % (MIP optimisation) and 39% (NLP optimisation) in a month where heating demand is high. The difference for a full year is lower, however, and from an overall system perspective the two optimisations show similar results. We thus conclude that the difference in the optimised operation by using the two methods is reasonable, and that the MIP optimisation is most appropriate from a viewpoint of accuracy and runtime.

The MIP optimisation model has been used in this paper, to reveal trends regarding optimal location, COP and capacity of heat pumps in the current Eastern Denmark system.

2. Method

The numerical model is implemented in General Algebraic Modelling System (GAMS) [iv] using the CPLEX solver. The model utilises the rolling horizon optimisation principle. The model is built to represent the dynamic operation of heat and electricity markets using based on the physical principles, such as the thermodynamic laws. External data processing is handled by Matlab, using the interface gdxmrw [v]. The model approach used for implementation of the plants in the energy system is generic and easily customisable .

The energy system of eastern Denmark has been used as a case. The current operation of the utility production in this area distinguishes the system from other European utility areas, as electricity is produced by wind turbines and by CHP-plants. According to the statistics for the combined Danish energy system [vi] (including the area of western Denmark) more than 99.7% of the produced electricity in 2011 originates from the two utility technologies.

Historical data are available online for electricity production and consumption in each region [vii]. Hourly values for wind production, local production (small scale CHP-plants) and gross consumption are used. The used data from this source is from 2011.

The electricity production system in eastern Denmark is composed mainly of small scale and central CHP-plants, along with a high number of wind turbines. Additionally there are 4 central CHP waste incineration units in the energy system layout, but in terms of installed capacity for electricity production they represent a small fraction. For the majority of the central CHP-units and incineration plants, the produced heat is transmitted to only one large district heating network (network #1). One central CHP-plant is connected to a separate network (network #2). The hourly demand of the networks has been collected from one of the network operators (HOFOR) for the entire year 2011. The data received is subdivided into five areas, ranging from central Copenhagen to one of the low intensity suburbs, and is thus considered representative for all the areas in the study. The derived “central” electricity demand and the total heat demand in the DH-networks for 2011 are presented in Fig.1.

Transmission lines for import/export with neighbouring regions are not studied in the analysis. Thus, the operation can be characterised as an island operation.

For each of the 18 thermal power plant units in the utility system, information regarding capacity and consumption is available online, from either the plant owners [viii] or from the TSO [ix]. From the information, it is possible to derive the plant characteristics listed in table 1. Most of the data in the table is referring directly to the design parameters, but the table also includes prices of the used type of fuel for 2011 using IEA prices [x]. Waste has been estimated to have a cost of 2 [EUR pr. GJ].

It should be noted that both electric efficiency and maximal thermal efficiency is calculated for the plant in back pressure operation mode. In extraction power plants, the efficiency of the electricity production is variable according to the c_v value of the power plant. A schematic representation of an extraction plant is presented in Fig. 2.

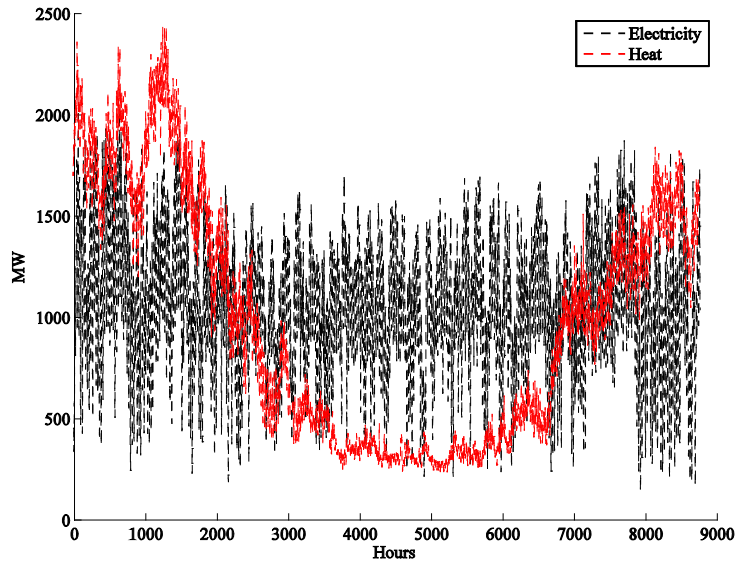


Fig. 1. Total electricity and heat demand for the system (2011).

