# 6 Heat pumps (AAU)

## 6.1 Key findings

The purpose of this paper has been to explore options for using large-scale heat pumps for the purpose of relocation. Particular attention should be given to the following 5 key findings:

1. Large-scale compression and absorption heat pumps are competing options for increasing the overall efficiency of CHP production by utilizing condensed flue gas. In concurrent operation CHP plants with heat pumps (CHP-HP plants) reaches overall plant efficiencies of above 100% (based on LHV). While absorption heat pumps are currently better positioned market-wise and the preferred short-term choice by investors, only compression heat pumps may potentially serve the purpose of relocation.

2. While forcing CHP producers away from fixed tariffs onto market conditions (spot market and regulating market) has already effectively solved the problem of critical excess electricity production in the Danish energy system, additional instruments are being introduced to stimulate relocation-driven use of electricity. However, the L1417 instrument introduced in 2006 that reduces energy and environmental taxation on electricity use for district heating production at CHP plants without concurrent power production penalizes efficient use of electricity and excludes the use of compression heat pumps in favour of less efficient electric boilers.

3. In this paper, we are introducing the 1st generation CHP-HP Cold Storage (2007-2012) concept, that integrates CHP and heat pumps (HP) using heat recovered from flue gasses as the heat pump's heat source, storing this heat in a "cold storage" allowing for flexible and integrated operation of CHP unit and heat pump. The CHP-HP Cold Storage concept is the most effective CHP plant principle around, and would effectively stimulate a flexible and relocation-driven operational praxis in distributed generation. Furthermore, it implies a breakthrough for transcritical heat pump technologies and a first step towards the 2nd generation CHP-HP Cold Storage concept (2010-2015) that introduces supplementary low-temperature heat sources, like ground-source, allowing for greater flexibility, and higher HP production rates.

4. However, current taxation instruments, at least in Denmark, makes it difficult for CHP plants to opt for the CHP-HP Cold Storage concept despite its' system-wide benefits. Compared to the in-flexible CHP-HP option with mechanical drive compression, CHP-HP Cold Storage with electrical drive compression currently results in annual financial cost savings that are lower for mechanical drive. In a specific case, for a CHP-plant currently on triple tariffs, both options will be subject to financial payback periods of 10 years or more. In conclusion, our assumptions about efficiencies, investment costs, prices shows that are it is likely that no break-through incentives in the current market place for large-scale heat pumps serves the purpose of relocation.

5. Aalborg University recommends for the Danish Parliament to allow for the compensation of energy and environmental tax of up to 10 % of self-produced electricity for use in compression heat pumps producing district heating (the 10%-instrument), which would be a targeted and suitable incentive for replacing current un-flexible distributed CHP plants with relocation-oriented 1st and 2nd generational CHP-HP Cold Storage plants, supporting higher penetration levels of wind power and CHP in the energy system.

## 6.2 Heat pumps and the principle of relocation

In February 2003, the Danish Ministry of Finance announced that a cost-effective climate strategy for Denmark [1] should be based not only on the continued build-up of wind power capacity (for what it is worth), but also include the penetration of large-scale heat pump projects ”substituting” combined heat and power production. MoF’s initial assessment indicated a potential of 1,5 mill. ton of CO2 per year from 2012 at an economic CO2 shadow cost of DKK -60 (negative sixty) per ton of CO2 for decentralized CHP, and 5,0 mill. ton of CO2 per year at an economic CO2 shadow cost of DKK 250 for centralized CHP, i.e. a combined CO2 reduction potential of 6,5 mill. ton per year, or about 13% of the Danish energy sector’s CO2 emissions in 2002.

The appropriateness of such strategy is backed by more recent assessments by Aalborg University [2] which concludes that the introduction of large-scale heat pumps is a feasible option for sustaining an energy system with fluctuating electricity supply (CHP and wind), and quite recently also by the Danish Board of Technology [3]. This and other research introduces the principle of relocation and provides theoretical energy balances and cost assessments that involve electricity use for heat production, even substantiating comparative preference to heat pumps over electric boilers.

