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Case study of Denmark towards 50% wind power in 2020 and technology data for large-scale heat pumps

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Contents

1. Introduction

In general two types of heat pump technologies exist – absorption heat pumps (using external heat like steam, flue gas, hot water etc.) and compressor heat pumps (using electricity) – but only the compressor heat pumps are efficient in terms of integrating more intermittent renewable energy in the energy system. Absorption heat pumps are also important in a renewable energy system to increase the share of renewable energy in the district heating production, but serve the purpose of e.g. enabling the use of geothermal energy. In this report only compressor heat pumps are included.

2. Technology and concepts

The heat pump technology is under constant development, illustrated by the fact that the efficiencies of the heat pumps have increased by 50-100% within the last 25 years, equivalent to the technical lifetime of a heat pump (Poulsen 2007). Therefore this chapter will be divided into current and near term technologies, thus outlining the type of heat pump technologies which can be used for integrating renewable energy.

The heat output is calculated by a measure called COP, representing the thermal output in comparison to the electricity input. In practice, the COP will be lower because of the loss of heat in the system. The COP value – the heat output – is generally between 2 to 5 times the drive energy.

2.1. Large heat pumps concepts

A heat pump always produces heating and cooling simultaneously. In fact, the most efficient application of heat pumps is for the combined supply of heating and cooling. Nevertheless, heat pumps are most often used for producing either heating or cooling considering the associated bi-product as recovered heat in heating-only mode, and as heat loss in cooling-only mode.

Figure 2 illustrates the basic concepts for large-scale heat pump applications in district heating:

- Top row: HP-ES: heat pump either co-producing cooling or relying on heat recovery from external source (ES) such as ground source, waste water, or other external low temperature heat source. Optionally integrated with an existing CHP plant or boiler (CHP-HP-ES).
  These concepts are currently possible to integrate in district heating.

- Bottom row: CHP-HP-FG: heat pump relying on heat recovery from flue gas (FG) of existing CHP plant or boiler. Optionally integrated with an intermediate cold storage (CS) that allows for non-concurrent operation of HP unit and CHP/boiler unit (CHP-HP-FG-CS).
  These types of heat pumps in combination with CHP and possibly a cold storage are using the newest technologies and concepts for heat pumps. To date they have not been implemented in many district networks and the CHP-HP-FG-CS concept is still in the demonstration phase. It may however be on the market in the near term.

