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Heat pumps in Smart Energy-Efficient Buildings A State-of-the-Art Report

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Smart Energy-Efficient Buildings
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TECHNICAL REPORT

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Heat pumps in Smart Energy Efficient Buildings
– A State-of-the-Art Report

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RESULT (summary)

This report has been written in relation to the *Smart Energy Efficient Buildings* (SmartBuild) project at NTNU/SINTEF, and provides an overview of the present use of heat pumps in larger buildings in Norway. Throughout the SmartBuild project, the aim for this task (*3.2 – Heat pumps*) will be to develop new knowledge and technology for heat pumps used in effective energy systems for heating and cooling suitable non-residential buildings. In order to do this successfully, close multi-disciplinary co-operation is required.

Heat pumps represent a very energy efficient technology for heating and cooling, but several market barriers exist. However, as energy prices soar, among with more focus on energy efficiency, these barriers become less important and heat pumps become more popular. The last 3 years there has been a large increase in sales of heat pumps in Norway, total annual sales is estimated to reach beyond 10 000 units in 2002. Still, there is far left to cover what's considered to be the commercial economic potential for heat pumps – about 4 TWh heat is produced annually, compared to the economic potential of at least 10 TWh.

Since the 1990's, there has been much concern for refrigerants' contribution to global warming, which has led to the search for more environmentally benign alternatives. One of the most promising is CO_2, that when used in heat pumps is a natural and perfectly environmentally benign working fluid. Heat pumps with CO_2 can expect same, or higher COP than the corresponding conventional alternative, in addition to providing new possibilities. However, in order to make CO_2-based heat pumps for heating and cooling of buildings commercially available, more research and development is needed.

Heat pumps are smart technology!

KEYWORDS

SELECTED BY AUTHOR(S)	SmartBuild	Smart Energy Efficient Buildings
	CO2	Heat Pumps

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1 INTRODUCTION

This report has been written in context with task 3.2 of the SmartBuild (Smart Energy Efficient Buildings) project. The status report provides an overview of the field of heat pump technology that task 3.2 will focus on throughout the project period, as well as identifying important areas where multi-disciplinary co-operation is required. Chapter 4 is dedicated to interaction with other tasks and expert groups

This report is intended to form the basis for additional work within the SIP/SUP programme.

2 CENTRAL CONCEPTS

2.1 BACKGROUND

In near future, electricity prices are expected to rise due to shortage of electricity and a liberalised market. Norway has almost reached the exploitable potential for hydropower, and has in later years been forced to import electricity, mostly from Danish coal-fired power plants. This is one of the reasons for the growing governmental support for energy conservation activities, and several governmental institutions, for instance the Norwegian Water Resources and Energy Administration (NVE), the Norwegian Research Council (NFR) and the Department of Petroleum and Energy, consider the use of heat pumps as an important mean to achieve sustainable energy use.

In the recent years, there has also been an increasing demand for space cooling in Norwegian non-residential buildings. The need for space cooling will in some building categories appear in large parts of the year, and makes a good starting point for combined heat pump and cooling systems. Traditionally, electricity has often been used directly for heating purposes and to run refrigeration machinery, even in places where there are good alternative sources of energy.

In this task of the SmartBuild project, the integration of heat pumps in effective energy systems for heating and comfort cooling in suitable non-residential buildings is examined.

2.2 THE BASIC CONCEPT OF HEAT PUMPING

The following text is copied from the website of the IEA Heat Pump Centre (HPC); www.heatpumpcentre.org /1/:

“Heat flows naturally from a higher to a lower temperature. Heat pumps, however, are able to force the heat flow in the other direction, using a relatively small amount of high quality drive energy (electricity, fuel, or high-temperature waste heat). Thus heat pumps can transfer heat from natural heat sources in the surroundings, such as the air, ground or water, or from man-made heat sources such as industrial or domestic waste, to a building or an industrial application. Heat pumps can also be used for cooling. Heat is then transferred in the opposite direction, from the application that is cooled, to surroundings at a higher temperature. Sometimes the excess heat from cooling is used to meet a simultaneous heat demand.

In order to transport heat from a heat source to a heat sink, external energy is needed to drive the heat pump. Theoretically, the total heat delivered by the heat pump is equal to the heat extracted from the heat source, plus the amount of drive energy supplied. Electrically-driven heat pumps for heating buildings typically supply 100 kWh of heat with just 20-40 kWh of electricity.

The great majority of heat pumps work on the principle of the vapour compression cycle. The main components in such a heat pump system are the compressor, the expansion valve and two heat exchangers referred to as evaporator and condenser. The components are connected to form a closed circuit, as shown in Figure 2-1. A volatile liquid, known as the working fluid or refrigerant, circulates through the four components.

