LARGE-SCALE HEAT PUMPS IN SUSTAINABLE ENERGY SYSTEMS: SYSTEM AND PROJECT PERSPECTIVES

by

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This paper shows 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 (HP) with existing combined heat and power (CHP) plants, is critically sensitive to the operational mode of the HP vis-à-vis the operational coefficient of performance, mainly given by the temperature level of the heat source. When using ground source for low-temperature heat source, heat production costs increases by about 10%, while partial use of condensed flue gasses for low-temperature heat source results in an 8% cost reduction. Furthermore, the analysis shows that when a large-scale HP is integrated with an existing CHP plant, the projected spot market situation in The Nordic Power Exchange (Nord Pool) towards 2025, which reflects a growing share of wind power and heat-supply constrained power generation electricity, further reduces the operational hours of the CHP unit over time, while increasing the operational hours of the HP unit. In result, an HP unit at half the heat production capacity as the CHP unit in combination with a heat-only boiler represents as a possibly financially feasible alternative to CHP operation, rather than a supplement to CHP unit operation. While such revised operational strategy would have impacts on policies to promote co-generation, these results indicate that the integration of large-scale HP may jeopardize efforts to promote co-generation. Policy instruments should be designed to promote the integration of HP with lower than half of the heating capacity of the CHP unit. Also it is found, that CHP-HP plant designs should allow for the utilization of heat recovered from the CHP unit's flue gasses for both concurrent (CHP unit and HP unit) and independent operation (HP unit only). For independent operation, the recovered heat is required to be stored.

Key words: *large-scale heat pumps, sustainable energy system design, relocation, techno-economic analysis*

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 [1-7]. Such development requires innovative solutions in the design and operation of the overall energy system, in particular with respect to providing balancing services in periods of excess power production, maintaining power quality, and increasing the capacity value of small power producers.

In the case of Western Denmark, with 24% of annual electricity demand being supplied by wind power in 2005 and plans for further increasing the share of wind power, measures are being developed for securing a continued efficient and cost-effective integration of grid-connected wind power.

Besides large-scale penetration of wind power, the Danish energy system is furthermore characterized by continued policy strategies to promote system energy efficiency in the form of distributed combined heat and power (CHP) production, which supplied 26% of electricity demand in 2006, while centralized large-scale CHP plants supplied 39% of electricity demand.

Under current operational strategies, such large shares of wind power and CHP are resulting in periods of excess electricity supply. While recorded data may not correspond to the most current projections, fig. 1 illustrates the increasing significance of this challenge as projected by the Danish Energy Authority in 2001 [8].

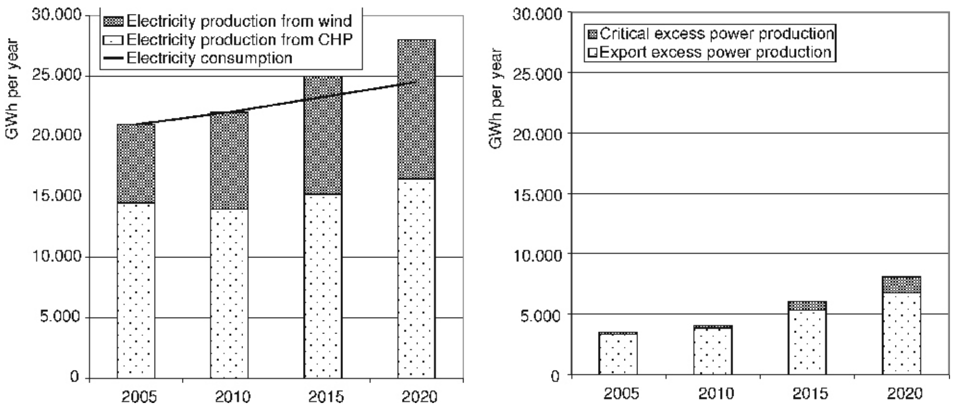

Figure 1. The current and projected share of wind power and CHP-based power generation in Denmark's Western grid (left), and the resulting projected excess power generation (right)

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 neighbouring countries Germany, Norway, and Sweden. Meanwhile, alternative strategies that 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) may be more cost effective [2]. Such alternative strategies focus on increasing the flexibility of the internal supply and distribution network. Strategies to limit excess electricity production by increasing the closed system flexibility, involves the design of sustainable energy systems which relies on the integration of effective storage and relocation technologies. Figure 2 illustrates the principle by energy system design for the integration of storage and relocation technologies.