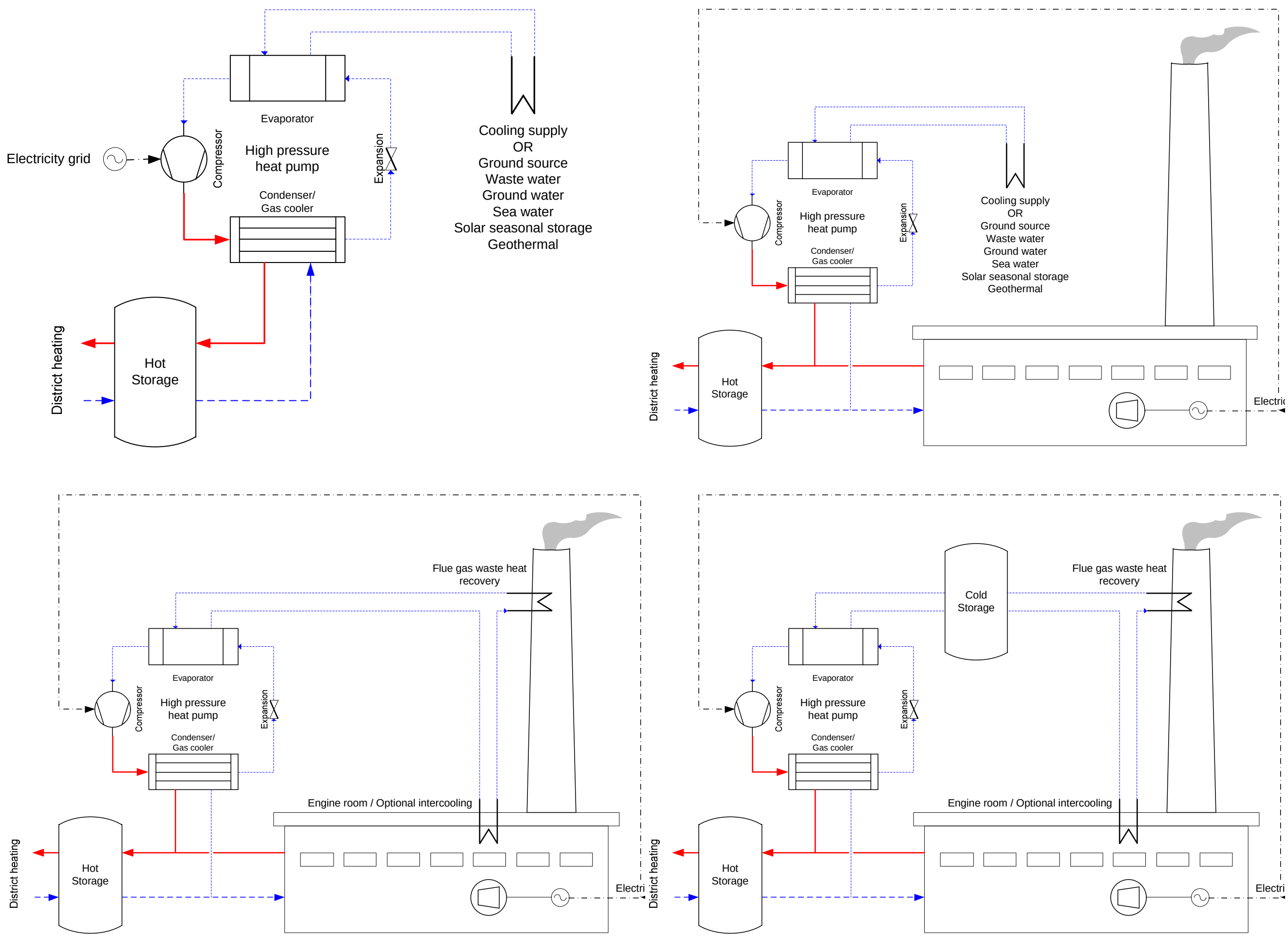

Table 1: Basic concepts for large-scale heat pump applications in district heating. Top left: HP-ES. Top right: HP-ES with CHP. Bottom left: HP-FG with CHP. Bottom right: HP-FG-CS with CHP (Blarke 2008; Blarke and Dotzauer 2011; Blarke 2012) .

In the CHP-HP-FG concept, the heat pump may be established anywhere on the district heating grid using the grid's return line as low-temperature heat source. A lower return temperature at the plant allows for further cooling of the flue gasses, thus allowing the heat pump to indirectly utilize flue gas heat recovery. This alternative solution will also allow for reducing heat losses in the district heating grid. Research points to CHP-HP-ES as the technically most effective option for introducing intermittency-friendly patterns of operation in district heating, while CHP-HP-FG-CS may be the most cost-effective option (Blarke and Lund 2007).

2.2. Fluid/Refrigerant

A heat pump relies on a thermodynamic cycle that utilizes the thermal properties of a working fluid/refrigerant. Early ozone depleting chlorofluorocarbon (CFC) and hydrochlorofluorocarbon (HCFC) working fluids are being phased out by 2015 under EC Regulation 2037/200. The development of future heat pump technologies are focusing on the natural working fluids hydrocarbons (HCs, e.g. propane), ammonia (NH_3), and carbondioxide (CO_2).

The heat pump's application determines the thermal property requirements of the working fluid. However, also non-thermal characteristics influence the choice of working fluid (**Fejl! Henvisningskilde ikke fundet.**). For example, the high toxicity of NH_3 limits its application to large industrial applications and the flammability of HCs requires certain safety measures. While hydrofluorocarbons (HFC) remain the most widely applied group of working fluids, it will likely be subject to phasing out and other regulations due to a high global warming potential.

Table 2: Non-thermal properties of modern working fluids.