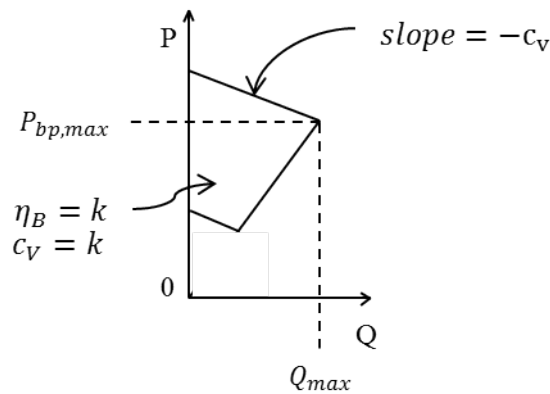


Fig. 2. Schematic representation of an extraction CHP-plant with linear constraints. Efficiency is calculated at full load back pressure operation (Q_{max} , $P_{bp,max}$).

For some of the energy technologies considered, it is required to include detail about the unit's ramp rate. Ramp rates are typically a concern in high pressure boilers, where material properties limit the boiler operational usability. These constraints are included for all the plants in table 1. The ramp rate denotes the maximal allowed change in boiler fuel input per operation hour. The ramp rate has been assumed for all CHP-plants. Four of the power plants (KYB1, KYB2, KYB3 and KYB4) are emergency and peak load facilities. Thus the units must react quickly in case of imbalance between production and demand. The ramp rate has been set to 1 in this case.

In both DH-networks, stratified storage tanks for hot DH-water are in use. The capacity and ramp rate of the storage are included in table 2. As the duration of the storage is short term (hours), thermal losses are neglected.

Table 1. Thermal power plant unit characteristics

Plant name	DH Area	Type	Capacity Boiler [MW]	Elec. eff. in backp. [/]	Max. Therm. eff. [/]	Max. boiler Ramp rate [/]	C _v value [MW/MJs]	Fuel	Fuel price [EUR pr. GJ]
AMV1	1	Backp.	365	0.21	0.90	0.2	-	Biom.	6.5
AMV3	1	Extraction	600	0.36	0.91	0.2	0.11	Coal	3.5
HCV2	1	Backp.	180	0.18	0.90	0.2	-	Nat. Gas	7.3
HCV7	1	Backp.	300	0.29	0.90	0.2	-	Nat. Gas	7.3
HCV8	1	Backp.	125	0.20	0.90	0.2	-	Nat. Gas	7.3
SVM1	1	Backp.	175	0.17	0.90	0.2	-	Nat. Gas	7.3
SVM7	1	Backp.	485	0.17	0.90	0.2	-	Nat. Gas	7.3
AMF1	1	Backp.	131	0.19	0.83	0.2	-	Waste	2.0
AVV1	1	Extraction	600	0.36	0.91	0.2	0.11	Coal	3.5
AVV2	1	Extraction	1150	0.43	0.93	0.2	0.14	Biom. & Nat. Gas	6.9
KARA5	1	Backp.	65	0.18	0.81	0.2	-	Waste	2.0
VF5	1	Backp.	95	0.12	0.99	0.2	-	Waste	2.0
VF6	1	Backp.	110	0.18	0.99	0.2	-	Waste	2.0
ASV2	2	Extraction	430	0.34	0.90	0.2	0.12	Coal	3.5
STI1	-	Elec. only	900	0.30	0.30	0.2	-	Oil, heavy	8.5
KYB1	-	Elec. only	850	0.30	0.30	1	-	Oil, light	14.9
KYB2	-	Elec. only	850	0.30	0.30	1	-	Oil, light	14.9
KYB3	-	Elec. only	72	0.25	0.25	1	-	Oil, light	14.9
KYB4	-	Elec. only	504	0.25	0.25	1	-	Oil, light	14.9