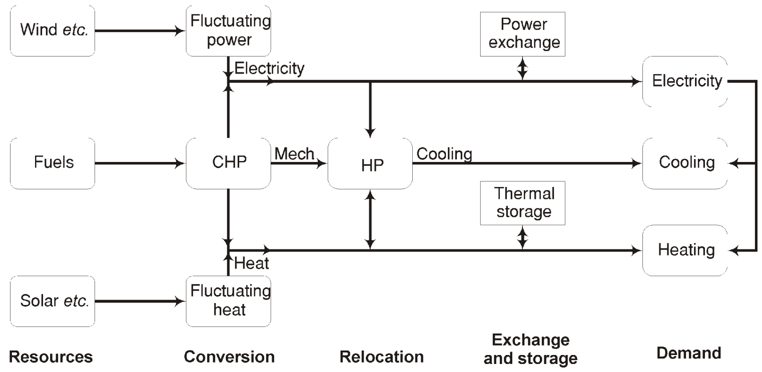

Figure 2. The 2nd generation sustainable energy system (2G) introducing relocation and thermal storage for added operational flexibility

But which storage and relocation options are more feasible from a technical, environmental, economic, and financial perspective? Heat pumps (HP), electric boilers, hydrogen storage, pumped storage? Comparative techno-economic analyses are required in order to assess comparative advantages and disadvantages, and possibly to identify 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; the integration of large-scale HP with existing CHP plants. From extensive system analyses for Denmark, Lund finds that the levelized economic benefit in the case of West Denmark amounts to €2.5 mill. per year at current wind power penetration levels. The analysis shows that it will be feasible to integrate a total of 350 MW_e HP, equivalent to the installation of one 1 MW_e HP at the site of the average CHP-plant.

In fact, standard large-scale compression HP are typically available up to about 1 MW_e, equivalent to 3-6 MW heat output, though the integration of HP is likely to be requiring a custom design process [9, 10]. 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 CO_2 and H_2O. Findings suggest that natural working fluids are introduced without compromising the coefficient of performance (COP), however it is known that using CO_2 as a working fluid in compression systems generates high pressure differences across the compressor as well as large efficiency losses associated with the throttling process [11]. 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 HP using CO_2 as the working fluid [12].

A strategy intended to promote the integration of HP suggests the emergence of a new role for distributed 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 of distributed producers to supply reactive power would increase the flexibility of the system and allow for the system authority to postpone certain investments in for example condensators [13].

However, in order to establish such new regime and role for distributed 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 MW_e to the transmission grid operator, thereby suggesting a model for how it may become financially attractive for distributed producers to provide regulative capacity [14]. Distributed producers may furthermore provide additional balancing services and operational flexibility by making use of HP for the purpose of taking excess power production in situations of such and generally optimize their operational strategies according to spot market fluctuations.

Objective and methodology

In this paper, it is evaluated whether claimed economic feasibility of system integrated large-scale HP is currently reflected in the market place, *i. e*. whether it is financially feasible under current market conditions for distributed producers to install and operate a large-scale HP.

The analyses are making use of a design and optimization model of a typical CHP-plant with and without HP, on the basis of which a financial cost-benefit analysis is prepared. The energyPRO software [15. 16] is used to model and optimize the simulated operation of the plant over the planning period under given techno-economic constraints. No other proprietary tools are used for this purpose. On the basis of the financially optimized plant operation, the resulting net present value is used as key criteria for assessing the comparative financial feasibility of the options included under the analysis.

Techno-economic assumptions

In the comparative analysis of options for integrating large-scale HP with existing CHP plants, three options are compared (fig. 3):

- Reference: Continued operation of an existing 4 MW_e (3 MW_e + 1 MW_e) natural-gas fired CHP plant with 1,200 m^3 thermal storage (grid-connected, heat used for district heating).
- Option A: Reference plus 1 MW_e HP, for which ground source is used for low-temperature heat source.
- Option B: Reference plus 1 MW_e HP, for which flue gas heat recovery in combination with ground source is used as low-temperature heat source.

For Option A, low-temperature heat is recovered from ground source by a closed system of tubes placed in boreholes or shallow trenches. For Option B, low-temperature heat is recovered from cooling and condensation of flue gasses for concurrent operation of CHP unit and HP, and from ground source in combination with stored heat recovered from flue gasses for independent operation of HP unit (without CHP unit).

All options are optimized according to an operational strategy that allows heating demand at any given hour to be met by the production unit that provides heat at the lowest financial costs, shifting between or combining the CHP unit, the HP unit, and the heat-only boiler, producing to thermal storage whenever feasible.

