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The Role of Heat Pump Technologies in the Design of Future Sustainable Energy Systems

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ABSTRACT

In this paper, it is shown that in support of its ability to improve the overall economic cost-effectiveness and flexibility of the Danish energy system, the financially feasible integration of large-scale heat pumps with existing CHP units, is critically sensitive to the operational mode of the heat pump vis-à-vis the operational coefficient of performance (COP), which is set by the temperature level of the heat source. When using only ambient air as the heat source, the total heat production costs increases by about 10%, while the partial use of condensed flue gas from the CHP unit as a heat source results in an 8% cost reduction. Furthermore, the operational analysis shows that when a large-scale heat pump is integrated with an existing CHP unit, the projected spot market situation in Nord Pool, which reflects a growing share of wind power and heat-bound power generation electricity, will reduce the operational hours of the CHP unit significantly, making the heat pump a preferred heat production unit.

KEY WORDS

Flexible sustainable energy systems, small power producers, large-scale heat pumps for process and district heating, Denmark.

INTRODUCTION

Large-scale integration of intermittent renewable energy technologies such as wind power and photovoltaics into existing energy systems represents a major opportunity for increasing energy efficiency, reducing emissions, and optimizing the economic feasibility of the energy system [1].

Such development will be requiring innovative solutions in the design and operation of the overall energy system, in particular in order to regulate in periods of excess power production, maintaining power quality, and increasing the capacity value of small power producers.

In the case of Denmark, with about 20% of the total electricity supply coming from wind power and plans for increasing the share of wind power to 25% by 2010, measures are being developed for securing a continued efficient and cost-effective integration of grid-connected wind power. Besides the large-scale penetration of wind power, the Danish energy system is furthermore characterized by a continued policy strategy to promote system energy efficiency in the form of distributed combined heat and power production, which supplies about 50 of total heating demand and 50% of total electricity demand in 2003.

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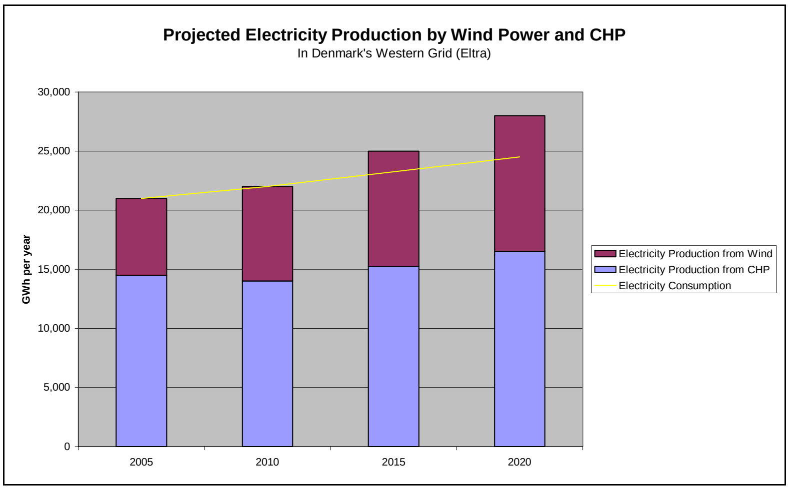
In the Western part of the Danish electricity system (Eltra), annual electricity production from wind and CHP is currently matching annual electricity demand, and new off-shore wind farms and the increasing demand for district heating, are giving rise to a situation in which supply surpasses demand, and periodically results in critical excess supply. Figure 1 illustrates the increasing significance of this challenge [2].