Refrigerant	HFC	Natural		
		HCs	NH3	CO2
Global warming potential (GWP 100 years)	☹☹ 1300-1900	😐 3-5	☺ 0	☺ 1
Toxicity	☺	☺	☹☹	😐
Flammability	☺	☹☹	☹	☺
Materials	☺	☺	☹	☺
Pressure	☺	☺	☹	☹☹
Availability	☺	☺	☺	☺
Familiarity	☺	☺	☺	☹

In conventional district heating systems, a delivery temperature of 80°C or higher is required. In the past, compression heat pumps have failed to deliver heat at this temperature level, at least not without heavily compromising the COP. In consequence, systems for combined electricity, heat, and cooling production have typically been designed with absorption heat pumps (an absorption heat pump uses high-temperature heat for driving energy, which is not particularly relevant in the context of SmartGrid enabling technologies).

3. Heat pump development and suppliers

Recent developments indicate that CO_2 and NH_3 are the most promising refrigerants for future heat pumps. Today two high-pressure compressor technologies are offered with an attractive combination of high delivery temperature and high COP which is ideal for district heating purposes: CO_2 (carbon-dioxide/R744) transcritical piston-compressor heat pumps and new NH_3 (ammonia/R717) heat pumps using Vilter's single-screw compressor. Also the twin-screw compressor technology using NH_3 is under strong development and is expected to be introduced within a short term (Brædstrup Totalenergianlæg A/S, Vildbjerg tekniske værker et al. 2011). In Denmark CO_2 compressor heat pumps have been installed in Frederikshavn and Marstal in combination with a CHP plant and a high-temperature NH_3 single-screw heat pump is under construction in Drammen in Norway (Nielsen 2011). But as the technology is still rather new, experiences about efficiencies and dependability is still to come. The technologies are given below:

CO2 heat pump Modular from 50 kWq Sample supplier: Advansor A/S http://advansor.dk/ Key component suppliers: Bitzter compressors, Alfa Lawal gas coolers and heat exchangers	
NH3 heat pump Modular from 500 kWq Sample supplier CoolPartners Aps http://coolpartners.dk/ Key component suppliers: Vilter single-screw compressors, Alfa Lawal heat exchangers	

In Denmark heat sources like sea- and freshwater are not typically used for heat pumps, unlike in other Nordic countries. This could be caused by the fact that the water temperatures vary a lot more in the Danish seas than for instance in Norway, and also since water temperatures below 2°C are not legal to use for heat pump sources in Denmark the potential has been rather low. A new technology called the water vapor compressor may however extract the latent energy in the water when it freezes by forming a vacuum that means that the water boils at freezing point. This technology is however still under development (Brædstrup Totalenergianlæg A/S, Vildbjerg tekniske værker et al. 2011).

Heat pumps using CO_2 as working fluid are ideal for use in situations where there is a small temperature difference at the cold side and a large temperature difference on the warm side, for instance when using sea water for heat source, where the cooling in the heat pump typically is around 3-4°C. On the other hand heat pumps using NH_3 as working fluid can achieve higher efficiencies if the heat source is above 10-15°C (Brædstrup Totalenergianlæg A/S, Vildbjerg tekniske værker et al. 2011).

In Table 3 selected applications of installed heat pumps in the Nordic countries is outlined to show the current technologies available with different refrigerants, capacities etc.

Table 3, Selected examples of heat pumps in operation.

Frederikshavn district heating (Nielsen 2011)	Operation start 2010 1 MWq CO_2 heat pump (16 units) Heat delivery at 70°C Heat recovery from waste water at +15°C COP: 3.1-3.4 (measured)
Drammen district heating (Backer 2011)	Operation start 2011 15 MWq NH_3 heat pump (5 MW packs) Heat delivery at 90°C Heat recovery from sea source at +8/+4°C Design COP = 3.3
Stockholm district heating/cooling district cooling supply. Example: Hammarby plant (FORTUM 2011)	Operation start 1986 Currently 120 MWq R134a heat pumps (5 units) Heat delivery at 62-80°C. Heat recovery from waste water at +7-22°C. COP up to 3.48.

List of heat pump suppliers (heat pumps in all sizes - not complete list):

- Advansor
- Sabroe / Johnson Controls
- EMD International A/S
- Brix og Kamp
- SEG
- Dansk Fjernvarme
- Munters
- Cool Partners ApS
- Industri-Montage Vest A/S
- ICS Energy

4. Role of heat pumps in energy systems until 2020

With increasing penetration of intermittent renewable resources in the electricity grid, an increasing demand for *smart energy systems* is required. In *smart energy systems* the focus is not only on the electricity grid and the supply/demand for electricity. The focus is sector integration by integration sectors using the flexibility in demands and various storage options:

1) Heat storages and district heating with CHP plants and large heat pumps.
2) New electricity demands from large heat pumps and electric vehicles as storage options.
3) Electrolysers and liquid fuel for the transport sector enabling storage as liquids.
4) The use of gas storage.