In December 2006, the Danish system grid authority (energinet.dk) announced awarding Aalborg University, EMD International, and Danish Technological Institute DKK 11 mill. for a full-scale demonstration project that attempt to exploring the feasibility of integrating a large-scale heat pump using CO2 as working fluid with an existing distributed CHP plant.

The analyses includes with this paper relates to concepts of integrating large-scale heat pumps with CHP plants in general, and to the concept of CHP-HP Cold Storage in particular.

### 6.2.1 The principle of relocation

High penetration levels of intermittent energy resources and combined heat and power (CHP) plants require innovations with respect to storage and relocation, i.e. system flexibility by storing energy or by bridging energy carriers [4]. This paper explores large-scale heat pumps as a relocation technology.

*Figure 6-1* illustrates the principle of relocation in a 2$^{nd}$ generation sustainable energy system. The heat pump provides cooling and heat, using either mechanical or electrical drive to produce the required work.

While this paper focuses on the application of large-scale heat pumps used for heating purposes in district heating and industry, it will initially review the main principles and technology applications with respect to the principle of relocation.

### 6.2.2 Early modern large-scale heat pumps

In 1980, the world’s largest compression heat pump was established in Frederikshavn, Denmark. The 10 MWq heat pump was powered by a diesel generator, using sewage discharge as the low-temperature heat source, and supplying district heating to the municipality. Around the same time, Ronneby Municipality, Sweden, installed a 0,5 MWq diesel-powered compression heat pump to supply heating to 55 individual houses. This heat pump was using ambient air as the low-temperature heat source.

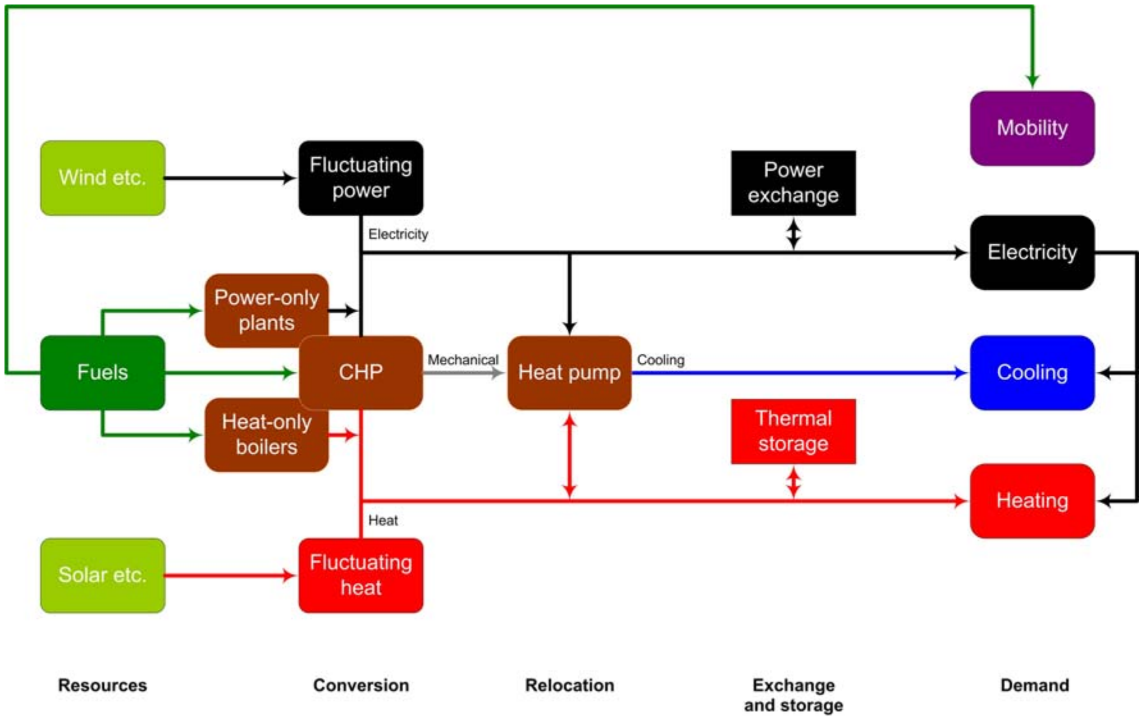


*Figure 6-1: 2nd generation sustainable energy system introducing relocation and thermal storage* for added operational flexibility