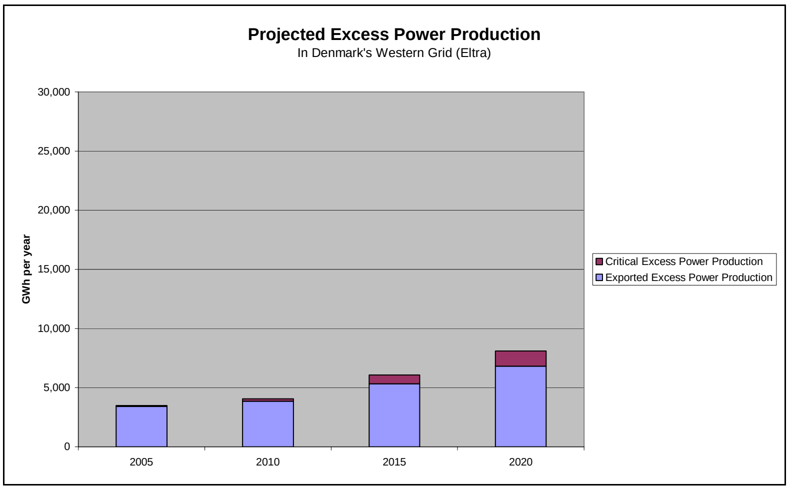


Figure 1. The current and projected share of wind power and CHP-based power generation in Denmark's Western grid, and the resulting projected excess power generation.

To avoid the foreseen problems in planning for extensive penetration of wind power in Denmark's Western grid, current plans suggests that new wind farms should better target export markets. Such strategy will involve major investments in increasing transmission capacities to neighboring countries Germany, Norway, and Sweden. Meanwhile other strategies, which attempts to assess opportunities for allowing an even larger share of intermittent renewables into the Danish energy system (50% or more of total annual electricity production) might be more cost effective [3]. Such alternative strategies seeks to increasing the flexibility of the existing supply and distribution network; strategies that may be more cost-effective, while neutralizing the problems related to critical excess production of electricity.

The strategy to limit excess electricity production by increasing the flexibility of the national system, involves the design of sustainable energy systems which relies on the integration of effective storage and relocation technologies. Figure 2 exemplifies the overall principle for the integration of selected storage and relocation technologies.

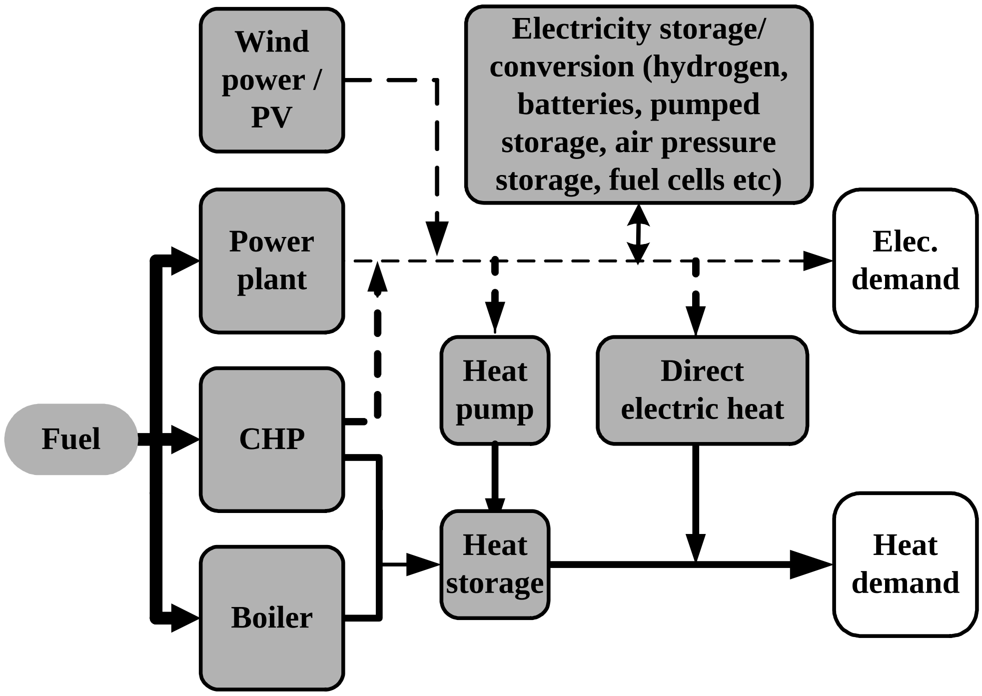


Figure 2. Integration of storage and relocation technologies in the energy system

But which options are more feasible, from a technical, environmental, economic, and financial perspective? Heat pumps, hydrogen storage, or pumped storage? Comparative techno-economic analyses of advanced system designs are required in order to assess the comparative advantages and disadvantages, and possibly to identify those options which could benefit from particular attention by policy makers and project developers.