A s*mart energy system* enables a flexible and efficient integration of large amounts of fluctuating electricity production from e.g. wind turbines (Mathiesen, Lund et al. 2011). The gas grids and liquid fuels allows for long term storage while the electric vehicles and large heat pumps allows for shorter term storage and flexibility. If the large-scale integration of renewable energy is accompanied by the integration of sectors, the increased fuel efficiency can decrease costs of the total energy system. The most important step and the first step is the integration between the heating and the electricity sectors. In Denmark approximately 50% of the electricity demand is produced by CHP plants so the integration is in place already to some extent. This integration requires thermal storages of today's sizes, a boiler, and district heating networks to enable the flexible operation of the CHP plants as already implemented in the Danish energy system. This can reduce the fuel consumption and help integrate fluctuating wind power effectively. 20-25% of the wind power can normally be integrated without significant changes in the energy system. With more than 20-25% wind power, the next step in the integration is to install large heat pumps in district heating areas and hence making a further integration of the heating and electricity systems.

In Denmark large-scale heat pumps are crucial to integrate the 50% wind power anticipated to be installed before 2020. Other means however will also be required. Once some imbalance will occur in the electricity grid, but the heat pumps alone are not able to accommodate this. The transport sector needs to be integrated into the energy system with more than 40-45% wind power or else wind power will have to be exported. This is a significant challenge in the coming years, as it is expected that Denmark will go beyond the 50% wind power share of the electricity demand.

Analysis have proven that heat pumps and battery electrical vehicles (BEV), when ready, should be the first options to be implemented if a fuel-efficient and cost-effective integration of wind power is the main objective while also reducing the excess electricity (Mathiesen and Lund 2009). Also, in the study "Heat Plan Denmark 2010" (Dyrelund, Lund et al. 2010) installing more heat pumps is one of the first measures to be recommended for the energy system for integrating more intermittent energy production in the district heating network (Dyrelund, Lund et al. 2010).

In the long term heat pumps will have an important role in the energy system where heat pumps among others can contribute to the minimisation of biomass consumption as base load in the energy system (Mathiesen, Lund et al. 2011). In the "IDA Climate Plan 2050" from 2009, the potential of large heat pumps for district heating is assessed to be 250 MWe in a proposed energy system with 48% wind in 2015 (Mathiesen, Lund et al. 2009). In the CEESA-project, pathways towards 100% renewable energy have been assessed and here a 2020 energy system is proposed with 50% wind power and the necessary heat pump proposed is 450 MW (Mathiesen, Lund et al. 2011). It is crucial to understand that the use of inexpensive thermal storages allows for the large-scale heat pumps to replace boiler production and still allows for a significant CHP production. After 2020 the coverage from heat pumps in the district heating sector should increase further.

A smart energy system strategy implies the development and integration of a wide range of supply and end-use technologies, markets, and control systems, including electric boilers and heat pumps in distributed generation, electric vehicles, mechanical and electro-chemical storage systems, flexible demand mechanisms, and more.

Large-scale compression heat pumps in district heating and cooling are – with proper designs and operational strategies – one of the most effective technologies. With proper market designs and in combination with thermal storages, compression heat pumps (using electricity) may be designed for providing system balancing services by being operated during periods of relatively high output from intermittent renewables, while not being operated during periods of relatively low output.
Figure 1 illustrates the central role that compression heat pumps could have in future intermittency-friendly energy systems introducing a balancing mechanism that couples energy carrier's electricity and heating/cooling.

