High-Efficiency Heat Pump Water Heater System for Apartment Buildings of Passive House Standard

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"Bergen og Omegn Boligbyggelag" is about to construct a number of apartment buildings of passive house standard at Damsgårdssundet in Bergen, Norway. The total energy demand for domestic hot water (DHW) heating for one of the buildings with 40 flats has been estimated to be 170,000 kWh/year, i.e. 4,250 kWh/flat. In passive houses the annual energy demand for heating of DHW typically constitutes 70 to 85% of the total annual heating demand of the building. It was therefore regarded as interesting to carry out an in-depth study of a centralized heat pump water heater system.

Four different heat pump designs were simulated in order to find the maximum theoretical coefficient of performance (COP). The simulations showed that a heat pump water heater using carbon dioxide (CO_2, R744) as working fluid will achieve about 20% higher COP than high-efficiency state-of-the-art heat pump systems using R134a or R290 (propane) as working fluid. CO_2 is also a non-flammable and non-toxic fluid that does not contribute to global warming as the HFC working fluids.

An in-depth analysis was carried out for a 26 kW CO_2 heat pump water heater system. Four different heat sources were evaluated, including ambient air, sea water, ground water and grey water (waste water). The CO_2 heat pump unit was simulated with CSIM, which is an advanced simulation tool for design and optimization of CO_2 heat pump and air conditioning systems. The calculated COP for a CO_2 heat pump water heater using 7ºC groundwater as heat source was about 3.8 when supplying 70ºC hot water. This corresponds to a *net energy saving of about 70-75%* compared to state-of-the-art electric immersion heaters in single-shell hot water tanks.

The calculated maximum allowable investment cost for the CO_2 heat pump water heater system was about €125,000 when assuming an average COP of 3.5, 6% real interest rate, 15 years system lifetime and an electricity price of approx. 0.1 €/kWh. Due to the high energy efficiency, the excellent profitability and the favourable environmental properties of CO_2, CO_2 heat pump water heaters are regarded as a very promising alternative for centralized hot water heating in apartment buildings and block of flats of low-energy and passive house standard. Air-to-water CO_2 heat pump water heaters in the capacity range from about 5 to 30 kW are now available from several Japanese manufacturers.

1. Domestic Hot Water Demand in Apartment Buildings

"Bergen og Omegn Boligbyggelag" is about to construct a number of apartment buildings of passive house standard at Damsgårdssundet in Bergen, Norway with about 300 flats. An in-depth analysis has been carried out for one of the buildings with 40 flats in order to develop the most energy efficient design for a centralized heat pump water heater (HPWH) system.

Figure 1 shows a sketch of the 2nd floor of the apartment building has been analyzed (Hjerkinn, 2007).