Lund et. al [3] points to one most promising option in a short- to medium-term perspective; integration of large-scale heat pumps at the site of existing CHP-plants. From extensive system analyses using the model EnergyPLAN it is found that the levelized economic benefit in the case of Western Denmark amounts to €2.5 mill. per year at current wind power production levels. The analysis shows that it will be feasible to integrate a total of 350 MWe heat pumps, equivalent to the installation of one 1 MWe heat pump at the site of the average CHP-plant.

In fact, standard large scale compressor heat pumps are typically available up to about 1 MWe, equivalent to 3-6 MW heat output, though the integration of heat pumps is likely to be requiring a customized design process in most cases [4,5]. Issues related to ozone-depleting and global warming contributing refrigerants is a problem of the past as CFC and HCFC are being phased out, introducing natural working fluids like carbon dioxide and water. Findings suggest that natural working fluids are introduced without compromising the COP, however it is known that using carbon dioxide as a working fluid in compression systems generate high pressure differences across the compressor as well as large efficiency losses associated with the throttling process [6]. The Danish Technological Institute is currently collaborating with the Centre for Positive Displacement Compressor Technology to design and demonstrate a technology that balances the rotor forces in twin screw compressors for high pressure applications, thereby significantly improving the efficiency of large-scale heat pumps using carbon dioxide as the working fluid.

A strategy intended to promote the integration of heat pumps suggests the emergence of a new role for small power producers in the regulation of supply and demand for electricity. Certain key conditions needs to be taken into account for this purpose; most importantly the communication between the system authority and the individual plant operator and the ability of the plant to react quickly to supply requirements. Research projects indicate that starting and stopping plants currently may take from as little as 10 minutes to as much as 4-6 hours. Furthermore, the ability and willingness of the small power producer to supply reactive power would increase the flexibility of the system and allow the system authority to postpone certain investments in for example condensators [7].

However, in order to establishing such new regime and role for small power producers, regulators will be required to establish new conditions for grid-connection under which investment and operational strategies will be reflecting the economic costs and benefits.

In fact, in March 2005, 26 Danish CHP plants offered their combined capacity of 361 MWe to the Western grid authority, thereby suggesting a model for how it may become financially attractive for small power producers to become providers of regulative capacity [8]. Taking it a step further, small power producers may just as well also provide an additional regulative option by allowing the central grid authority to bid for making use of heat pumps at the site of the CHP plants for the purpose of taking excess power production in situations of such.

OBJECTIVE AND METHODOLOGY

In this paper, it is assessed whether the suggested economic feasibility of system integrated large-scale heat pumps is currently reflected in the market place, i.e. whether it is financially attractive under the current market conditions for small power producers to install and operate a large-scale heat pump.

The analyses are making use of a design and optimization model of a typical CHP-plant with and without heat pump, on the basis of which a financial cost-benefit analysis is prepared. The energyPRO software [9,10] is used to model and optimize the simulated operation of the plant over the planning period. On the basis of the financially optimized plant operation, a simple net present value approach is used as the key criteria for assessing the comparative financial feasibility of the options included under the analysis.

TECHNO-ECONOMIC ASSUMPTIONS

In the comparative analysis of the performance of large-scale heat pumps, 3 options are compared:

1. Reference: Continued operation of an existing 4 MWe (3 MWe + 1 MWe) natural-gas fired CHP plant with 1,200 m^3 thermal storage (grid-connected, heat used for district heating).
2. Alternative A: Reference plus cold source heat pump (ambient air is always used as heat source).

3. Alternative B: Reference plus partial hot source heat pump (flue gas is condensed and periodically used as heat source).

All options are optimized according to an operational strategy that allows demand at any given hour to be met by the cheapest production component, shifting between or combining the engine-generator, the heat pump, and the heat-only boiler, producing to the thermal storage, whenever feasible.