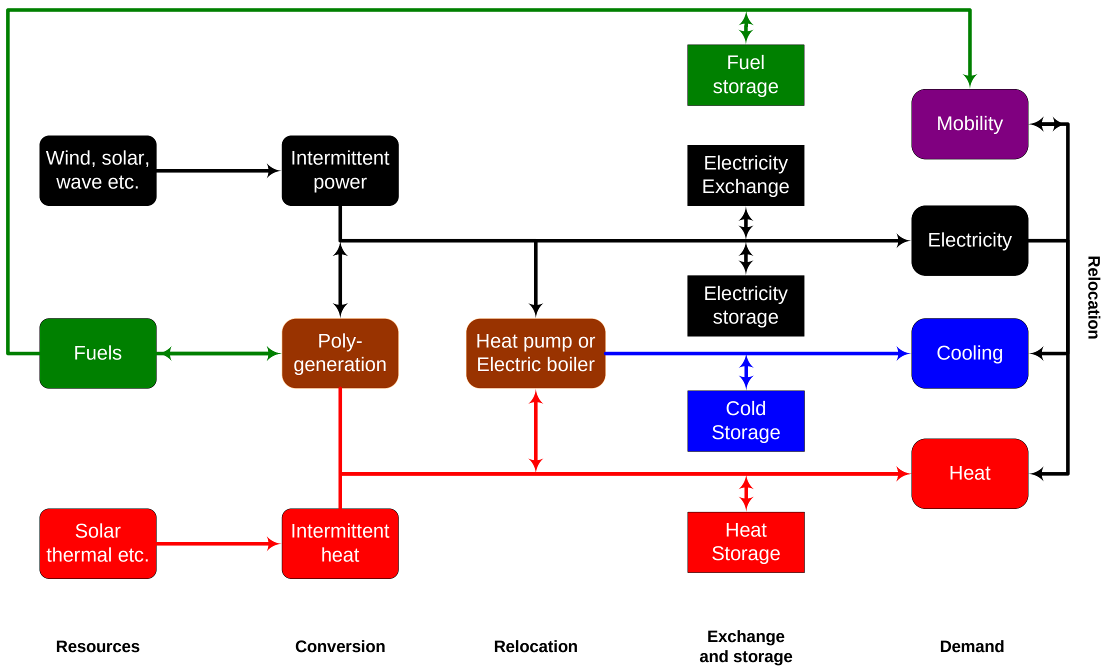

Figure 1: The intermittency-friendly energy system illustrating the central potential role of heat pumps (Blarke 2008).

Compared to other traditional technologies heat pumps can be quite expensive in investments, but may result in considerable savings in the operation costs. The investment and O&M costs for heat pumps are outlined in section 0. In addition to transmission and distribution costs, the cost of power for heat pumps is determined according to the price in the Nordic power market called NordPool, where power is being traded between the Nordic countries, Germany, Great Britain and Estonia ensuring a more liquid market and a more secure power supply (Nord Pool Spot). The price is given by the balance between supply and demand, taking transmission capacity into account.

4.1. Energy system analysis/case study

In November 2011 a case study using large scale heat pumps with increasing amounts of wind until 50% in 2020 was conducted for the Danish newspaper "Ingeniøren" using the technology data outlined in this report. By using the Danish energy system for 2010 and increasing the amount of wind power, it is possible to analyse the effects on the energy system. The energy system analyses have been done by analysing the system hour by hour in the energy system analysis model EnergyPLAN. The focus here has been a technical optimisation in which the electricity and heat supply/demand is balanced in a way that minimises the overall fuel consumption and uses as much wind power as possible. The model is also able to perform market economic optimisation as well as conduct electricity exchange analyses, which has also been used here. It is an input/output model that performs annual analyses in steps of one hour. The model makes it possible to use different regulation strategies putting emphasis on heat and power supply, import/export, ancillary services, grid stability and excess electricity production. The inputs are demands, capacities of the technologies included, demand distributions, and fluctuating renewable energy distributions. A number of technologies can be included enabling the reconstruction of all elements of an energy system and allowing the analyses of e.g. wind integration technologies, as well as the interrelation between the electricity and heat supply with high penetrations of CHP. Outputs are energy balances, resulting annual productions, fuel consumption, and import/exports. The EnergyPLAN model is particularly suitable for analysing radical changes in energy systems and renewable energy systems with high intermittency (Lund 2011).