Table 2. Storage units in district heating networks

Unit name	DH Area	Type	Capacity [MW]	Assumed Therm. eff. [/]	Ramp rate of storage [MWh/h]
STO1	1	Heat storage	750	1	300
STO2	1	Heat storage	2600	1	330
STO4	2	Heat storage	1200	1	300

One electric heater is installed in DH-network #2 at the site of unit ASV2. The Coefficient of Performance (COP) of the electric heater is estimated to be 95%. Its characteristics are presented in table 3.

Also presented in table 3 are the basic properties of a typical heat pump unit. The COP of the considered heat pumps is estimated to 3, based on already installed units in other DH networks [^{xi}]. Several types of heat pumps for this temperature range are investigated in [^{xii}]. The COP is highly influenced by the availability of the heat source and the sink temperature. The appropriate area and condenser capacity are not fixed, but are determined by the optimisation.

Table 3. Characteristics of electric boiler and heat pump unit.

Plant name	DH Area	Type	Capacity Condenser [MW]	COP [/]	Fuel	Fuel price [EUR pr. GJ]
ASVe	2	Elec. Heat	98.0	0.95	Elec.	-
Heat Pump	??	Elec. Heat	??	3	Elec.	-

3. Results

In order to utilise the already installed CHP units optimally, the correct capacity of DH-network heat pumps is of main concern. The two networks far from identical, so each network must be considered. Results of a study of heat pump capacity for DH area #1 are presented in Fig 3 A and for DH area #2 in Fig. 3 B.

The figures illustrate the relative, equivalent full load operation as a function of heat pumps capacity for the optimum system operation. The evaluation covers the period of January 2011. We find that the installation of heat pumps result in up to 2% lower fuel consumption. More heat pump capacity will result in higher total heat production, even though the capacity ratio decreases. The heat pumps will also substitute operation of the less efficient electric heater.

A significant improvement in fuel savings with a fixed capacity of heat pumps is found for area #1, compared to the area #2. Several factors contribute to the results, of which two are mentioned here:

- Area #1 is subject to a significantly higher district heating demand, than in area #2.
- Operation optimisation of multiple CHP units (in contrast to one unit) allows higher flexibility for variables such as ramp rate and minimum/maximum load.

Considering the results in figures 3 A and 3 B, the capacity is fixed for the remaining of this study to 300 [MW] in area #1 and 100 [MW] in area #2.

The operation of the considered heat pump capacity for the full year of 2011 is presented in Fig. 4. The capacity installed in DH-area #1 has an operational time of 1389 hours a year, with an average load of approximately 228 [MW]. The heat pump capacity considered for DH-area #2, is only operated 247 hours with an average load of 71,5 [MW]. The electric heater is used as little as 22 hours during the full year with an average load of 48 [MW].