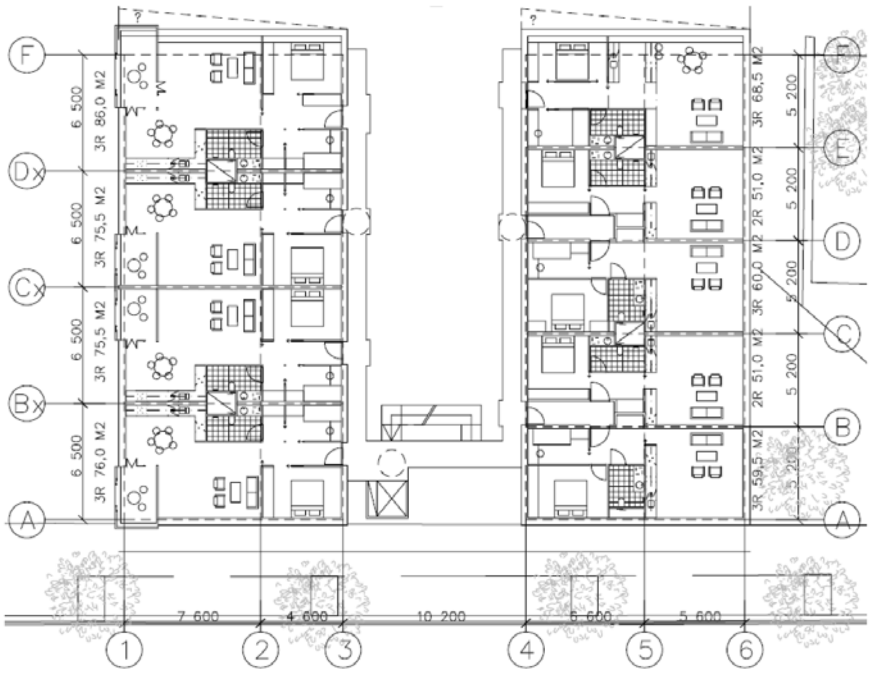

Figure 1 Sketch of the 2nd floor of the apartment building [Hjerkinn, 2007].

Domestic hot water (DHW) is normally used for washbasins, bath-tubs, showers, washing up, cleaning etc. If an energy efficient heat pump is being used for DHW production, DHW can be supplied to washing/dish-washing machines and thereby reduce the electricity demand for the building.

The energy demand for heating of DHW was estimated to be approx. *170,000 kWh/year*, i.e. about 12 kWh per 24 hours and 4,220 kWh/year for each flat. The calculated annual energy demand for heating of DHW (*E*) was based on Eq. 1.1, where *p* is the number of residents for each flat (in average 2 persons), and 620 kWh/year is the total annual DHW heating demand for one washing machine and one dish-washing machine [Hjerkinn, 2007].

$$E = [4{,}300 + 700 \cdot (p - 3) + 620]\,\text{kWh/year} = [4{,}300 - 700 + 620] = 4{,}220\ \text{kWh/year} \qquad (1.1)$$

The required heating capacity for the HPWH was estimated to be *26 kW*. The capacity was calculated assuming 18 hours operating period per 24 hours for the heat pump unit and the application of DHW storage tanks to cover large momentary DHW demands. The city water temperature and the average DHW temperature at the tapping sites was 5ºC and 45ºC, respectively.

Based on 26 kW heating capacity for the HPWH (*E*) and a minimum and a maximum DHW storage temperature of 55 and 70ºC, respectively, the total volume for the DHW storage tanks was calculated using Eq. 1.2. *Q* is the maximum DHW energy demand over an estimated period of 2.8 hours (*t*) and *a* is the calculated accumulation factor for the DHW storage tanks (Hjerkinn, 2007).

$$V = \left(\frac{Q - E \cdot t}{a}\right) = \frac{300\,\text{kWh} - (26\,\text{kW} \cdot 2.8\,\text{h})}{0.06\ \text{kWh/l}} \approx 3{,}800\ \text{litres} \qquad (1.2)$$

Figure 2 shows the 24 hour DHW consumption diagram for the apartment building, with the maximum DHW demand between 16-19 o'clock in the evening (approx. 3 hours maximum, ref. Eq. 1.2).

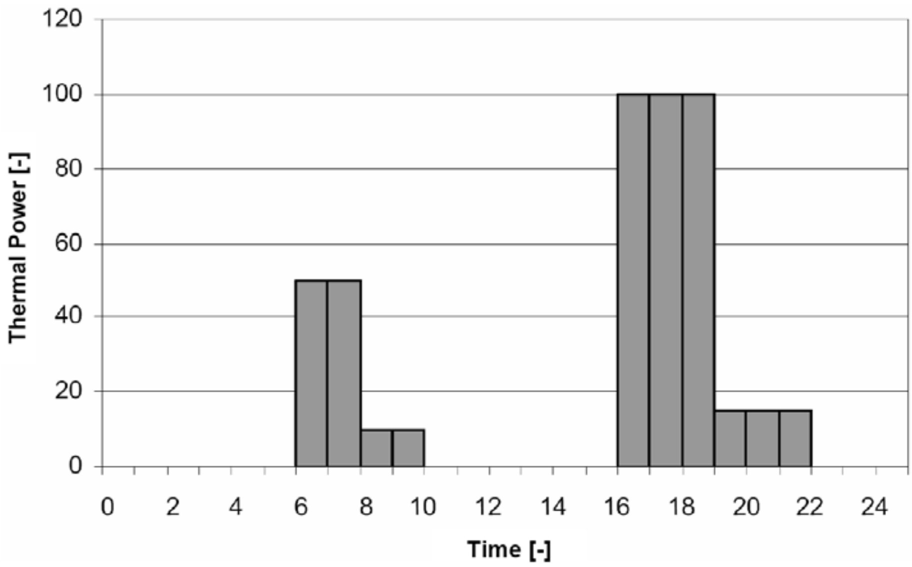

Figure 2 24 hours DHW consumption diagram for the apartment building [Hjerkinn, 2007].