General assumptions

With 2005 as the first full year of operation, the case options are analyzed over a planning period of 20 years, equivalent to the assumed life time of the heat pump, furthermore assuming that to be the remaining lifetime of the existing CHP unit; making all investments fully depreciated within the planning period.

A nominal financial discount rate of 15% p.a. is applied in the calculation of the financial net present value. While this discount rate may seem rather high, it is assumed to mirror well the time preference for new investments among the stakeholders in focus. Current fiscal premiums and taxes are assumed constant in nominal terms. Fixed and variable O&M costs are assumed to increase at the rate of inflation, which is assumed to be 2% p.a. A 70/30 debt-equity ratio is assumed, debt being financed over 10 years at 5% p.a. effective. The results and conclusions are not particular sensitive to these assumptions.

Table 1. Key techno-economic assumptions

	Reference	Alternative A	Alternative B
Heating demand			
Annual supply	24.5 MWh		
Installed capacities			
Heating (excl. heat-only boiler)	6.5 MW	Plus 3 MW (1 MWe compressor)	Plus 4 MW (1 MWe compressor)
Electricity	4.0 MWe		
Efficiencies			
CHP unit – thermal	39%		
CHP unit – overall	90%		
Heat-only boiler – overall	95%		
Heat pump – COP		3	4
Investments			
Heat pump incl. piping, el. system, construction		0.7 mill. €	0.9 mill. €
Variable Annual O&M costs			
CHP unit (€/MWh el. prod.)	6.5 €/MWh		
Heat-only boiler (€/MWh heat delivered)	1.5 €/MWh		
Heat pump (€/MWh heat delivered)		4.0 €/MWh	4.0 €/MWh

Financial fuel costs and revenues from the sale of electricity are based on previous year values (March 2004 to February 2005) projected to develop over the planning period at rates similar to those projected for economic costs according to the Danish Energy Authority [11]. The initial natural gas price is based on fixed monthly prices for large consumers [12], and the electricity selling and purchase tariff is based on Nord Pool spot market prices [13]. Electricity purchase taxes for heating purposes apply for electricity used to feed the heat pump.

Case options

Table 1 holds the key techno-economic assumptions for the 3 options under analysis. Particular uncertainty relates to the coefficient of performance (COP) of the heat pump, which is highly sensitive to the temperature levels of the heat source as well as of the heat sink. The average temperature level of the heat source is uncertain due to the various conditions under which the heat pump will operate: in periods the engine-generator will not operate and the heat pump will have to operate on the basis of a low temperature heat source, perhaps ambient air, under which conditions the COP may be as low as 2, and is unlikely to reach a COP higher than 4 (Alternative A). In other periods the heat pump may operate in parallel with the engine-generator, possibly allowing for heat recovery by condensation of flue gasses, which will result in a relatively small temperature lift of the heat pump, as a result of which a COP of between 3 and 5 may be achieved (Alternative B). By including these two alternatives in the comparison, the aspect of this uncertainty is partially explored.

The specific investment cost for large-scale heat pumps is not expected to change towards 2030; however the COP for new heat pumps may be expected to improve by as much as 20% by 2030 without any increases in investment and O&M costs (ref). The potential increase is not considered under this analysis. The technical life time of the heat pump is assumed to be 20 years at the specified O&M costing levels.

RESULTS

Figure 3, 4 and 5 illustrates the operational characteristics of the 3 case options during a week in November 2005. It appears from a review of this and other weeks over the planning period that following the integration, the heat pump will significantly overtake heat production from the CHP unit, Alternative B more so than Alternative A.

Table 2 shows the key financial results for the operation of the 3 case options. It appears that the financial conclusion as to which option is the more feasible depends on the operational mode of the heat pump. Alternative A, which uses ambient air as the only heat source increases total costs of operation, while Alternative B, which is assumed periodically to be using condensed flue gases as heat source, reduces total costs of operation.

Table 2. Key financial results.