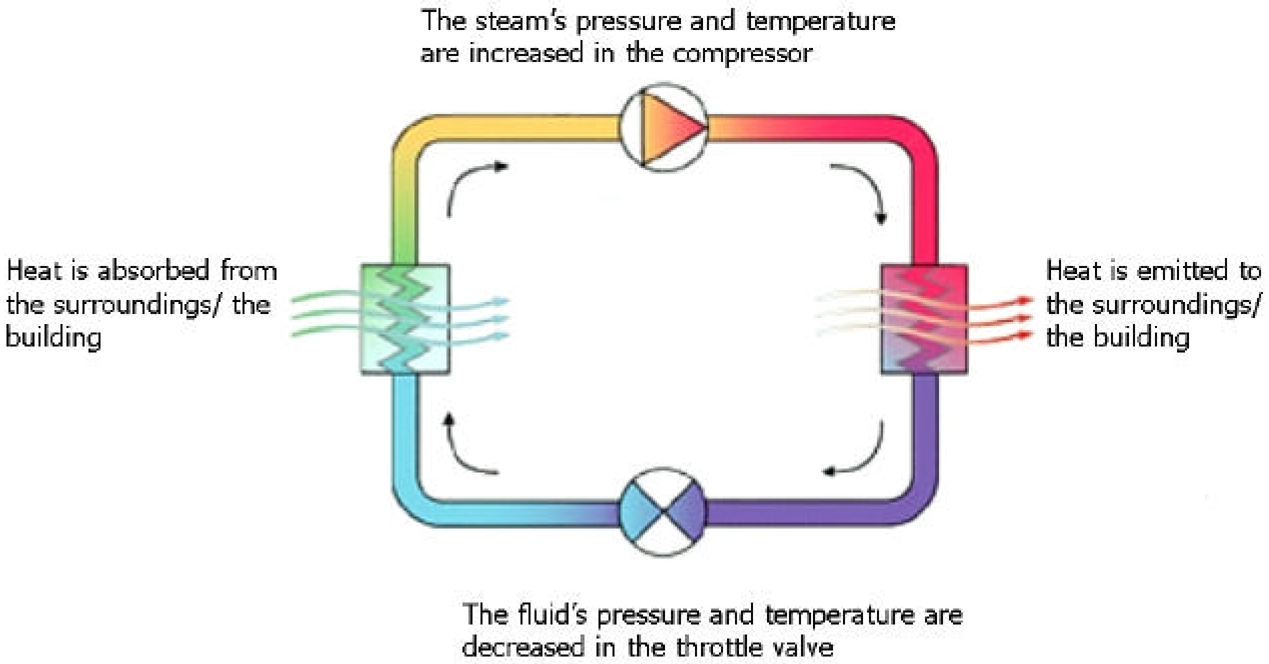

Figure 2-1: Simple heat pumping circuit. (Source: Gemini; www.ntnu.no/gemini)

In the evaporator the temperature of the liquid working fluid is kept lower than the temperature of the heat source, causing heat to flow from the heat source to the liquid, and the working fluid evaporates. Vapour from the evaporator is compressed to a higher pressure and temperature. The hot vapour then enters the condenser, where it condenses and gives off useful heat. Finally, the high-pressure working fluid is expanded to the evaporator pressure and temperature in the expansion valve. The working fluid is returned to its original state and once again enters the evaporator. The compressor is usually driven by an electric motor and sometimes by a combustion engine."

3 TECHNOLOGY AND MARKET

3.1 HEAT PUMPS IN NORWAY

By the end of 2001, there was about 37,000 heat pump installations in Norway /2/, with an annual heat production of approximately 4-5 TWh and an estimated annual energy save of 2.5 TWh. Most of these heat pumps are small split-type air-to-air-units, but the majority of heat production comes from medium-sized and large units in commercial buildings and in industrial applications. In 2001, the total sales was more than 6,300 units, the main part had a capacity in the area of 3-10 kW.

The 2002 sales figures are (by November 2002) expected to reach 10,000 units before the end of the year /3/. Approximately 90% of the units sold this year are small capacity units, in the area of 3-10 kW. Figure 3-1 shows the annual heat pump sales' over the last decade.

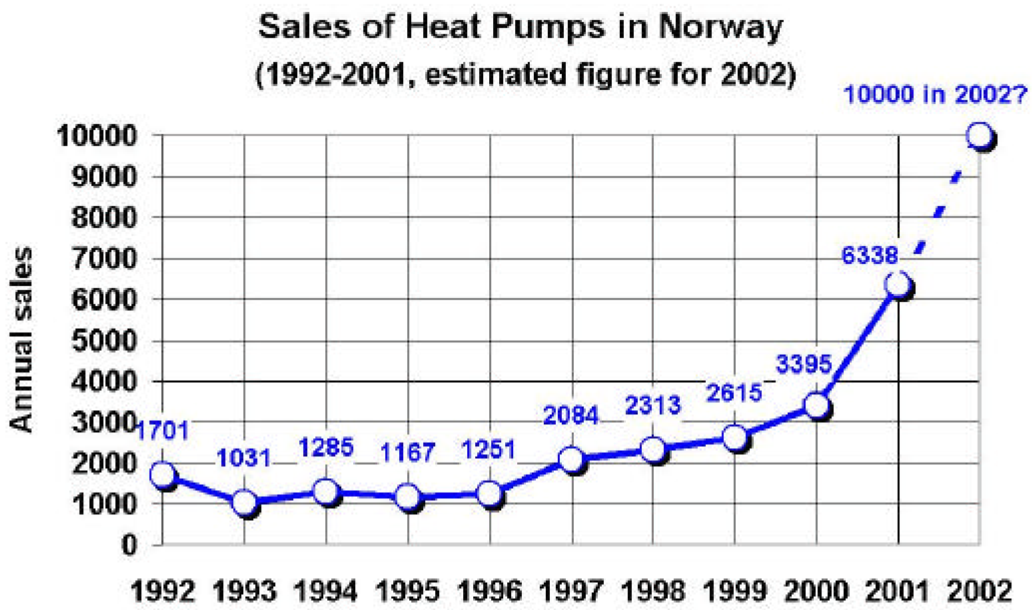

Figure 3-1: Annual sale of heat pumps in Norway. Sales figure for 2002 is predicted based on sales by November 2002. **(Source: NOVAP; www.novap.no /2/)**

Still, heat pumps are in most cases connected with a higher investment cost than other, less environmentally benign alternatives. This is assumed to be a considerable market barrier, even in cases with great long-term profit. One possible reason for this can be that building owners normally are interested in reducing the investment costs as much as possible, and aren't too concerned about the users' energy consumption, even in cases where the installation of a heat pump would be very profitable.

The investment cost of a heat pump depends on a great number of factors, therefore it is difficult to provide correct information about prices without analyzing each case separately. However, based on supplier data, some general lines can be drawn. Figure 3-2 shows specific investment costs of heat pump units and complete heat pump based energy systems including peak load units. Since the supplier data are from 1999, some changes can be expected in 2002.