Using the reference energy system for 2010 from the CEESA-project (Mathiesen, Lund et al. 2011) the amount of wind power can be increased to 50%. In this energy system the total energy consumption is about 850 PJ. The technical and economic inputs in this energy system are documented in WP1 (Blarke and Lund 2007). In the analyses the amount of wind power is expanded using offshore wind such as the Anholt offshore (2013) park and the proposed park at Kriegers Flak (2017). In table 1 the capacities installed in the 2010 energy system are listed. No other changes are proposed in the energy system.

Table 4, Wind power and heat pump capacities installed in the analyses.

MW installed	2010	2013	2017	2020
Onshore	2934	3134	4134	4500
Offshore	868	1268	1868	2510
Large heat pumps	-	50	300	450

In the Danish energy system it is important to note that 50% of the electricity demand is currently covered by CHP (combined heat and power). Also more than 20% of the electricity demand is covered by wind power. When erecting wind turbines the purpose is to reduce the fuel consumption in power plants. With more than 20% wind power as in the Danish energy system, some of the wind power will start replacing CHP production. The sign of this is already evident in Danish statistics. As a result the heat production in boilers increases. This is illustrated in Figure 2, where the CHP fuel consumption decreases and the boiler production increases as the wind power share increases. These results represent an hour-by-hour energy system analyses in which the wind power is prioritised to first replace power plants. Even though the CHP plants still operate quite often and can use heat storage to produce power and heat at times with low wind power production, the operation of CHP plant decreases as wind power increases. As a consequence the boiler district heating production increases, as also evident in Figure 2.

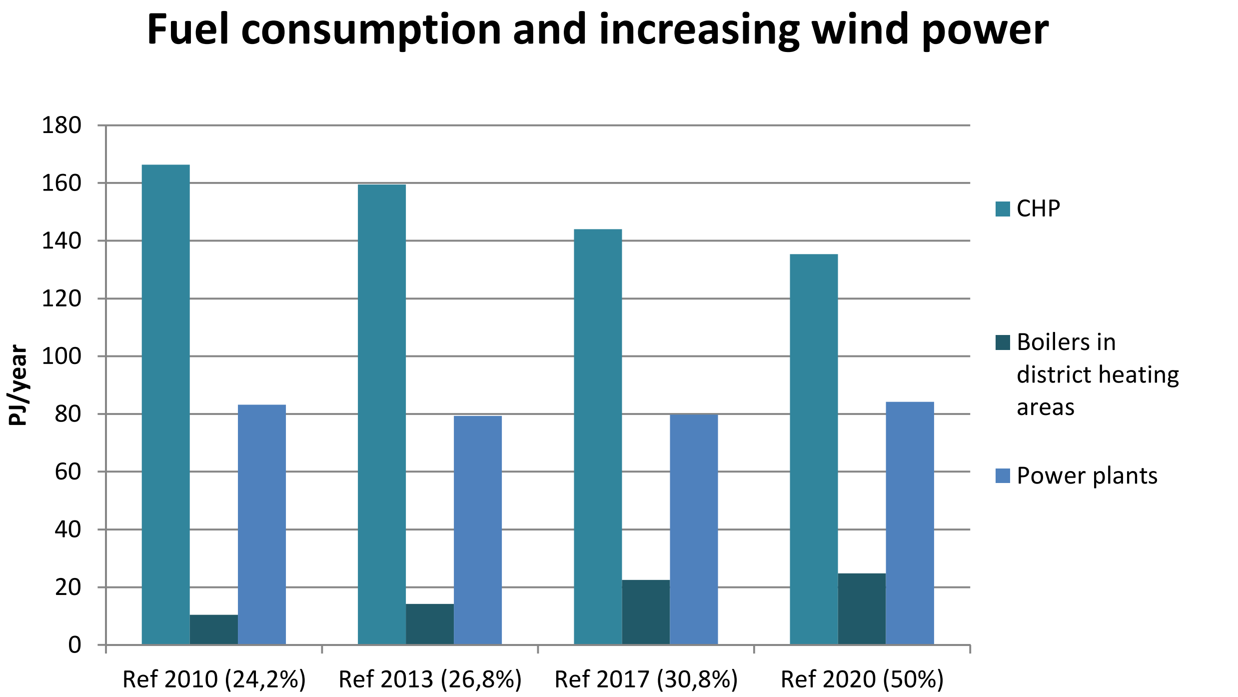

Figure 2, Fuel consumption and consequences with increasing wind power.