2. Evaluation of Different Heat Pump Water Heater Systems

2.1 Heat Exchanger Design and Configuration

Four different heat pump water heater (HPWH) systems were simulated and optimized in order to determine the maximum Coefficient of Performance (COP[1]) at varying evaporation temperature (-10 to +10ºC), varying inlet water temperature (5 to 30ºC) and varying outlet water temperature (60 to 85ºC). The HPWH units were as follows:

- System 1 – Heat pump with condenser and desuperheater
- System 2 – Heat pump with condenser, desuperheater and subcooler
- System 3 – Heat pump with condenser, desuperheater and suction gas heat exchanger
- System 4 – CO_2 heat pump with a single gas cooler

Heat pumps for low- and medium-temperature space heating reject heat in a single condenser by condensation of the working fluid at virtually constant temperature and pressure. In order to enable production of DHW in the required temperature range (60-80ºC) and still achieve a relatively high COP for the heat pump, state-of-the-art HPWH systems are always equipped with a desuperheater and possibly a subcooler. A *desuperheater* is a heat exchanger that is cooling down the hot exhaust gas from the compressor for reheating of DHW, while a *subcooler* is a heat exchanger that is cooling down the working fluid from the condenser (condensate) for preheating of DHW. Many HPWH systems are also using a combination of a desuperheater and a *suction gas heat exchanger*. The latter heat exchanger transfers heat from the hot working fluid after the condenser (condensate) to the cold suction gas at the compressor inlet, and increases the exhaust gas temperature, the superheating enthalpy and the COP of the heat pump.

Figure 3 shows an example of a cooling curve of the working fluid and a heating curve of the water for a HPWH in a Temperature-Enthalpy diagram (T-h diagram). In this case the water is being heated from 5 to 70ºC (Hjerkinn, 2007).

[1] COP – The ratio of the heating capacity of a heat pump (Q) and the input power to the compressor (P), COP=(Q/P). The higher the evaporation temperature/pressure and the lower the condensation temperature/pressure, the higher the COP.

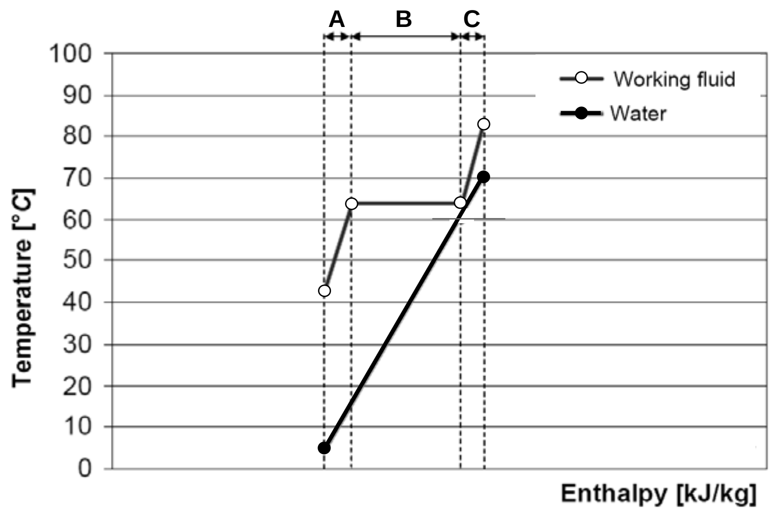

Figure 3 Sequential heat rejection in a subcooler (A), condenser (B) and desuperheater (C) in a heat pump water heater (HPWH) for heating of water from 5 to 70ºC (Hjerkinn, 2007).