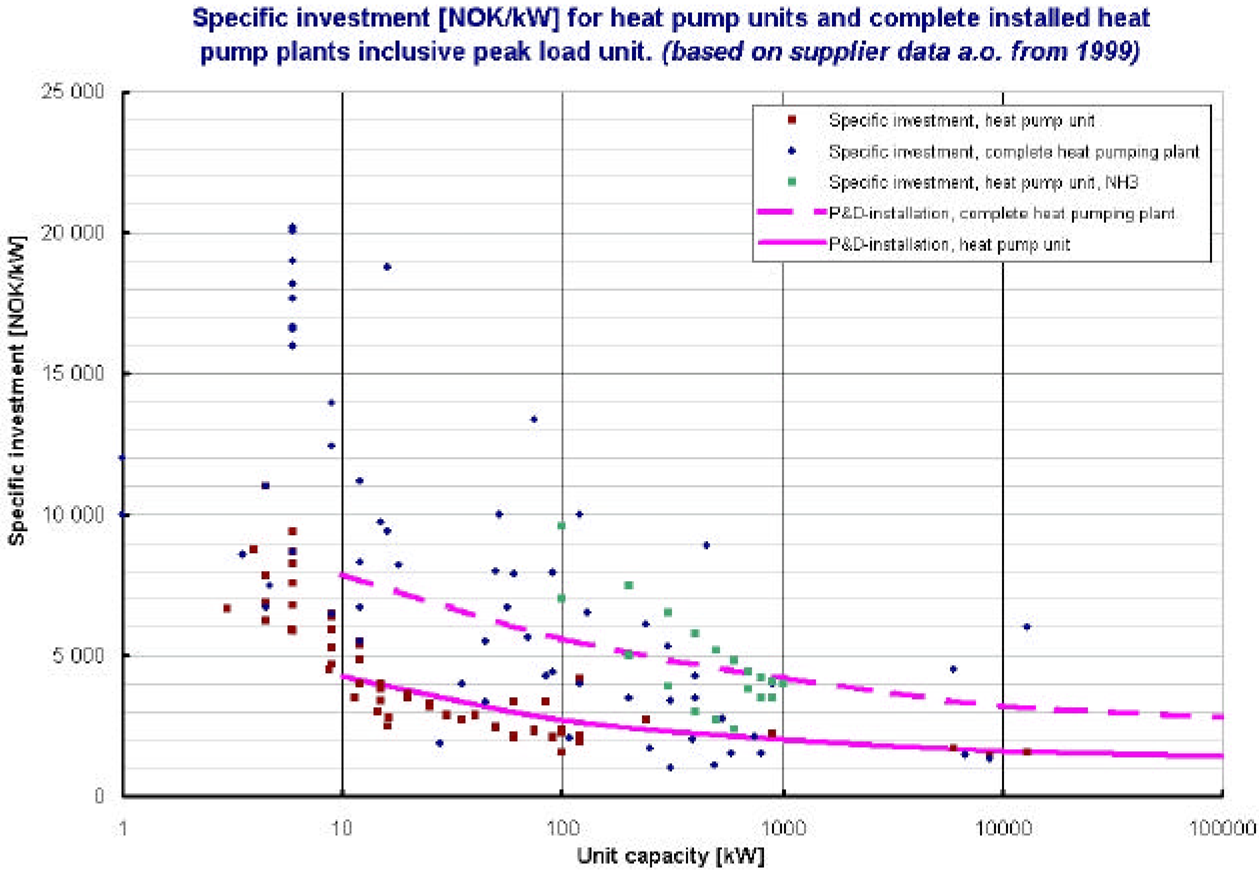

Figure 3-2: Specific investment for heat pump units and complete heat pump energy systems including peak load units in Norway.

3.2 HEAT PUMPS BRING REDUCED CO_2 EMISSIONS

When installing a heat pump instead of an oil-, gas-, or coal-fired boiler, there is an alteration in the building's CO_2-emissions related to power consumption. Whether the total emissions increase or decrease, depends on a series of factors; the *Seasonal Performance Factor* (SPF) of the heat pump, the efficiency of the compared boiler and the specific CO_2-emissions from electricity generation.

If hydropower with zero CO_2-emission is used to run a heat pump, there will be no associated CO_2-emissions due to energy consumption. However, when the electric power that runs the heat pump comes from a generation process with high CO_2-emissions, the case is quite different. At some point, the emissions related to production of electric power to run the heat pump is greater than the emissions from the boiler that the heat pumps replaces, and the building's total CO_2-emissions increases. In this case, installation of a heat pump is no longer the best environment-preserving initiative.

Based on the world-average specific emissions, 0.57 kg CO_2/kWh_{el}, replacing a state-of-the-art gas-fired boiler (95% efficiency) with a heat pump with COP = 3 will result in an approximately 15% reduction in CO_2 emissions. Based on emissions from energy production in UCPTE-countries, 0.4 kg CO_2/kWh_{el} (European continent), the same conditions will give a 40% reduction in CO_2 emissions. If the heat pump is compared to an oil boiler, the reduction will be even greater.

Figure 3-3 shows the alteration in CO_2 emissions that is achieved when replacing an oil or gas boiler with a heat pump, based on specific emissions from energy generation. The vertical, black dotted lines shows typical values for specific CO_2-emission from efficient gas-, oil- and coal-fired power plants, respectively.