	Reference	Alternative A	Alternative B
Net present value (€)	-6.3 mill.	-7.0 mill.	-5.7 mill.
Levelized production cost (€/MWh-heat)	41.1	45.7	37.7

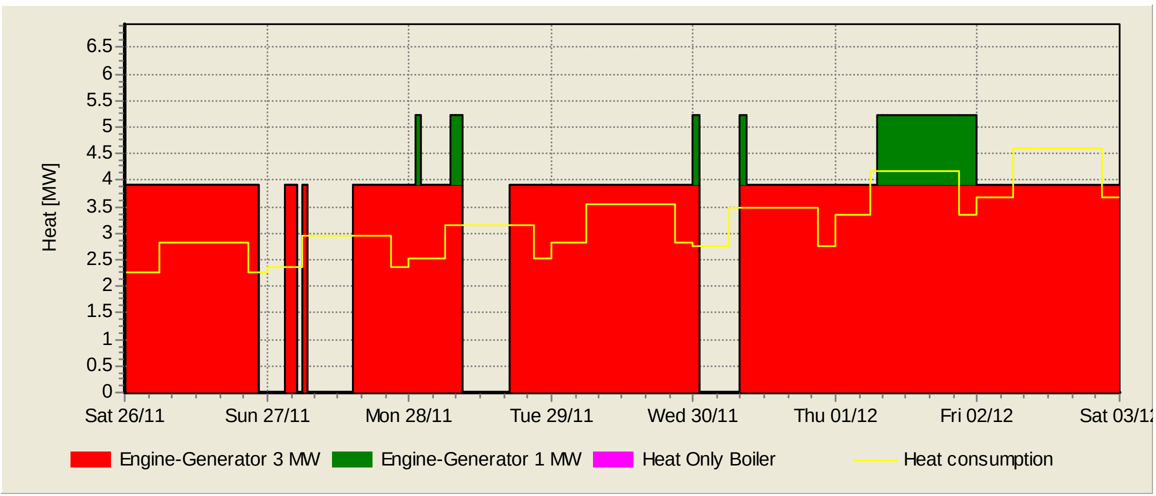


Figure 3. Sample operation profile for optimized natural gas fired CHP plant without heat pump.

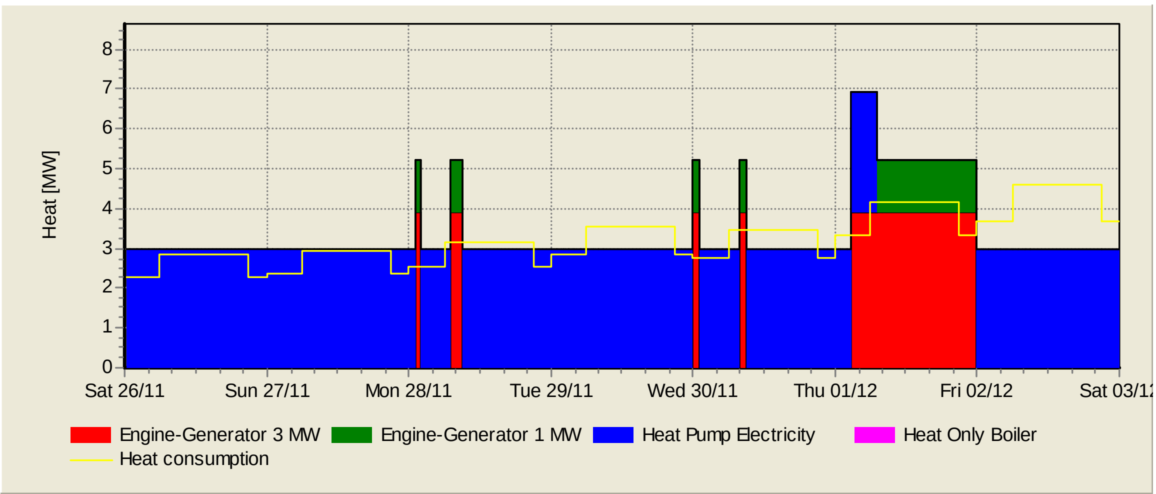


Figure 4. Sample operation profile for optimized natural gas fired CHP plant with Alternative A heat pump.