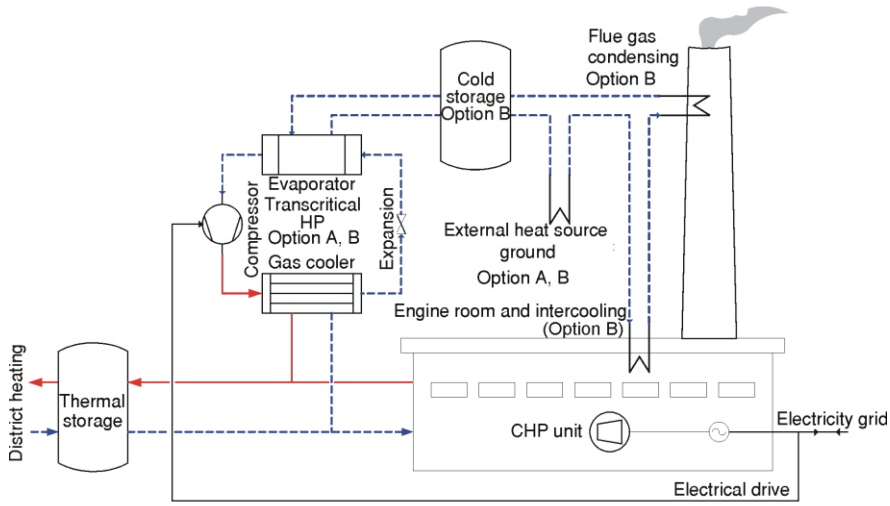

Figure 3. Conceptual plant diagram for options for integrating a large-scale HP with a CHP unit allowing for independent operation of CHP unit and HP unit for operational flexibility by relocation

General assumptions

With 2005 as the first full year of operation, all case options are analyzed over a planning period of 20 years, equivalent to the assumed life time of the HP, 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% per year is applied. 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 operational and maintenance (O&M) costs are assumed to increase at the rate of inflation, which is assumed to be 2% per year. A 70/30 debt-equity ratio is assumed, debt being financed over 10 years at 5% per year effective. The results and conclusions are not particular sensitive to these assumptions.

Financial fuel costs and revenues from electricity sales are based on previous year values (March 2004 to February 2005) projected to develop over the planning period at growth rates similar to those projected for economic costs according to planning assumptions suggested by the Danish Energy Authority [17]. The initial natural gas price is based on fixed monthly prices for large consumers [18], and the electricity selling and purchase tariff is based on Nord Pool spot market prices [19]. Electricity purchase taxes for heating purposes apply for electricity used to feed the heat pump.

Case options

Table 1 holds key techno-economic assumptions for the options under analysis. Particular uncertainty relates to the COP of the HP, 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 HP will operate. For Option A, the HP will operate on the basis of low-temperature ground source under which conditions the COP may be less than 2, and is unlikely to be higher than 4. An annual average COP of 3.0 is assumed. For Option B, the HP may operate in parallel with the engine-generator, allowing for heat recovery by condensation of flue gasses, which will result in a relatively small temperature lift of the HP, as a result of which a COP of between 3.5 and 5 may be achieved. Heat recovered from flue gasses may be stored for independent operation of the HP, which in combination with using ground source for low-temperature heat source, will allow for an assumed annual average COP of 4.0.

Table 1. Key techno-economic assumptions

	Reference	Option A	Option B
Heating demand			
– Annual supply including grid losses	24.5 GWh		
Installed capacities			
– HP heating	–	3 MW	4 MW
– CHP heating	6.5 MW		
– CHP electric	4.0 MW_e		
Efficiencies (annual average)			
– CHP unit, electric	39%		
– CHP unit, overall	90%		
– Heat-only boiler	95%		
– HP, COP	–	3	4
Investments			
– HP	–	0.7 mill. €	0.9 mill. €
Variable annual O&M costs			
– CHP unit (€/MW_h electric production)	6.5 €/MWh		
– Heat-only boiler (€/MWh heat production)	1.5 €/MWh		
– HP (€/MWh heat production)	–	4.0 €/MWh	4.0 €/MWh

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

Results

Having established optimized operational strategies under given constraints on an hourly basis for each year of operation, *i. e.* strategies for using available production units for providing heating at lowest financial costs, fig. 4 illustrates the operational profiles for the three options under analysis for a selected week in November 2005.