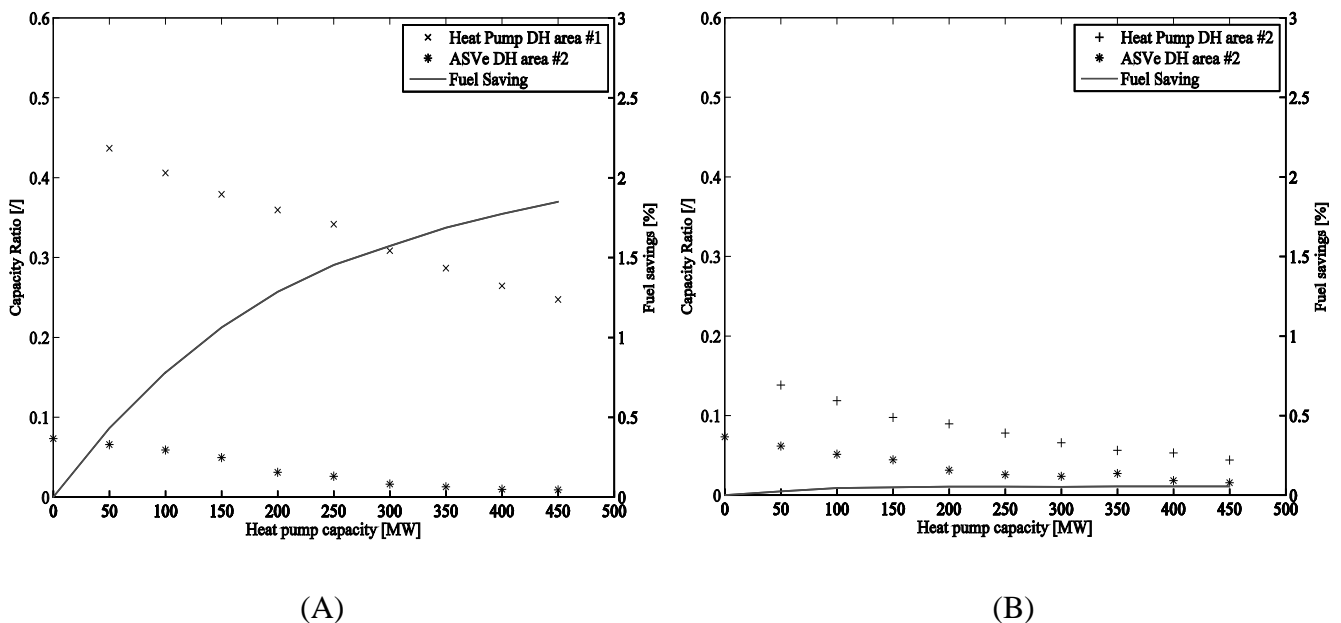


Fig. 3. Capacity ratio and fuel savings of heat pump integrations as a parametric study of the capacity to be installed in DH-area #1 (Fig 3 A) and DH-area #2 (Fig 3 B) for January 2011. In both figures, the capacity ratio of the electric heater, for the 'ASVe'-unit, is included as the operation pattern of this unit will be significantly changed.

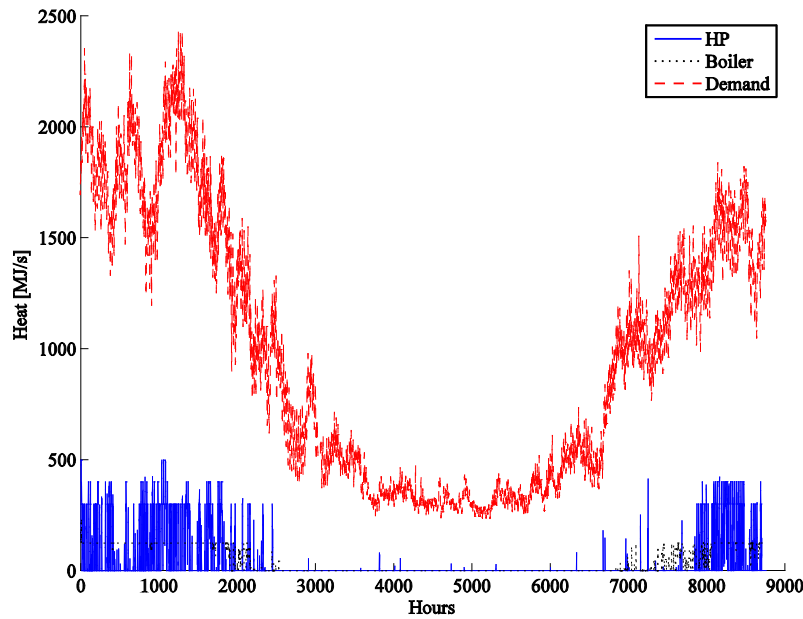


Fig. 4. Operation of heat pumps based on demand and production data from 2011.