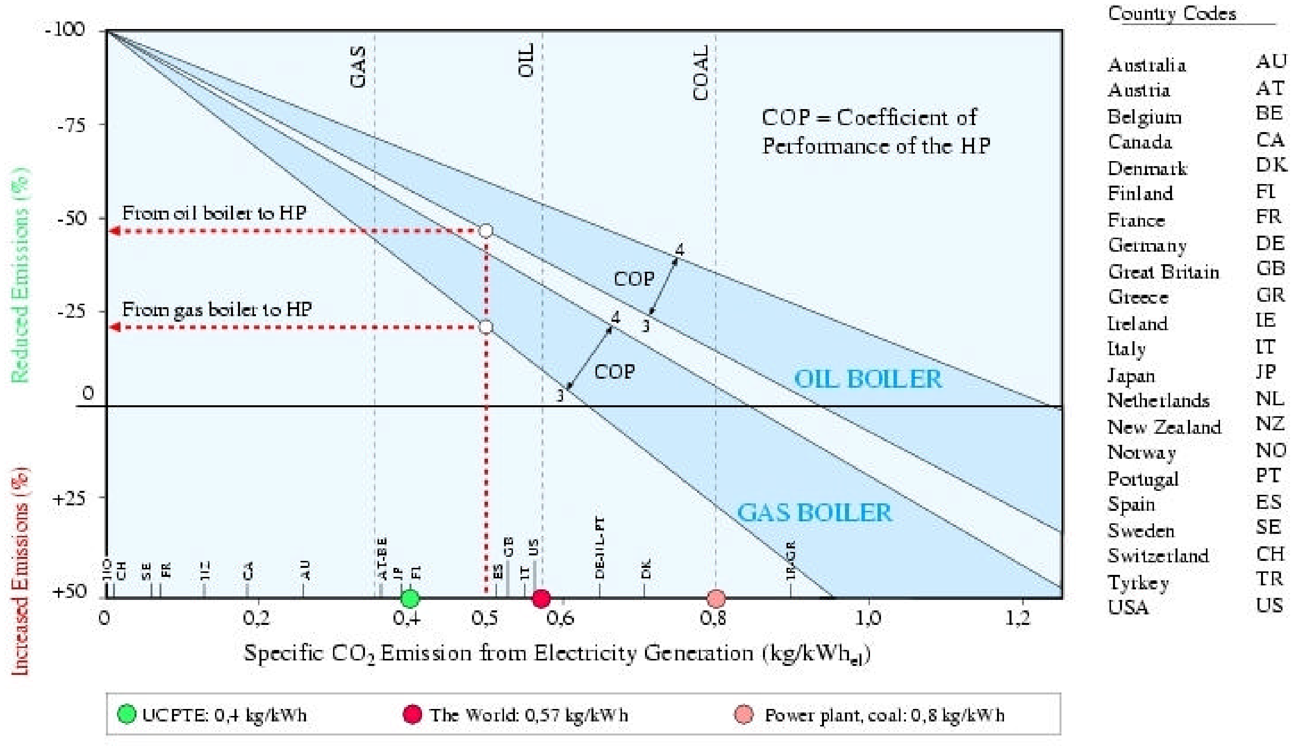

Figure 3-3: Alteration in CO_2-emissions when replacing oil/gas-fired boiler[1] with heat pump /4/.

3.3 MARKET POTENTIAL AND BARRIERS

The annual primary energy consumption in Norway is 220 TWh, out of which 110 TWh is electric power. The total energy consumption for heating space, ventilation air and hot tap water in Norwegian buildings, is in a normal year approximately 50 TWh /5/. Of this, as much as 28 TWh is covered using electric energy.

In 1990, the Norwegian company *Energidata AS /6/*, calculated the socio-economic and private-economic potential for heat pumps in Norway by the year 2000 to 25 TWh/year and 10 TWh/year,

[1] Efficiencies for boilers: $\eta_{oil} = 0.8$, $\eta_{gas} = 0.95$. 10% network loss included for the electric power supply.

respectively. This is far from today's actual case, with only approximately 5 TWh/year realized. Replacing 10 TWh/year of oil-fired boilers with heat pumps, would reduce Norway's total CO_2-emissions with 10% (ref. 1996 level) /7/.

Table 3-1 lists some common barriers that exist today. However, it is a matter of fact that most existing systems are working well, and has been good investments despite Norway's low electricity prices.

Table 3-1: Known barriers and challenges

Barrier / Challenge	**Description**
Lacking competence in consulting engineers, contractors, craftsmen, etc.	- Need for skills upgrading through training and education. Heat pumps are advanced technology. - Need for multi-disciplinary co-operation and quality assurance
Installation of heat pumps in existing buildings	- Hydronic heat distribution system often required, which exists in only 60% of in non-residential buildings. - Existing hydronic systems are often designed for higher distribution temperatures, meant for use with oil-fired boilers or similar. The heat pump's COP is reduced when operating at higher temperatures.
Installation of heat pumps in new buildings	- Radiators in non-residential buildings are still often designed for 60/40°C turn-/return temperatures.
Heat pumps have a somewhat bad reputation due to operational problems in earlier systems.	- Designed too large capacity heat pump units, which cause higher investment, shorter running time and unfortunate operational conditions - Heat pumps installed in buildings with high-temperature hydronic energy systems, which cause very unfortunate operational conditions - Poor control and regulation - Problems with heat source system

3.4 CHARATERISTICS OF HEAT PUMPS IN LARGER BUILDINGS

In this project, the focus will be on heat pumps for larger buildings. The reasons for this are many, but the following are of the most important:

- There is a need to focus due to limited funding.
- Larger buildings often have both heating and cooling needs, sometimes also simultaneously.
- Larger systems are normally run or regularly inspected by qualified personnel. These personnel can also perform maintenance operations.
- Larger buildings often have more qualified users that are more aware of the possibilities for the technology.
- Larger heat pumps make more complex system designs economically viable, and the opportunity to customize each plant for maximum adaptability and efficiency.

4 INTEGRATION WITH OTHER TASKS

4.1 THE USERS AND THE ENVIRONMENT (WP 1)

4.1.1 User culture and user requirements (Task 1.1)

Among other things, the users will have an opinion on what level of technology they want in the building, which tasks they would like to be taken care of automatically, and what level of control they require. User requirements affect energy use on a basic level, as the users often have preferences on anything from structural design to temperature levels.

There seems to be different motives for selecting smart building technology. Some are interested in the energy saving potential, but not all. Others are more concerned with conserving resources, the technology itself, comfort-related aspects or symbolic value. It's important to have an understanding of this when designing and developing new heat pump systems.

One major barrier regarding the implementation of heat pumps is the building owner's reluctance against high investment costs when he is not the actual user himself. Instead of selecting heat pumps, that have relatively high investment cost and low operational cost, the building owner will often prefer low investment-equipment like electric resistance heating with considerably higher operational costs. This also occurs in cases where the use of heat pumps would provide a significant long-term economical profit.

4.1.2 Environmental criteria (Task 1.2)

Heat pumps are in general environmentally friendly. But still, it's important to realize the three main ways that heat pumps affect the environment:

- Heat pumps reduce the use of electric power compared to direct electric heating systems, which again leads to less CO_2-emissions from fossil–fuelled power plants
- Heat pumps often replaces fossil-fuelled boilers in buildings, directly decreasing CO_2-emissions.
- Heat pumps contain working fluids of different types. Some of them, like (H)CFC's have high Ozone Depletion Potential and Global Warming Potential. HFC's don't deplete the ozone layer (ODP=0), but are still strong greenhouse gases. The later years there has been a great interest in natural working fluids, substances that already exist naturally in the biosphere (CO_2, NH_3, hydrocarbons).