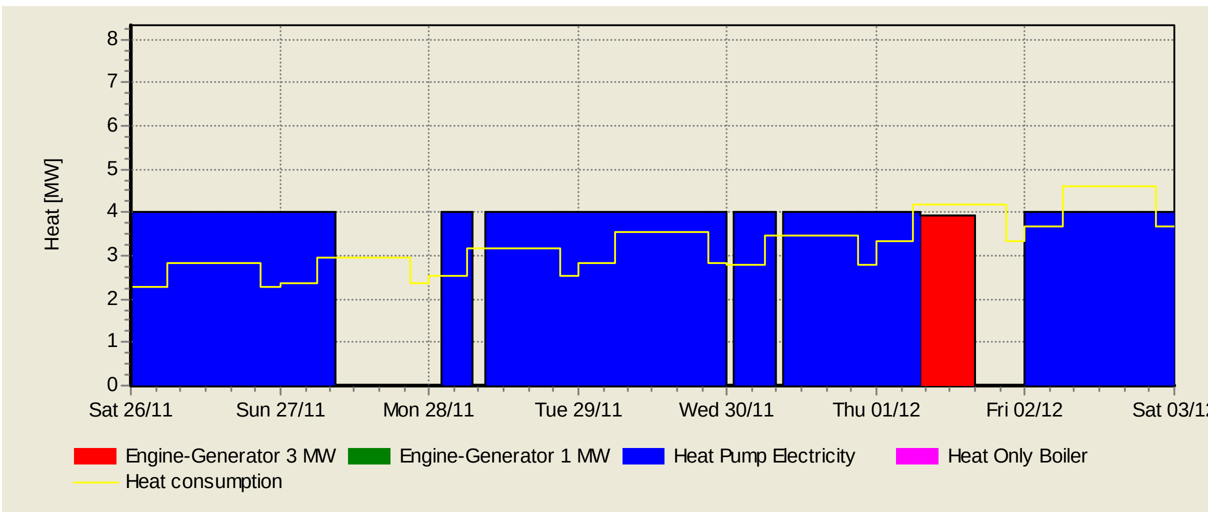


Figure 5. Sample operation profile for optimized natural gas fired CHP plant with Alternative B heat pump.

CONCLUSION

In conclusion, the results indicate that when a large-scale heat pump is integrated with an existing CGP plant, the current and projected spot market situation in Nord Pool supports a significant preference in the operation of the heat pump over the CHP unit. However, uncertainties related to the performance of the heat pump under various operational strategies must be further explored through tests and demonstration projects.

On the financial feasibility, the results indicate that when using only ambient air as the heat source (Alternative A), the overall heat production costs increases by about 10%. In an operational situation that allows a COP increase by 25% accompanied by an almost 30% increase in investment costs (Alternative B), the overall heat production costs are reduced by about 8%.

The financial results are obviously sensitive to the conditions for grid-connecting small power producers. The recent move by small power producers teaming up to supply firm capacity to the grid may benefit the CHP unit relatively if rewarded. Another potential impact will be the combination of the increase in electricity demand due to the use of heat pumps and the decrease in electricity produced by the CHP unit, which will drive up market prices for electricity and thereby benefit the CHP unit relatively over the heat pump. Analyses will be required in order to assess the feed-back effect on the Nord Pool spot market from the possible increase in demand from heat pumps and the reduced electricity production from the CHP units.

Possibly, financial instruments are required effectively to improve the financial viability of large-scale heat pumps. Most importantly, it seems relevant to discuss which options the market may reasonably introduce in order to introduce the option for regulating electricity demand and supply by the use of heat pumps in order to avoid critical excess power production and exports of excess power production, whenever feasible. Also of current interest, will be the effects of introducing CO2-credits and RE-certificates.

With construction periods of less than 1 year, the integration of large-scale heat pumps with existing small power producers may be the key to allowing a large share of intermittent renewables into the power grid in the short to medium-term. Such integration would help to securing a flexible and cost-effective operation of the energy system and policy strategies and market conditions should be developed accordingly.

ACKNOWLEDGEMENT

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