On a monthly scale, the operation hours of each individual heat pump is presented in table 4. The heat pumps are mainly operated in four months during winter. A small part of the operation is during spring and fall, and during summer period, the operation is negligible.

Table 4 Operational hours of separate months in 2011.

	Jan	feb	mar	Apr	may	jun	jul	Aug	sep	oct	Nov	Dec
HP DH - Area #1	240	418	226	33	1	3	0	0	2	18	54	394
HP DH - Area #2	40	73	32	1	1	4	3	2	0	0	2	89
ASVe – Area #2	0	19	0	0	0	0	0	0	0	0	1	2

The load/duration curves of both heat and electricity production for the four central extraction CHP plants are presented in Fig 5. The extraction plants present an important control possibility in a highly constrained energy system. Comparing the operation hours of electricity production (Fig. 5 A) with the operation hours of heat production (Fig. 5 B) it is clear, that the extraction plants are still mainly operated for electricity production. This suggests, that heat pump introduction mainly is advantageous due to the high fluctuations of electricity production, as heat pumps may assist in levelling the demand.

Both AVV2 and ASV2 run in full load back pressure operation approximately 280 hours a year. This suggests, that the operation pattern of heat pumps is not related to constraints from installed utility capacity, but rather to:

- High fluctuations in boiler load for the CHP-units.
- Mismatch between heat and electricity demand concurrency.
- Mismatch between heat and electricity demand and CHP-plant production.
- Introduction of heat pumps shift power plant production from units with high fuel cost, to units with lower cost.

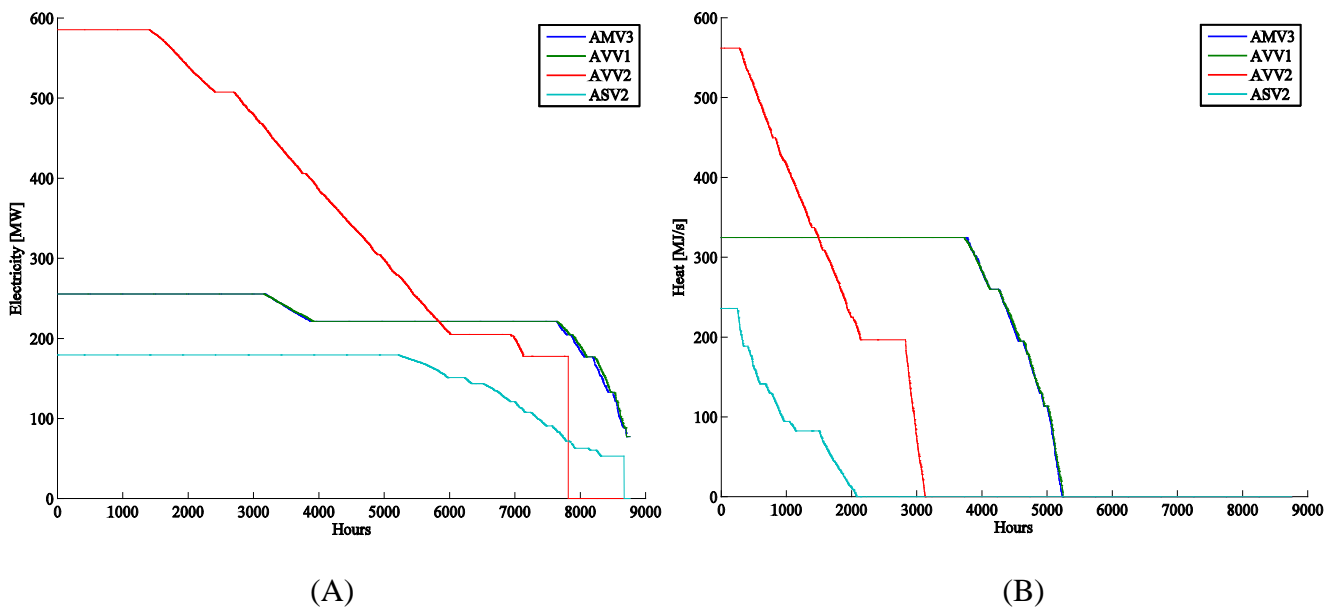


Fig. 5. Load duration curve for the operation of the central extraction CHP-plants in terms of electricity (Fig. 5 A) and heat (Fig. 5 B) for 2011.