4.1.3 Indoor environment (Task 1.3)

Heat pumps don't directly affect the indoor environment. It is more common to see heat pumps as one possible mean to achieve the desired environment with respect to noise, emissions, temperature and moisture. In this way, heat pumps are necessary to provide a high level of comfort in buildings, when air conditioning is required. When air conditioning is to be used, the additional costs for constructing a system for combined heating and cooling are low, making it a very profitable investment.

Indoor environment will greatly affect the design and use of heat pumps, as it will decide many of the boundary conditions for design and operation.

4.1.4 Implementation strategies (Task 1.4)

Only a few consultants, engineers and building owners have thorough knowledge on heat pumps. This is suspected to be one of the main reasons why this technology has not yet caught on to the same extent in Norway like it has in similar countries, like Sweden. Therefore, one can develop new and prosperous technology, but it often takes considerable work and time for the technology to be commonly accepted and used in buildings.

It is very important to think heat pump from the beginning of the building's design process. As previously mentioned, there are some specific technical and structural conditions that need to be fulfilled in order to ensure a well-designed and well-run heat pump. For instance, a low-temperature hydronic distribution system and a more accurate demand analysis are vital for heat pumps.

Operation of gas-, oil-, coal-fired and electric boilers are virtually insensitive to moderate over-sizing, while successful installations of heat pumps, on the other hand, are very dependant on correct dimensioning. This problem occurs quite often, mainly because consulting engineers and contractors are used to over-sizing boilers in preference to under-sizing. However, an over-sized heat pump is a poor investment. Firstly, the additional investment is higher, much higher compared to the extra cost of an over-sized boiler. Secondly, the operation time will consist of more running on part load or on/off-cycles, with lower COP's and more wear and tear on the machinery.

4.2 THE BUILDING (WP 2)

4.2.1 Integrated design (Task 2.1)

The main idea behind integrated design is to view all the important aspects of a building in context, not as isolated entities as it often is done. For heat pumps this is particularly important, as it depends on close integration with many parts of the building process as early as possible.

For the best solution, the choice of a heat pump for heating and cooling should affect many things early in the engineering phase, such as:

- Design distribution temperatures in the hydronic system. For conventional heat pumps, it is preferable with as low temperature as possible. CO_2-based heat pumps benefits from a high temperature difference in the system, and from connecting heating loads with different temperature demands in series. In both cases, one must ensure that the heating surfaces are dimensioned for its destined use.

- Need for structural changes related to heat source and –sink, pipelines, floor heating, noise insulation etc.

4.2.2 Building integrated energy systems (Task 2.2)

One could argue that all kinds of energy systems have some level of integration with the building. This is always the case with energy systems that contain heat pumps. The most important factors regarding integration are:

- In many cases, heat pumps are used with hydronic heating (and cooling-) system. This has consequences for the building body mainly due to pipelines and radiators. In buildings with floor heating, the integration is even more obvious.
- Optimizing heat exchanger surfaces is an important issue when using heat pumps. In that respect, floor heating is quite common and it is also possible to use whole walls as radiators with low distribution temperatures for good COP in the heat pump.
- There has also been some research on small autonomous heat pumps/air conditioners built directly into cladding panels in outside walls.
- Heat pumps need heat sources and heat sinks.

4.2.3 Lighting systems (Task 2.3)

Lighting systems can affect heat pumps indirectly in several ways. All artificial lighting produce heat as well, and will therefore influence the heat balance, reducing heat demand in winter, and increasing cooling demand in summer. Natural lighting often enters the building through windows, and will normally affect the heat balance in a similar way, but may increase the heat demand in winter due to lower U-values, and also increase the cooling demand in summer due to high sun radiation.

4.2.4 Building integrated photovoltaics (Task 2.4)

PV systems are expected to be quite independent of the presence of heat pumps, as it produces power that can be used for all purposes within the building. However, one can easily imagine air conditioners run directly by PV systems. In this way, some form of automatic control can be achieved, as the need for cooling varies in phase with the sun’s irradiance. This system will probably be most effective when used on several independent, smaller a/c-units in preference to a larger, centrally placed unit.

One can also imagine a PV-system working with a thermal storage to increase the temperature of the heat pump’s heat source.

4.3 ENERGY SYSTEMS (WP 3)

4.3.1 Systems for heating, cooling and ventilation (Task 3.1)

Heat pumps are a part of systems for heating, cooling and ventilation. Task 3.1 will therefore be closely connected to heat pumps, but on a somewhat more superior level.

Close co-operation is required to obtain a good result. Task 3.1 is dependent on boundary conditions for dimensioning and design of heat pumps. Likewise, task 3.2 will receive input on important requirements, such as low-temperature distribution systems, adaptation of the energy systems to use with heat pumps and other conditions to improve the overall performance and efficiency of the energy system.

As explained in chapter 2.2, the COP of a heat pump decreases when the temperature lift of which the heat pump operates, increases. Therefore, the heat pump must always deliver the base heating load in the system, not activating the peak load unit until it is necessary.

Some important conditions related to energy systems are listed below:

- The heat pump must always deliver heat at as low temperature as possible, so the peak load unit must be placed in a serial connection with the heat pump. For CO_2-based systems, serial connection of heat loads may also be needed.
- Good estimate of heating/cooling design capacity essential to correct dimensioning of heat pump and heating surfaces.
- Good estimate of variation and duration of heating/cooling demand through the year is very important for correct dimensioning of the heat pump.

4.3.2 Heat pumps (Task 3.2)

This task.

4.3.3 Operation and automation (Task 3.3)

The purpose of operation and automation is to increase the indoor environment quality as well as ensuring efficient energy use. It will be nearly impossible to implement a heat pump without any form of automation, and it is a crucial point for efficient running of the heat pump.

There are many issues concerning the control of heat pumps in energy systems, of the most important are:

- Always have the heat pump running at full capacity before connecting the peak load unit.