Both experiments were later terminated due to operational challenges. In 1987, the Frederikshavn heat pump was replaced by a natural gas fired CHP plant, and in 1993, the Ronneby heat pump was replaced by a wood-fired boiler. While these projects turned out to be long-term misfits, valuable experiences for future large-scale heat pump systems were produced:

1. The delivered heat should meet the actual needs of the heat takers. In Ronneby, no supplemental heating supply in a low-temperature district heating design with a 60°C plant temperature did likely not satisfy consumers.[6]

2. The heat pump's integration with the operational profile of other elements in the system of operation should be carefully assessed. In Frederikshavn, the prioritized district heating production from the local MSW plant severely restricted the operational space for the heat pump.

3. The design efficiency should carefully match the operational efficiency. In Ronneby, the design COP of 2,0 turned out to be less than 1,6 under actual long-term operation. In Frederikshavn, the actual operational COP of 1,8 was however according to design.

4. The potential threats from using particular working fluids should be carefully assessed. Both Frederikshavn and Ronneby were using the most aggressive ozone depletion and global warming potent cooling liquids (R114 and R12)[7] in complex mechanical driven heat pump systems. In fact, Frederikshavn had particular problems with leaking sealings [5].

[6] My hypothesis.

[7] R12, dichlorodifluoromethane, ODP: 0.95, GWP (100): 10,600; R114, dichlorotetrafluoroethane, ODP: 0.70, GWP (100): 9,800.

5. Particular technical challenges points to flue gas cooling heat exchanger corrosion and leaking sealings.

6. None of these heat pump applications would fit well within a 2nd generation sustainable energy system as they are mechanically powered and do not provide any significant flexibility.[8]

The large-scale plants in Frederikshavn and Ronneby represent an early phase of modern heat pump technology application for district heating purposes. Much has happened since 1980, most notably the nation-specific widespread dissemination of individual heat pumps with supplemental electric heaters, in the US and Japan often combined with A/C, the integration of large-scale heat pumps with combined heat and power plants, including MSW plants, in Sweden and Denmark, and the application of large-scale heat pumps for the utilization of low-temperature geothermal resources.

Sweden is particular rich with past and present case studies; large-scale heat pumps with heat capacities between 5 and 40 MW are found in Stockholm, Gothenburg, Solna, Örebro, Borlänge, Eskilstuna, and Malmö, using sea water or purified sewage water as low-temperature source. In Lund, Sweden, a large-scale heat pump utilizes low-temperature geothermal water.

### 6.2.3 Selected existing large-scale heat pump applications

In fact, Sweden is the dominant European arena for heat pumps, both in terms of individual and large-scale heat pumps for district heating. In 2005, 100,000 individual units, mainly ground-source or rock-source, were installed, or about one third of the total number of units sold in the European market for individual heat pumps. And in 2004, 12% of Sweden's district heating production was supplied by heat pumps operating at an average COP of 3,5[9] [6].

As such, it is not surprising that the world's largest district heating compression heat pump is located in Sweden, in the town of Umeå, where it has been in operation since September 2000. The 3,4 MWe heat pump uses R134a for working liquid and is an integrated component of a 15 MWe CHP plant that uses wood and industry waste for fuel. The heat pump utilizes condensed flue gas, and delivers heat at an output temperature of 70°C, which is subsequently heated further by turbine condensation to a grid delivery temperature of 105°C. A rather low 10 degree temperature lift allows for an average COP of about 4,0. The heat pump can only be operated concurrently with the CHP plant, reportedly raising the overall efficiency from 94% (without heat pump) to 107% (with heat pump) based on the lower heating value.

But other significant large-scale heat pumps applications are found in the Netherlands, in Norway, and in Denmark.