Heat pump systems using carbon dioxide (CO_2, R744) as working fluid, represent a new and promising technology, e.g. for HPWH systems. CO_2 is a non-flammable and non-toxic fluid that does not contribute to global warming as the HFC working fluids, i.e. GWP[2]=0. Due to the unique thermo-physical properties of CO_2, high energy efficiency can be achieved if the heat pump system is correctly designed and operated in order to utilize the properties of the fluid. Due to the low critical temperature of CO_2 (31.1ºC), a CO_2 heat pump water heater will be operating in a so-called transcritical heat pump cycle were heat is rejected by cooling of CO_2 vapour at supercritical pressure in a single counter-flow gas cooler. Typical temperature profiles for CO_2 and water in a CO_2 gas cooler for hot water heating is shown in Figure 5, Chapter 2.2.

2.2 Computer Simulations and Optimization

With reference to Chapter 2.2, heat pump systems no. 1-3 were simulated with both R134a and R290 (propane) as working fluids since these fluids have a sufficiently high condensation temperature (60 to 70ºC) when using components and auxiliary equipment with standard 25 bar pressure rating.

In order to attain equal boundary conditions for the four different heat pump units, the various heat exchanger combinations were simulated with equal maximum UA-values, which limited the size and heat transfer efficiency of the heat exchangers. The UA-value ranged from *1,800 to 2,400 W/K*, and the higher the UA-value the lower the condensation temperature. Consequently, the highest COP was achieved when using an UA-value of 2,400 W/K.

Figure 4 shows the calculated maximum COP for the different HPWH systems as a function of the evaporation temperature, t_E (Hjerkinn, 2007). In the calculations it was assumed a max. UA-value of 2,100 W/K for the condenser and gas cooler, 5 K superheated vapour from the evaporator, 5ºC inlet water temperature and 70ºC hot water temperature. The overall isentropic efficiencies for the compressors were calculated on the basis on typical efficiency curves from laboratory measurements.

The R744 HPWH system achieved in average 20% higher COP than the state-of-the-art units with R134a and R290 due to higher compressor efficiency and the excellent temperature fit in the gas cooler between the CO_2 and the water. The latter affected the average temperature during heat rejection and thereby the COP of the system. Figure 5 shows the heating and cooling curves for water and CO_2 at 12 and 70ºC inlet and outlet water temperature, respectively (Hjerkinn, 2007).

[2] Global Warming Potential – GWP=0 for CO_2 when it is used as a working fluid in a heat pump.

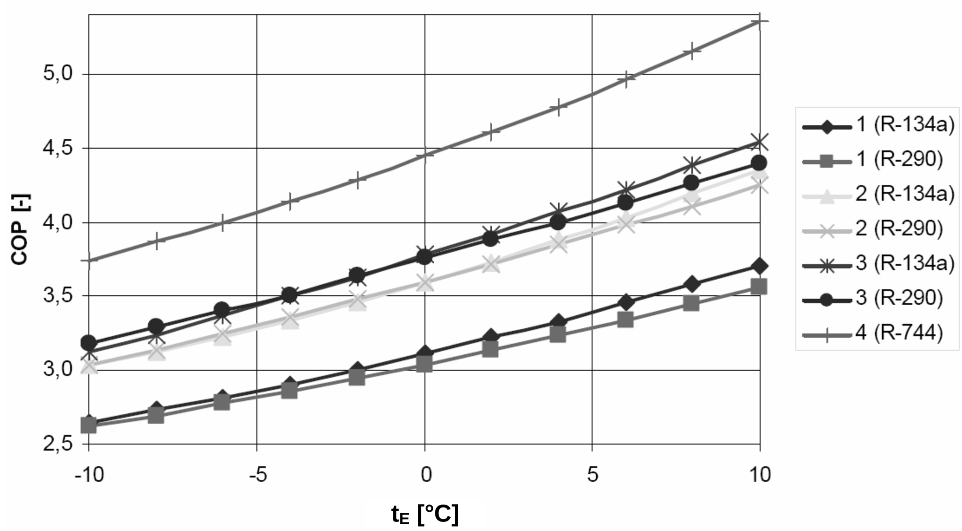

Figure 4 Calculated COP as a function of the evaporation temperature t_E (Hjerkinn, 2007).