- At least some degree of mass flow control in the hydronic distribution system. (This will be especially important in future heat pumps with CO_2 as working fluid. See chapter 5.3 for more information)

- To increase the COP, there should be as low temperature as possible in the distribution system. Besides increasing the heat surfaces, one way to achieve this is by using serial connection of heat loads with different temperature demands. For instance, one heat pump could deliver heat to (pre-)heating of tap water, radiators and heating of ventilation air. (This will be especially important in future heat pumps with CO_2 as working fluid. See chapter 5.3 for more information)

4.3.4 Thermal energy storage (Task 3.4)

By using thermal storage, a heat pump is expected to achieve a higher SPF. Dependent on the season, climate or characteristics of use, the heat pump can deposit surplus heat or cold to be used at a later time. This can decrease the need for running the heat pump on partial load at a lower COP. One can imagine many possibilities with this technology, for instance:

- The thermal storage can be used to exploit differences in electricity prices between night and day, by for instance heating or cooling large buffer tanks at night when the power is cheaper.

- Thermal storage can provide a much more stable and efficient operational environment for the heat pump, i.e. by reducing short-time fluctuations in outdoor-temperature.

- Heat pumps can absorb heat from the ground in winter, and deposit heat in the same drilling hole during summer. This can be used as a thermal storage, effectively improving the temperature levels for heat source and heat sink.

5 HEAT PUMPS AND SMARTBUILD

5.1 PREFACE

The last 10 years, one of the main activities at SINTEF Energy Research, department of Refrigeration and Air Conditioning, has been the development of equipment and technology for heating and cooling, using CO_2 as working fluid. This was initiated due to a desire to find a substitute for the environmentally hazardous CFC's, HCFC's and HFC's used in refrigeration equipment.

The CFC's (Chloro-Fluoro-Carbon) and HCFC's (Hydrogen-Chloro-Fluoro-Carbon) contain chlorine that strongly contributes to the depletion of the ozone layer. Due to the extensive impairment of the ozone layer, most users of CFC and HCFC worldwide agreed to phase out their consumption of CFC and some other hazardous substances by the year 2000, and HCFC by 2020.

Instead of CFC's and HCFC's, more HFC's (Hydrogen-Fluoro-Carbon) where taken into use. HFC's contain no ozone depleting chlorine, but are strong greenhouse gases. According to the Kyoto-agreement from 1997, the undersigned countries are committed to regulate the use of HFC's. HFC's are still commonly used today for almost all heat pumping and refrigeration applications.

Recently, there has been much attention to the introduction of a tax for all HFC and PFC working fluids, based on CO_2-equivalency factor. In Norway, the tax comes into effect from January 1. 2003, and constitutes 180 NOK per ton CO_2 equivalents[2] /8/,/9/. Applied on the working fluid R-404a, this amounts to 586.60 NOK per kg[3]. A similar tax has already been implemented in Denmark (13$ per ton CO_2 equivalents), and there exists a proposal in Sweden (65$ per ton).

CO_2 is a natural working fluid, which means that it exists naturally in the atmosphere. The CO_2 that is used in heat pumps is recycled from industrial processes, and is in fact the same as the CO_2 used to create the fizz in carbonated sodas and lemonades. Therefore, the CO_2 in heat pumps does not contribute to global warming (GWP = 0), nor does it affect the ozone layer (ODP = 0). CO_2 is in other words a perfectly environmentally benign working fluid. Recycled CO_2 used in heat pumps will not be subject to the previously mentioned tax.

5.2 HISTORY OF CO_2 AS A WORKING FLUID

CO_2's part as working fluid in refrigeration reach back more than a 100 years, and was in the beginning one of the most important working fluids for cooling foodstuffs and in air conditioning. In contrast to its rival working fluids at the time, CO_2 is neither flammable nor toxic, and was therefore preferred in applications where contact with foodstuff or people could occur.

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[2] The tax does not apply for recycled refrigerants, and will be reimbursed when returned.

[3] $GWP_{R\text{-}404a} = 3260$

The wish for improved energy efficiency led in the 1930's to the development of the fluorcarbons. These had considerable lower condensation pressure than CO_2, which meant less compressor work and thereby better efficiency. The fluorcarbons were also assumed to be harmless for both people and the environment, and quickly replaced CO_2 as preferred working fluid. Consequently, the CO_2 systems were phased out during the 1950's, and didn't see any use for the next 50 years /10/.

In present time, CO_2 has regained current interest, among other things due to its environmental qualities. NTNU/SINTEF has made a major contribution, and is one of the leading environments in the world in this field. Authorities worldwide intends to phase out the CFC's and HCFC's, after their environmentally hazardous characteristics where known. In addition to this, CO_2 inherits beneficial thermodynamical properties that haven't been previously recognized or exploited.

5.3 PROPERTIES OF CO_2-BASED HEAT PUMPS

Theoretical studies and preliminary laboratory testing have shown great potential for CO_2-based heat pumps for heating and cooling in large buildings, with efficiencies that match, or exceed existing heat pumps with conventional working fluids. Heat pumps with CO_2 differ from conventional ones on several important areas. Existing components and means of regulating are generally unusable, CO_2-based heat pumps represent a whole new technology.

CO_2 has a very low critical temperature at 31.1°C and 73.8 bar. This causes the heat pump to operate outside the 2-phase-area, in the supercritical area. While changes in thermo-physical properties occur by phase change in the 2-phase-area, the same elapse in single phase in the supercritical area. Here, the thermo physical properties can change fast and quite abruptly, especially close to the critical point. The pressure during heat rejection is also higher than usual, up to 130 bar. Comparatively, the maximum pressure for conventional components are usually 25 bar, 40 bar when using ammonia as working fluid. The high pressure in CO_2 cycles has also got beneficial consequences, for instance are the heat-transferring properties very good.

In heat pumps that operate within normal temperature ranges, conventional working fluids will give off most of the heat as latent heat by condensation. This happens at approximately constant pressure and temperature. Conventional heat pumps are less suited for heating water to high temperatures, since the whole condensation process will have to occur at higher pressure, which reduces the COP.

The CO_2-process is less sensible for this, because it among other factors is transcritical at normal running conditions. In this process, tangible heat is emitted at gliding temperature, which improves the temperature-adaptation between the cooled working fluid and the heated secondary medium. With good temperature adaptation, heat is transferred with approximately equal temperature difference between the fluids throughout the heat exchanger. This reduces necessary compressor work and the heat pump gains a higher COP.

Figure 5-1 and Figure 5-2 show temperature adaptation in principle for CO_2 and water, and a conventional working fluid and water, respectively. One can easily see how the cooling curve of CO_2 is well suited for heating water over large temperature differentials.