In Swifterbant, the Netherlands, what is probably the largest ground-source (non-geothermal) heat pump system in operation, 10 couple ground-source heat pumps supplies 79 houses with heating at an average COP of 2,2. Supplementary individual in-house heat pumps are used to supply hot tap water.

In Trondheim, Norway, a large shopping center is cooled and heated by a heat pump system that during the heating period uses the cooling distribution system of a telecommunication centre

[8] Innosys, who designed a natural gas powered heat in Ejby in 1984, during a period of evaluation in 1997 said that the major experience from operation is that the heat pump should preferably be split into an electricity producing part, and an electricity using heat pump.

[9] It is unclear to me whether absorption heat pumps integrated with CHP are included in these statistics, and if so, how. Likely, they are not included.

next-door as the heat source. In the summertime, the heat pump operates mainly for cooling, during which excess heat is distributed to pre-heat sanitary water in a neighbouring hotel. The COP for heating is 3,5.

The last application includes here is Vestforbrændingen, Denmark, an MSW plant, which in December 2006 began operating a flue gas condensation system with two absorption heat pumps.[10] The plant extracts 8,3 kg of steam per second at 163°C to produce 32-43 MW of district heating, equivalent to a COP of 1,9-2,5[11]. While the applied principle has not focused on adding any relocation-driven flexibility to the operation of the plant, it does in principle allow for the extracted steam either to be used for electricity generation[12], or for the heat pump.

These four large-scale heat pump applications represent the variety of the currently best available technologies in large-scale pumps. However, none of these applications provides any flexibility with respect to relocation-driven use of electricity.

### 6.2.4 Relocation-relevance of heat pump principles and technology applications

In conclusion, existing large-scale heat pump applications are not operated or possible to operation according the principle of relocation.

While an average COP of 3,5 suggest for Swedish heat pumps to be mainly closed-cycle compression systems, various heat pump principles are applied for district heating, individual heating, and industrial purposes.

*Table 6-1.* reflects on the likely relevance with respect to the principle of relocation of various heat pump principles and technology applications.

Transcritical compression heat pumps that allows for the operation of heat pump with no supplemental heat production (temperature lift), allowing production to thermal storage, is arguably the most promising heat pump technology awaiting application.

The question for researchers and practitioners is how large-scale heat pumps are better designed for the optional purpose of relocation, while assessing the comparative consequences of competing concepts for doing so. The research at AAU is focusing on a particularly promising candidate in this respect; the CHP-HP Cold Storage concept, introduced below and assessed preliminary, which utilizes the principle of transcritical operation.

[10] While the absorption principle is not an obvious choice with respect to the principle of relocation, as explained later in more detail, it is important to include here, as it is a major alternative option for utilization of flue gas condensation, the relevance of which will appear from the introduction of the CHP-HP Cold Storage below.

[11] Energy value of extracted steam can be made a matter of interpretation. In this case, the COP is calculated from the enthalpy of evaporation of the extracted steam, which, at 2 GJ per ton at 30 tons per hour equals 60 GJ, or 16,7 MWh.

[12] At the cost of decreasing overall plant efficiency.