As the input parameters may affect some of the above stated considerations, a parametric study has been conducted, based on the data from January 2011. This type of evaluation may highlight the influence of assumptions, or possibly allow a more in depth understanding of the mechanisms represented by the model. The evaluation is presented in Fig 6. Only key input parameters are considered.

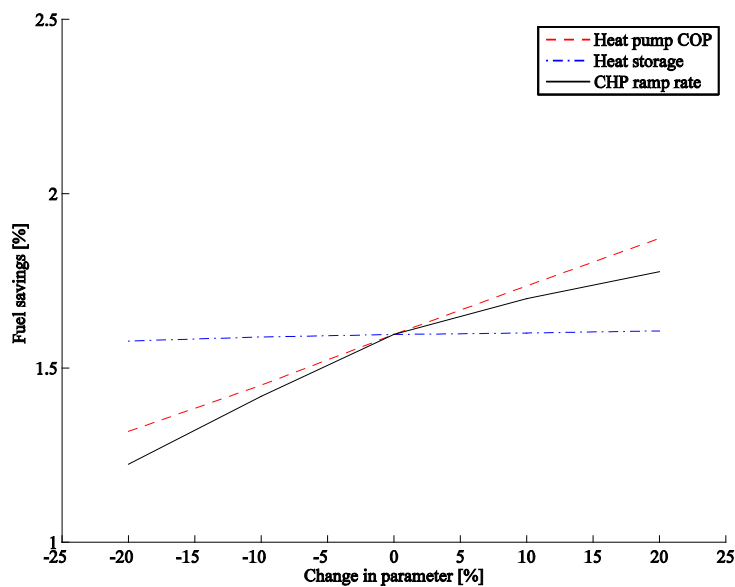


Fig. 6. Parametric study of selected input parameters in the numerical model. The study is based on data from January 2011.

The evaluation express how a slight change in the selected parameter will affect the result of the objective function, expressed as the fuel savings compared to the reference case, where no heat pumps are introduced.

Based on the evaluation it is clear, that the size of heat storage has a very low impact on the derived fuel savings from introduction of heat pumps. On the other hand, the magnitude of some of the key assumptions - heat pump COP and power plant ramp rate - influences the derived results significantly. In the case of a too high estimate of the parameters, the power plant ramp rate has the main influence on the results. If the estimated parameters are too low, the changed COP is the main influence in the system.

4. Discussion

Large scale heat pumps for high temperature applications are not easily available from manufacturers, and require in depth knowledge about the heat source and system integration. As the COP of the heat pump has a high impact on the results, further investigation is necessary, to establish the correct range of the COP.

Similarly, the ramp rate for each individual unit must be investigated, in order to establish the correct fuel savings in Eastern Denmark. Furthermore the level of detail can be increased for a few of the power plant units.

5. Conclusion

Efficient heat pumps can be used to decouple the constraints of electricity and heat production, and at the same time address the high energy efficiency needed to match the politically agreed carbon emission goals.

A newly developed energy system model can address the requirements in terms of COP, location, capacity and economy. At present, the model includes power plants, heat pumps and district heating consumption profiles. The model is developed with focus on accurate representation of the performance of the units in different locations and operating modes.

As a case study, the Copenhagen area is used. By introduction of the correct capacity of heat pumps, a 1,6 % reduction in fuel consumption for both heat and electricity production can be obtained in East Denmark in a month with high heating demand.

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