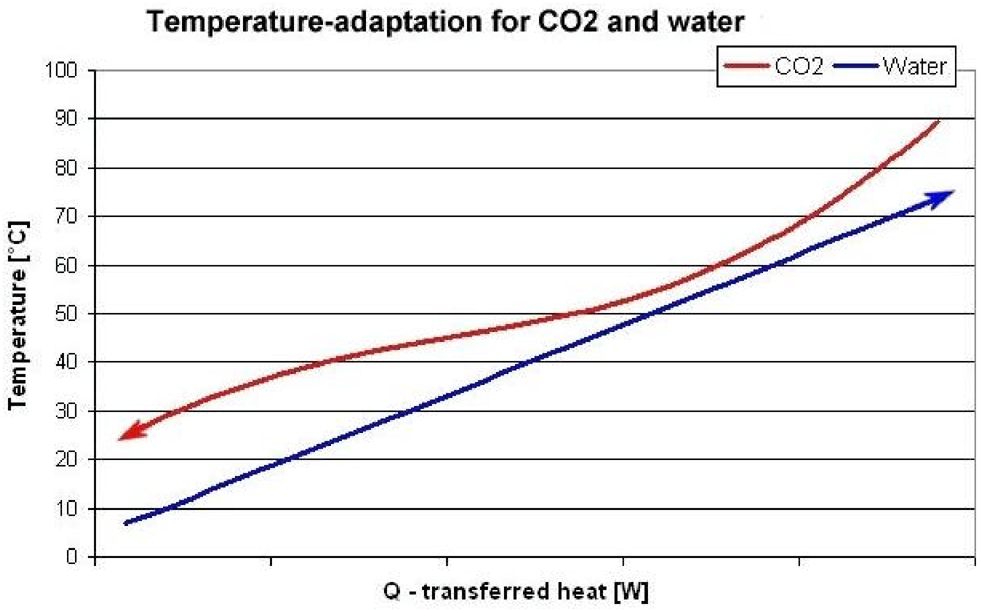

Figure 5-1: Temperature-Heat diagram for heat transfer between CO_2 and water[4].

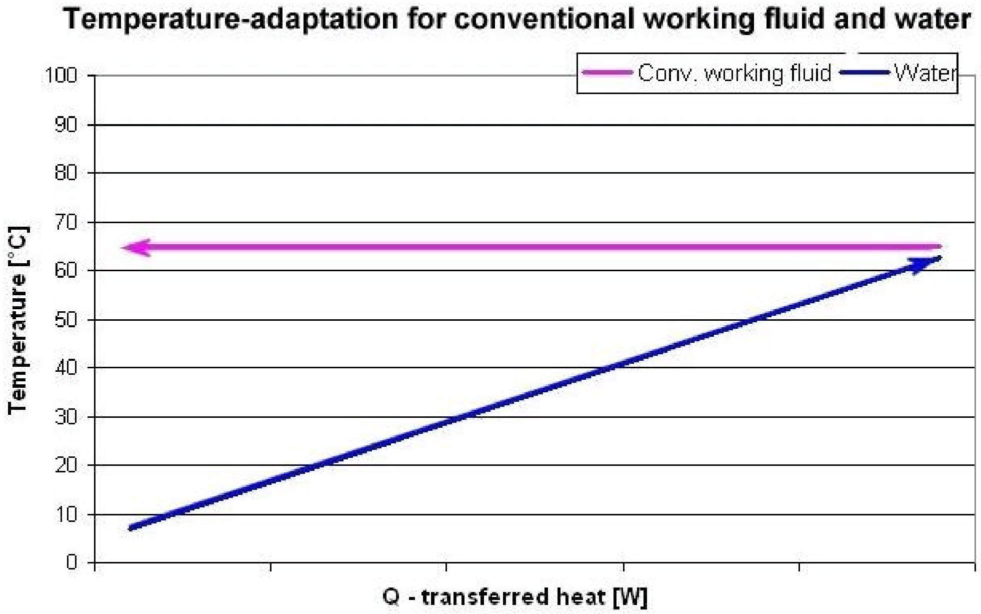

Figure 5-2: Temperature-Heat diagram for heat transfer between conventional working fluid and water.

[4] CO_2 pressure = 100 bar

There are other elements in CO_2 heat pumps as well, that must be taken into consideration. For one thing, it is essential that the CO_2-gas is sufficiently cooled in the gas cooler to maintain a high COP. This means that there should preferably be some heating demand at a low temperature level, for instance floor heating or preheating of tap water. Figure 5-3 shows an ideal CO_2-based heat pump's sensitivity for working fluid temperature at outlet of gas cooler (before throttle valve).