Table 6-1. *Heat pump principles and applications, and relocation relevance.*

| System | Applications | Efficiency | Relevance |
|---|---|---|---|
| Closed-cycle compression | Applied for production of heat/ cooling in industry and for district heating/cooling. Maximum output temperature given by working fluid. For ammonia and other non-transcritical working up to 70 ºC. Transcritical operation using CO2 allows for exit temperatures up to 120ºC. | Typically from 1,5 to 5,0 dependent on temperature lift and the nature of the low-temperature heat source. | Highly relevant, in particular with respect to transcritical operation, e.g. using CO2 as working fluid, enabling output temperatures that allows for the operation of heat pump with no supplemental production, allowing production to thermal storage. |
| Absorption | Applied either as heat pump or heat transformer. As heat pump, with water/lithium bromide as working pair, output temperatures up to 100ºC, temperature lift up to 65ºC. New technology (two-stage) up to 260ºC and higher temperature lifts and COPs. Limited use of drive energy. Heat transformers with no external drive energy, up to 150ºC, lift 50ºC. Widely applied for heat recovery in refuse incineration plants in Sweden and Denmark. | Typically from 1,2 to 1,4 for heat pump operation according to IEA (obviously the principle for the calculation the COP is open for translation, as mentioned above). | Relevant for further investigation, however limited drive energy is applied, or not at all. Allows for increased flexibility in plant operation due to increases in heat production. A widespread alternative to closed-cycle compression heat pumps in terms of cost-effective heat recovery, resulting in very high overall plant efficiencies, but without any relocation potential. |
| Adsorption | Applied as heat pump, e.g. by adsorption of ammonia into active carbon [7] or water into silica gel. | ? | Highly relevant for further investigation, but only with respect to the principle of chemical storage of heat, not for relocation. |
| Stirling or Stirling-Vuillumier | Multifunctional heat pumps, often heat assisted, using gas-engine drives. | 2-2,4 for gas-engine drive [8]. Possibly 3,0-4,0 for electric drives. | Highly relevant alternative to closed-cycle compression system. Currently few practical experiences from large-scale operation, mainly used for cryogenic cooling systems in which Stirling excels. |
| Vapour recompression | Vapour is compressed to a higher pressure and temperature, and condensed in the same process giving off heat. No evaporator, no condenser, small temperature lift (from 70-80ºC to 110-150ºC, up to 200ºC). Typically H2O as working fluid. | COPs of 10 to 30. | No immediate relevance, though systems may be redesigned for electrical work rather than integrated industrial mechanical work, allowing for load-shifting. |
| Reverse Brayton | Recovering solvents from gases. Solvent loaden air is compressed, and then expanded. The air cools through the expansion, and the solvents condense and are recovered. | N/A | Not relevant, does not serve any primary heating or cooling purposes. |

## 6.3 CHP-HP Cold Storage

The innovative CHP-HP Cold Storage concept (CHP-HP-CS) provides a solution to problems previously faced when applying large-scale heat pumps in district heating. Furthermore, the concept provides relocation by allowing for greater flexibility in plant operation, allowing for efficient and flexible use of electricity for heat production.

In CHP-HP-CS, low-temperature heat recovered from flue gasses is recovered and stored when the CHP unit is in operation. The recovered heat stored in the cold storage is used as heat source for a transcritical compression heat pump, which is operational at very high COPs due to the relative high temperature level of the heat source and available for operation even without the CHP unit operating. When the heat pump operates it generates cold water for subsequent flue gas cooling and condensation. Temperature levels of cold storage will be in the range of 20-60°C, possibly integrated with the thermal storage, then operating in the range from 20-90°C (Figure 6-2).

With respect to the operation of a heat pump without concurrent operation of CHP unit or supplementary heat production, it was previously not possible reaching the required exit temperature for district heating, which is typically above 80°C. With a transcritical heat pump using CO2 for working fluid, a technology successfully developed at Danish Technological Institute [9] being marketed through start-up company Advansor [10], this problem is solved in the CHP-HP-CS concept.

Aalborg University, EMD International, Danish Technological Institute, and Advansor join forces in a full-scale CHP-HP-CS demonstration project funded by Energinet.dk, the Danish TSO, to be implemented during 2007-2008.