As a result it becomes evident that the fuel savings with increasing wind power is lost due to the fact that CHP production decreases. In the analyses here an implementation plan for large-scale heat pumps is analysed. In the implementation plan 50 MW_e is proposed in 2013, 300 MW_e in 2017 and 450 MW_e in 2020. The results for the fuel consumption is evident in Figure 3. The increased efficiency with the heat pumps is due to the fact that the heat pumps can use the thermal storages which are normally used to produce power with the CHP plant during times of high electricity demand. Using this storage boiler production can be replaced and hence the overall efficiency of the energy system is intact.

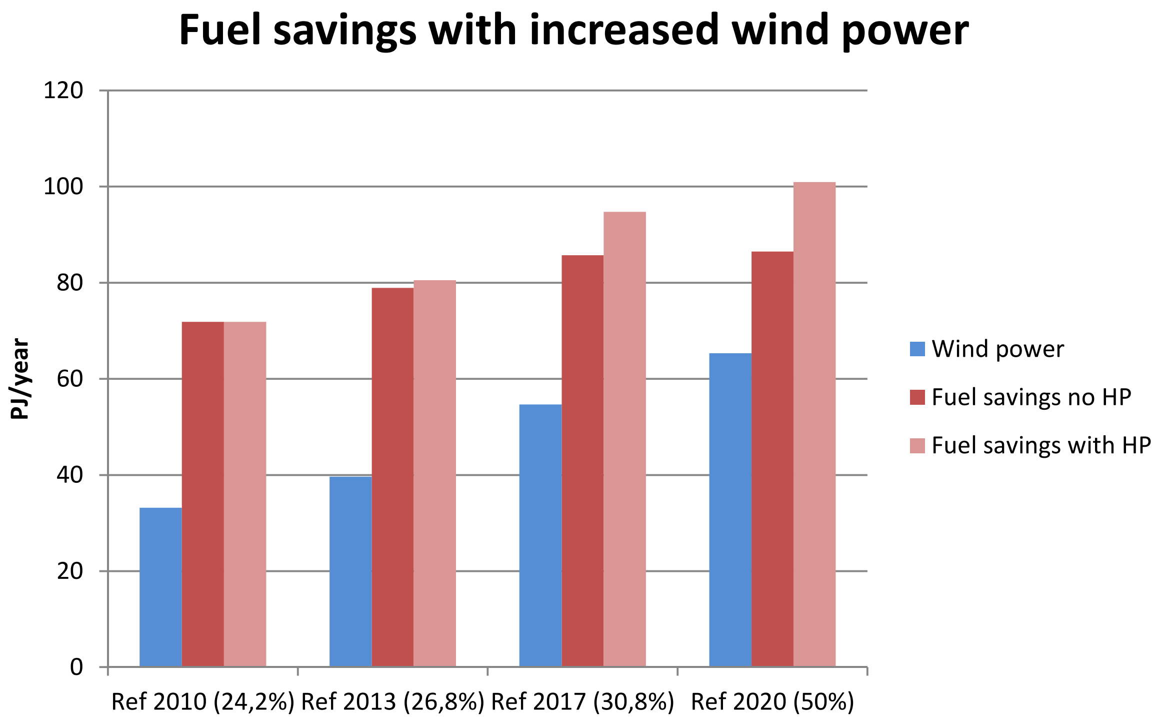

Figure 3, Fuel consumption and wind power production in energy systems with more and more wind power. Energy system analyses with and without the proposed implementation plan for heat pumps.

The economic consequences of this implementation is also analysed including the exchange of electricity in the Nord Pool market. The economic savings identified when the additional heat pumps are installed are 164 mio. DKK in 2013 with the 50 MW_e. This benefit increases in 2017 to 169 mio. DKK with 300 MW_e and 374 mio. DKK with 450 MW_e in 2020. Totally over the period the savings can be 1,500-1,700 mio. DKK. This illustrates the technical and economic benefits of installing large-scale compression heat pumps for integrating fluctuating renewable energy.