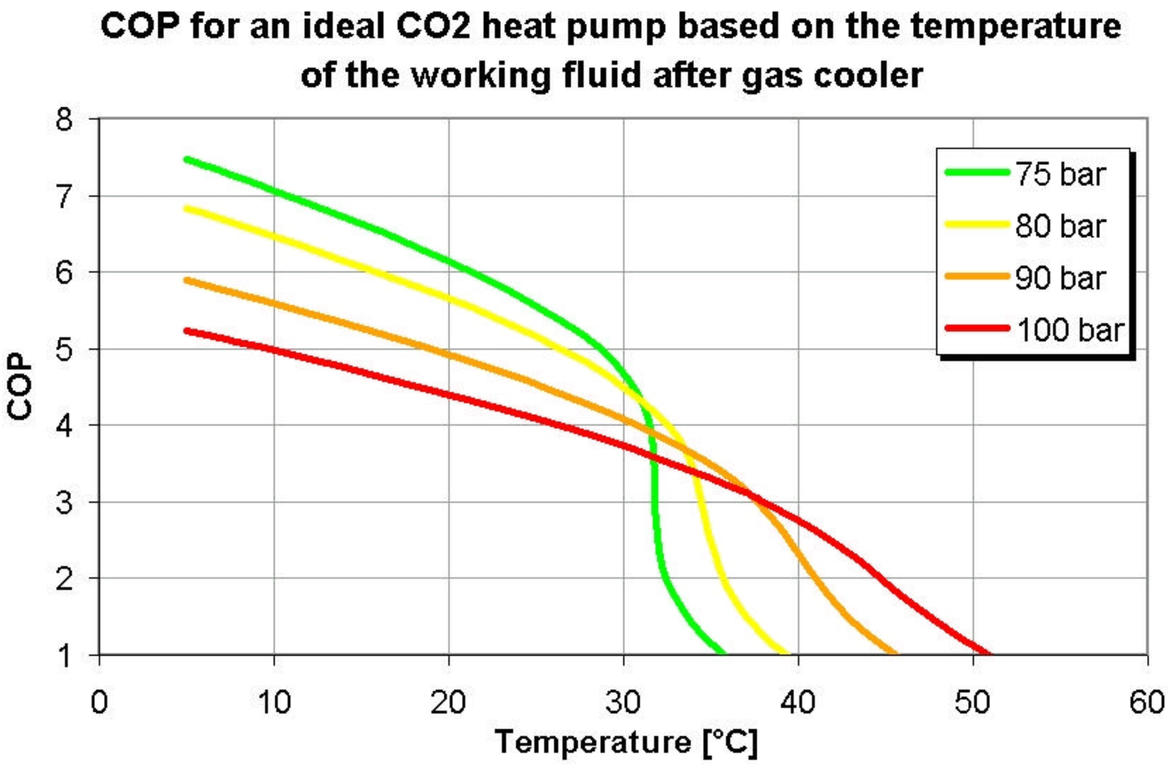

Figure 5-3: COP for an ideal CO_2 heat pump[5] as function of high pressure and working fluid temperature at the outlet of gas cooler.

Based on the figure above, it is easy to see why it is very important with low-temperature distribution systems for heating buildings with this type of heat pump. Since this system differs from heating systems based on boilers, and also other types of heat pumps, it is essential to take this knowledge into consideration at an early stage in the building design process.

5.4 SUMMARY

Heat pumps with CO_2 as working fluid for combined heating and cooling of buildings is a very promising technology. So far, CO_2 based heat pumps are used for heating of tap water /11/,/12/ and cascade plants for industrial freezing /13/,/14/, and is recently also taken into use for commercial refrigeration and in combined air conditioners and heat pumps in cars /15/,/16/. In all cases, the CO_2-based solution has same, or higher COP than the corresponding conventional alternative. CO_2-based heat pumping technology may have many other applications; the closest in

[5] Isentropic efficiency = 100%, evaporation temperature = 0°C, saturated suction gas.

time, besides heat pumps for heating and cooling of buildings is probably commercial refrigeration.

CO_2 is an environmentally benign alternative to conventional working fluids, as it neither affects global warming nor the ozone layer (GWP = 0, ODP = 0).

In order to make CO_2-based heat pumps for heating and cooling of buildings commercially available, more research and development is needed. There is still much to do in development of components, system analysis and building and testing prototype units.

Heat pumps are smart technology!

6 NOMENCLATURE

Word / Abbreviation	Explanation
COP	*Coefficient Of Performance*
Critical point	A substance's highest possible pressure and temperature where liquid and gas can co-exist.
GWP	*Global Warming Potential*
HCFC	*Hydrogen-Chlorine-Fluorine-Carbons*; working fluid consisting of the four elements.
HFC	*Hydrogen-Fluorine-Carbons*; working fluid consisting of the three elements.
Hydronic	Energy distribution system based on water as energy carrier
ODP	*Ozone Depletion Potential*
P&D (Norwegian: PoD)	*Prototype and Demonstration*
PFC	*Petro-Fluor-Carbons*
SPF	*Seasonal Performance Factor*
Supercritical	The thermodynamic state where pressure and temperature is above the pressure in critical point, P_c.
Transcritical	A thermodynamic process that occurs through both sub-critical and super-critical states.
UCPTE	*Union for the Co-ordination of Production and Transmission of Electricity*
WP	*Work Package* under the sip/sup program

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Appendix A: The energy balance of heat pumping systems

The first law of thermo dynamics states that within a closed system, the total amount of energy is constant. Energy can neither come into being, nor disappear. Energy can only transform into other shapes, and the total amount of energy is always constant in all transformations and transfers.

Applied on the simple heat pump cycle described above, the heat balance for the system can be identified. For simplicity's sake, heat losses to the ambient are ignored, assuming a perfectly insulated system. The energy is entering the system at two points; in the evaporator as latent heat (Q_0), and in the compressor as work done on the fluid (W). In order for the fluid to return to the evaporator at the same state as earlier, the heat given of in the condenser (Q_k) equals the sum of the two contributors, Q_0 and W. In other words:

$$Q_k = Q_0 + W \tag{1}$$

Based on this, the *Coefficient of Performance*, or COP, is defined. The COP is a measure for the energy efficiency of a heat pump or refrigeration machinery, and is defined as:

$$COP_{HeatPump} = \frac{Q_k}{W}\text{, for heat pumps} \tag{2}$$

$$COP_{Refrigeration} = \frac{Q_k}{W}\text{, for refrigeration machinery} \tag{3}$$

For combined systems, where both the hot and the cold side is utilized, the definition changes to:

$$COP_{Combined} = \frac{Q_k + Q_0}{W}\text{, for combined systems with 100\% utilization} \tag{4}$$

In most cases, there will not be complete utilization of both Q_k and Q_0 at the same time. In summer, for instance, one can expect full utilization of the cooling capacity, but only partial utilization, if any at all, of the heating capacity for pre-heating of tap-water. The surplus heat will in these cases be dumped to the ambient. Therefore, when calculating the $COP_{Combined}$, one can only use the utilized part of Q_k, $Q_{k,util}$. And in the same manner for Q_0, the corresponding value will be $Q_{0,util}$. Then yields:

$$\begin{aligned} Q_{k,util} &\leq Q_k \\ Q_{0,util} &\leq Q_0 \end{aligned} \tag{5}$$

The general expression for $COP_{Combined}$ then becomes:

$$COP_{Combined} = \frac{Q_{k,util} + Q_{0,util}}{W} \tag{6}$$

The *Seasonal Performance Factor*, or SPF, is an expression for the total energy efficiency factor on for the entire year, and is defined for the whole utilization time (t).

$$SPF_{Combined} = \frac{\int_0^t Q_{k,util}\, dt + \int_0^t Q_{0,util}\, dt}{\int_0^t W\, dt} \tag{7}$$