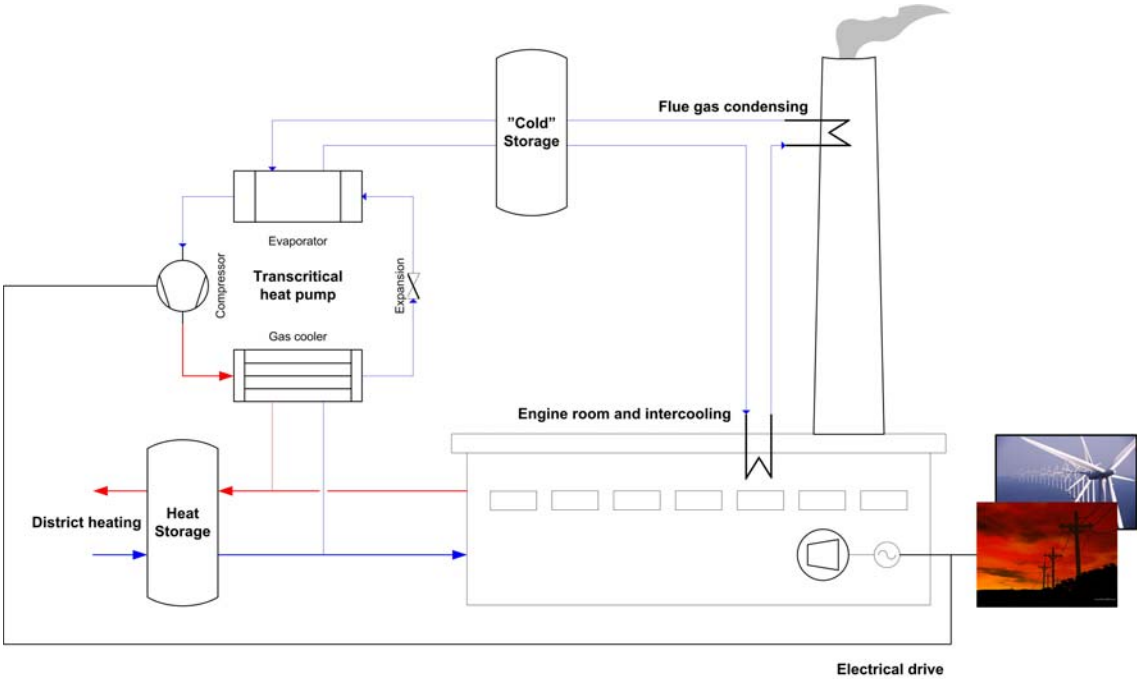


*Figure 6-2: 1st generation CHP-HP Cold Storage concept for utilization of heat recovered from flue gasses, concurrent operation AND relocation possible (i.e. operation of heat pump unit or CHP unit).*

Table 6-2. *Techno-economic datasheet for CHP-HP Cold Storage*

| | Status | Scenario assumptions | |
|---|---|---|---|
| | **2006** | **Low penetration** | **High penetration** |
| Working fluid | CO2 | | |
| Electric capacity | Up to 10% of installed CHP electricity generating capacity | | |
| Heating capacity | Around 30% of installed CHP heating capacity | | |
| COP | 3,7 | 3,8 | 3,9 |
| Investment costs[13] | DKK 19,5 mill. per MWe | DKK 19,5 mill. per MWe | DKK 15,0 mill. per MWe |
| O&M costs | 0[14] | | |
| Life time | 20 years | 20 years | 25 years |

Techno-economic research and results have been excluded from this paper due to limitations of space, but may be found in Blarke [4,11,12], articles all of which are acknowledging the DESIRE project.

## 6.4 Instruments for promoting relocation in distributed generation

The first step for introducing relocation and increasing the operational flexibility in an energy system with a high level of penetration of CHP and wind power like the Danish has been gradually to force decentralized power producers to operate on market conditions.

By January 2005, all Danish CHP plants above 10 MWe (49 plants @ 1.220 MWe) had moved away from fixed tariffs to market conditions (spot market, regulating market). Immediately, this effectively solved the problem of critical excess electricity production.[15] In January 2007, all Danish CHP plants between 5 and 10 MWe (74 plants @ 438 MWe) are being moved to operate on market conditions. All plants below 5 MWe (684 plants @ 713 MWe) may continue on triple tariffs at least until 2015. As of January 2007, 144 plants will be operating on market conditions, representing about 70-75 % of total electricity generating CHP capacity.

As the introduction of market conditions have effectively made the integration of CHP and wind power more practical, additional instruments are required in preparing for the further penetration of wind power, and substitution of non-CHP utility units.

In December 2005, the Danish Parliament agreed on Law L1417 [13] that introduces incentives to promote the relocation-driven use of electricity. L1417 introduces changes to existing energy and environmental taxes, most notably with respect to the taxation of the use of electricity for district heating production, and is mainly intended to stimulate the introduction of electric boilers at existing CHP plants.