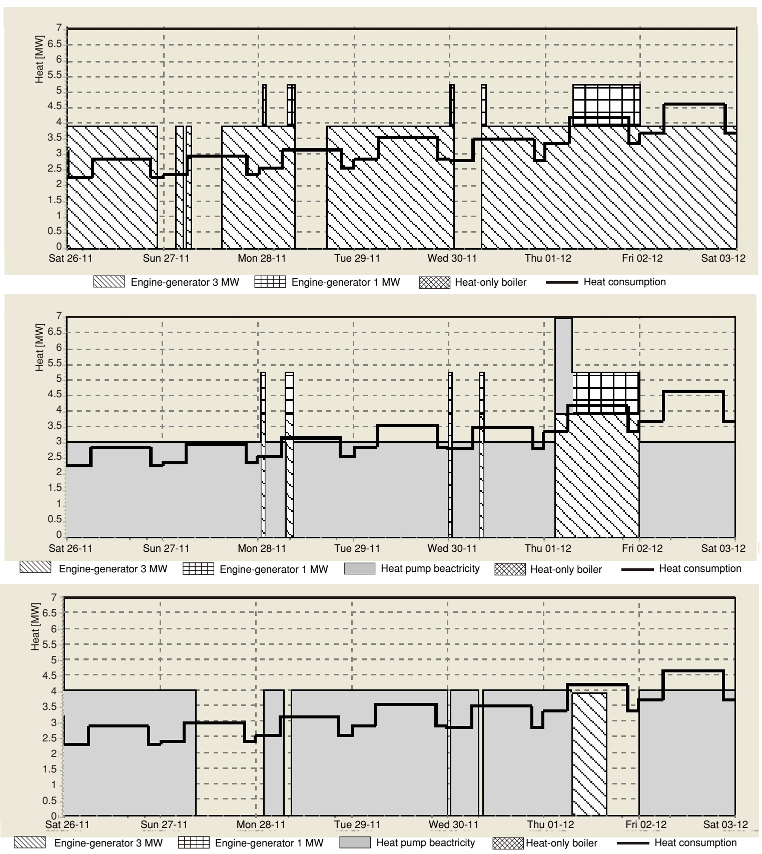

Figure 4. Operation profiles for optimized plant operation
top: reference, middle: option A, bottom: option B

The top figure illustrates the optimal mode of operation for the Reference for this week. It appears that the CHP units are priority production units. The middle figure illustrates Option A's optimal mode of operation, from which appears that the HP unit is the priority production unit for most hours, and generally overtakes the larger share of the heat production from the CHP units. The bottom figure illustrates Options B's optimal mode of operation, from which appears that the HP unit almost completely replaces heat production from the CHP unit.

It appears from a review of the operational profile over an entire year that following the integration of CHP unit and HP unit, the HP unit will significantly overtake heat production from the CHP unit, for Option B more so than for Option A.

Table 2 holds the key financial results for the operation of the three case options. A key criterion for comparison is the net costs of heat production for each option. The financial present values do not include income from heat sales and are thus negative. It is found that Option B supplies heat at the lowest costs under given assumptions. The financial present value for Option B is –5.7 mill. € corresponding to levelized heat production costs of 37.7 € per MWh-heat. In comparison to Reference operation, Option B thereby reduces heat production costs by 8%, while Option A increases heat production costs by 10% from € 41.1 to € 45.7 per MWh-heat.

The results presented in fig. 4 and tab. 2 shows that the integration of a large-scale HP (Option A and Option B) with an existing CHP plant (Reference) may be feasible from a financial perspective, in particular when the option includes heat recovery from flue gasses (Option B). However, a large-scale HP may have significant consequences to the operational strategy of the CHP plant. For example, for Option B, the HP unit almost completely takes over production from the CHP unit, replacing rather than supplementing CHP unit production.

Table 2. Key financial results

	Reference	Option A	Option B
Present value (mill. €)	–6.3	–7.0	–5.7
Levelized production cost (€/MWh-heat)	41.1	45.7	37.7

Conclusions

In conclusion, the results indicate that when a large-scale HP with 50-60% of the CHP unit's heating capacity is integrated with an existing CHP plant under given assumptions, the HP unit almost completely replaces the CHP unit as the financially preferred production unit. However, uncertainties related to the performance of the HP under various operational strategies must be further explored through tests and demonstration projects.

On the financial feasibility including investment costs for HP unit integration, the results indicate that when using only ground source for low-temperature heat source, the overall financial heat production costs increases by about 10% (Option A). A design that allows for the utilization of flue gasses in combination with ground source for low-temperature heat source, a COP increase by 25% combined with a 30% increase in investment costs, results in overall heat production costs being reduced by about 8% (Option B).

The financial results are sensitive to the conditions for grid-connecting distributed producers. The recent move by distributed producers teaming up to supply firm capacity to the grid may add operational benefits to the CHP unit, if rewarded. Another potential impact will be the combination of the increase in electricity demand due to the use of HP and the decrease in electricity produced by the CHP unit, which will affect spot market prices for electricity and thereby benefit the CHP unit relatively over the HP. 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 HP and the reduced electricity production from the CHP units.

With construction periods of less than 1 year, the integration of large-scale HP with existing distributed 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.

However, the results show that large-scale HP in combination with CHP plants should be introduced with care, not to jeopardize policies to promote co-generation. The integration of a large-scale HP may in some cases almost fully replace existing CHP unit operation, so it is to be considered to which extent large-scale HP should fully replace existing CHP producers, or consider options that limits the heating capacity of the HP to be integrated with the CHP unit. It is indicated that the HP 's heating capacity at given COPs should be much below half of the CHP unit's heat production capacity, estimated to about or less than 15-20% of heat the CHP unit's heating capacity.This would likely be the better option for introducing some system flexibility, while continuing supporting the principle of co-generation.

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