4.2. Policies to incentivise heat pumps

The installation of heat pumps dependent on the public regulation such as taxes, levies, and subsidies for heat pumps directly, but also for technologies typically influencing the use of heat pumps such as CHP plants and wind power. This is evident in Sweden where the amount of new established large heat pumps has decreased since the end of the 1990's. This is due to the new policy instruments, such as the green certificate scheme and the ban on land filling. Instead of using heat pumps the new policy instruments have increased the number of biomass boilers, biomass CHP plants and waste incineration (Eriksson and Vamling 2007). Also in Denmark some policy instruments influence the establishment of new heat pumps. For example, the use of electricity for district heating production is taxed on the output of heat, currently giving electric boilers an advantage. This means that an increased efficiency for using electricity results in a higher taxation (Dyrelund, Lund et al. 2010).

Policies should reflect that large-scale heat pumps should primarily substitute boiler-only operation, and complement CHP operation rather than replacing it. As an example this could be done by making CHP operators eligible for reimbursement of fiscal tax for electricity used in heat pumps limited to a maximum of 10 % of the co-generators electricity production (Blarke 2008). A somewhat similarly effective instrument could be to limit the reimbursement of fiscal tax for electricity used in heat pumps to the heat pump's number of full-load hours, e.g. up to 2000 hours in order to ensure that CHP is not replaced (Dyrelund, Lund et al. 2010). The fact that the electricity prices in the Nord Pool electricity market are heavily dependent on the water level in the Norwegian water reservoirs makes the construction of such a policy rather complex. This is due to the fact that in some years the heat pumps should operate more hours, if the electricity prices are low due to high water levels, while in other years the CHP plants should operate in more hours if the electricity prices are high.

5. Data sheets

The techno-economic assumptions in the data sheets are based on best available data from existing and planned projects. For all types a lifetime of 20 year is assumed at given annual O&M cost levels and the construction time of less than 1 year. The lifetime of investment in heat sources can be higher.

In these data sheets the current technology for heat pumps is described as well as the future development in COP, investments and O&M costs. The cost data in the data sheets includes the expected development in heat pump technology to 2050.

5.1. High-temperature heat output (current and future technologies)

These technologies have only been applied in few cases or are still in the demonstration phase. The technologies have a delivery temperature of 80°C. COP values are specified for various heat source temperature levels (Blarke 2011).

HP CO_2 compressor unit excl. heat source uptake:

Parameter	Unit	2010	2020	2030	2050
Capacity	MW heat	0.05 to unlimited			
COP at +2°C	-	2.0 - 2.5			
COP at +8°C	-	2.8 - 3.0			
COP at +15°C	-	3.2 - 3.4			
COP at +30°C	-	3.5 - 3.8			
Delivery temp.		80°C (Return 40°C)			
Investment	M€ per MW heat	0.8 - 1.0	0.7	0.6	0.5
Annual O&M	€ p.a.	2 – 5 % of investment p.a.		1 – 2 % of investment p.a.	

HP NH3 compressor unit excl. heat source uptake:

Parameter	Unit	2010	2020	2030	2050
Capacity	MW heat	0.5 to unlimited			
COP at +2°C	-	1.7 - 2.6			
COP at +8°C	-	2.7 - 3.3			
COP at +15°C	-	3.2 - 3.4			
COP at +30°C	-	3.5 - 4.5			
Delivery temp.		80°C (Return 40°C)			
Investment	M€ per MW heat	0.5 - 0.6	0.4	0.4	0.3
Annual O&M	€ p.a.	2 – 3 % of investment p.a.		1 – 2 % of investment p.a.	

5.2. Heat source uptake investment costs:

Heat source	Typical temperature level	Unit	2010	2020	2030	2050
Ground source excl. land costs	2 - 8°C	M€ per MW heat uptake	1.0			
Sea/waste/ground water	0 - 15°C	M€ per MW heat uptake	0.5			
Geothermal excl. land costs.[1]	30°C per vertical km	M€ per MW heat uptake per km	0.7 per vertical km			
Flue gas incl. Cold Storage.[2]	25 – 60°C	M€ per MW heat uptake	0.4			

1. Based on experiences from Hovedstadsområdets Geotermiske Samarbejde (HGS) where a 2.7 km deep 14 MW geothermal well project amounted to DKK 203 mill. incl. land facilities. Water temperature at surface is 73°C.
2. Included refurbishing existing plant for flue gas condensation incl. stainless steel core for chimney, waste water treatment, and more.

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