Prior to L1417 any use of electricity for heating production, also self-produced electricity, was subject to an energy and environmental tax of DKK 0,665 per kWh.[16] With L1417 this tax is reduced to DKK 50 per produced GJ of district heating[17], but applies on the condition of no

[13] Based on case study, plant specific: HP unit 60%, Cold Storage: 14%, generator: 2%, optional stainless stack kernel replacement: 10%, optional LP heat exchanger replacement: 14%.

[14] Meromkostning ift. eksisterende kraftvarmeproduktion. Baserer sig på en antagelse om at varmmepumpeanlæggets D&V omkostninger dækkes af D&V besparelser for kraftvarmeenheden.

[15] According to information obtained from energinet.dk in November 2006 (Jens Pedersen).

[16] DKK 0,576 per kWh (energy tax) plus DKK 0,09 per kWh (CO2 tax).

[17] DKK 45 per GJ (energy tax) plus DKK 5 per GJ (CO2 tax).

concurrent production at the CHP unit. The instrument's particular condition of no-concurrency illustrates the operational strategy hereby introduced for balancing wind power and CHP: on demand, reduce CHP-production, while increasing relocation-driven use of electricity.

However, the mischief in this respect is that L1417 while promoting the relocation-driven use of electricity also penalizes the efficient use of electricity. As the new energy and environmental tax is calculated on the basis of district heating production, not on electricity use, the more efficient use of electricity, the higher the resulting tax per kWh of consumed electricity. While the tax for electricity used in an electric boiler is reduced by 73% (from DKK 0,665 per kWh to DKK 0,18 per kWh), the tax for electricity used in an efficient compression heat pump is reduced only by 5% (from DKK 0,665 per kWh to DKK 0,63 per kWh)[18].

In result, the revised energy and environmental taxation scheme sustains the current situation for large-scale compression heat pumps, that, if found applicable, will, if compression heat pumps are favoured at all, result in the choice of mechanically driven compression, allowing only for concurrent operation of CHP-unit and heat pump. This result in fuel savings and high efficiency plant operation, however mechanical driven compression does not allow for relocation-driven use of electricity, as electrical drive potentially does. In fact, even for similar operational strategies, electrical drive is "disallowed" by existing energy and environmental taxation system.

In April 2006, communication with the Central Customs and Tax Administration is opening for the possibility that tax on the use of electricity in a CHP-HP-CS concept may be subject to principle that in praxis will burden a kWh of electricity used in a heat pump similar to that in an electric boiler.

However, looking forward to concept that includes external heat source, what kind of instrument would effectively stimulate the introduction of designs in distributed production that allows for relocation? Aalborg University is arguing for the introduction of an instrument that will allow for various CHP-HP concepts in the short-term future to be established using electricity-driven compression: the 10%-instrument. Aalborg University recommends for the Danish Parliament to allow for the compensation of energy and environmental tax of up to 10 % of self-produced electricity for use in compression heat pumps producing district heating.

The 10%-instrument would stimulate not only a more efficient CHP production for concurrent operation of CHP unit and heat pump, but also, in combination with L1417, support the relocation-driven use of electricity. Under the current Danish policy climate, the strength of this instrument is that it is arguably neutral with respect to fiscal revenues, as mechanical-driven and electrical-driven compression results in identical operation for concurrent operation of CHP unit and heat pump. Both options works similar to reducing electricity production, while increasing heating production, often reaching overall plant efficiencies of above 100 % (based on Lower Heating Value).

However, in praxis, the issue of fiscal revenues and other impacts is somewhat trickier, as the introduction of electrical-drive compression intentionally opens up for other concepts.

## 6.5 Conclusion and perspectives

Large-scale heat pumps should not be regarded an efficient alternative to electric boilers, but rather as an integrated system component that contributes to increased operational flexibility. In the future, large-scale heat pumps may be an efficient alternative to combined heat and power

[18] For a COP of 3,8.

production, but in the short to medium term to solution is to research options that integrate large-scale heat pumps with distributed generators, maintaining the benefits of cogeneration, while allowing for balancing intermittent resources.

From a review of large-scale heat pump applications, it is found that large-scale heat pumps are never an off-the-shelve turn-key solution, but always appears as a customized industrial component being integrated with other plant components. There is a particular important reason for this: heat pumps utilizes a low-temperature heat source, either recovered heat from flue gasses, ground or rock-source, solar, sea, lake, waste water, ambient air, cooling demand, or intercooling. The availability of low-temperature heat source is highly localized. The specific availability and temperature level of this localized low-temperature heat source is used to settle for a particular operational design and resulting COP. As such, the COP may range from as little as 1 to above 5 depending here mainly on inlet temperature to the evaporator, i.e. the temperature level of the heat source.

The CHP-HP-CS concept is a solution to many of the problems associated with integrating large-scale heat pumps in to the energy system, while increasing the flexibility required for greater penetration levels of CHP and wind power. Targets could be to set to achieve market penetration for this generation concept during 2007-2012.

However, the 1st generation CHP-HP-CS may be seen only as the first step towards the 2nd generation CHP-HP-CS concept that introduces supplementary low-temperature heat sources, like ground-source, and even combines heat pumps and electric boilers. Targets could be to set to achieve market penetration for this 2nd generation concept during 2010-2015, *Figure 6-3*.

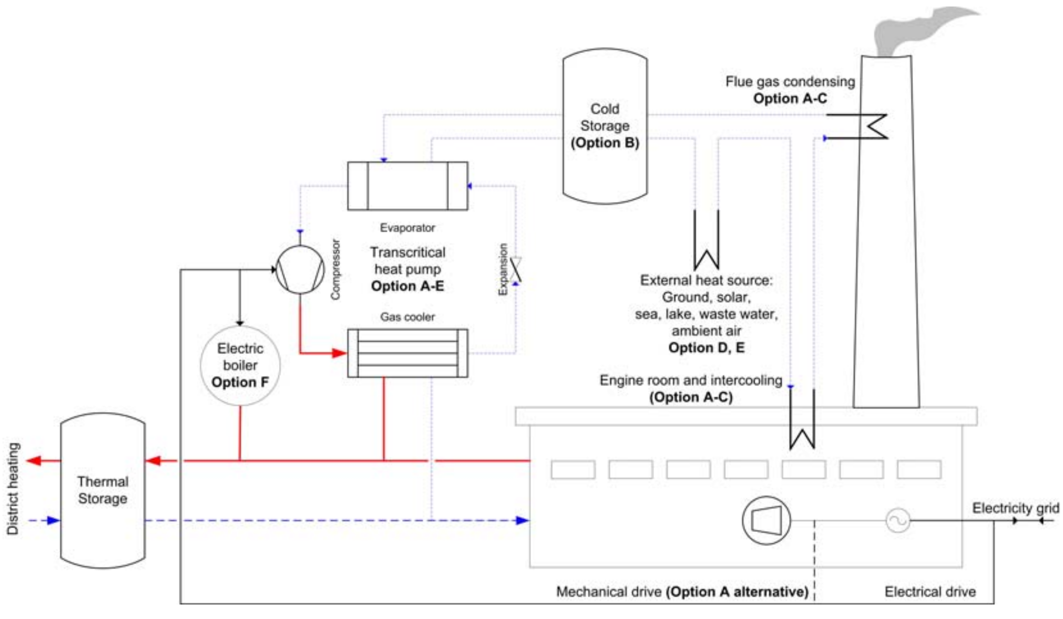


Figure 6-3: *2nd generation CHP-HP Cold Storage concept for utilization of condensed flue gas AND optional low-temperature source, like ground-source, possibly also combining heat pump and electric boilers.*

Energinet.dk, the Danish TSO, is sponsoring a DKK 11 mill. demonstration project for a CHP-HP-CS demonstration plant being in operation no earlier than by December 2007. DESIRE partners Aalborg University and EMD will particular be involved in further developing system and project modeling methodologies under the project.