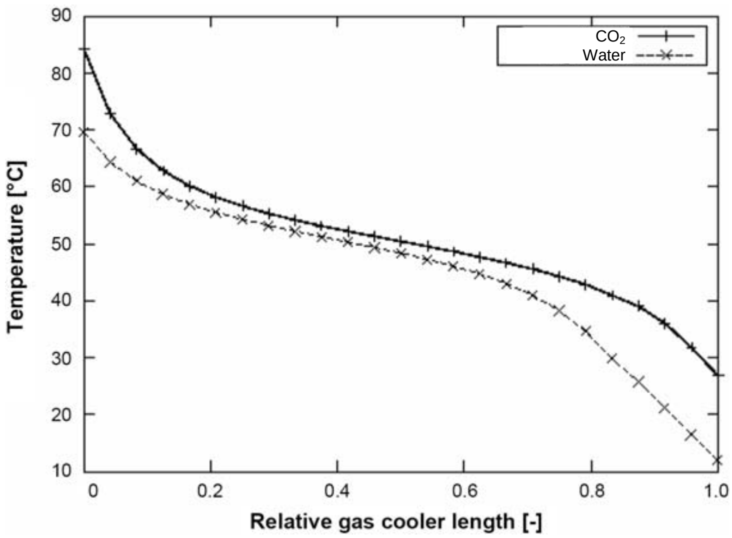

Figure 5 Calculated temperature profiles for CO_2 and water in the gas cooler (Hjerkinn, 2007).

For the state-of-the-art HPWH systems with R134a or R290 as working fluid, *System 2* (condenser, desuperheater and suction gas heat exchanger) and *System 3* (subcooler, condenser, desuperheater) achieved more or less the same COP at varying operating conditions. *System 1* (condenser and desuperheater) achieved roughly 15% lower COP than System 2 and 3. The main reason for the lower COP was that System 1 operated at a higher condensation temperature due to poorer temperature fit between the water the working fluid in the different heat exchangers.

In was decided to use the CO_2 heat pump water system for the apartment buildings in Bergen, since the heat pump achieved the highest COP, was able to cover the entire hot water demand up to 70-90ºC and the fact that CO_2 represent an environmentally friendly working fluid due to its zero GWP value.

3 Design and Evaluation of a CO_2 Heat Pump Water Heater

With reference to Chapter 1, the CO_2 heat pump water heater (HPWH) was designed for 26 kW heating capacity at 12ºC inlet city water temperature, 70ºC DHW temperature and 3 K difference between the outlet CO_2 and the inlet city water in the gas cooler. The isentropic and volumetric efficiency of the compressor was 0.70 and 0.75, respectively (Hjerkinn, 2007).

3.1 Component and System Design

The heat pump evaporator was designed for four different heat sources of current interest:

- Ambient air (DOT[3]=-10ºC, t_{ave}[4]=7.8ºC in Bergen)
- Seawater (indirect system design, 0ºC average temperature)
- Groundwater (7ºC average temperature in Bergen)
- Grey water (waste water from the apartment building, 20ºC average temperature)

For ambient air the evaporator was a fin-in-tube heat exchanger with copper tubes and aluminium fins with 12 mm spacing. For seawater, groundwater and grey water the selected evaporator was a 60 bar plate heat exchanger. Furthermore, the CO_2 heat pump unit was equipped with a reciprocating compressor with 150 bar pressure rating, a 140 bar counter-flow plate heat exchanger as gas cooler, a counter-flow tube-in-tube suction gas heat exchanger, an automatic back-pressure valve (expansion valve) and a low-pressure receiver (LPR). The expansion valve and the LPR was used for optimization of the pressure in the gas cooler at varying operating conditions.

The inlet water temperature in the gas cooler has a considerable impact on the COP of a CO_2 HPWH, and the lower the temperature the higher the COP. A low inlet water temperature leads to a low CO_2 outlet temperature from the gas cooler and with that a large enthalpy difference during heat rejection. Figure 6 shows simulated relative COPs for a CO_2 HPWH unit at varying inlet water temperature and 60 and 80ºC DHW temperature. By increasing the inlet water temperature from 5ºC to 15 and 25ºC at 60ºC DHW temperature, the COP was reduced by 10 and 25%, respectively (Stene, 2004).

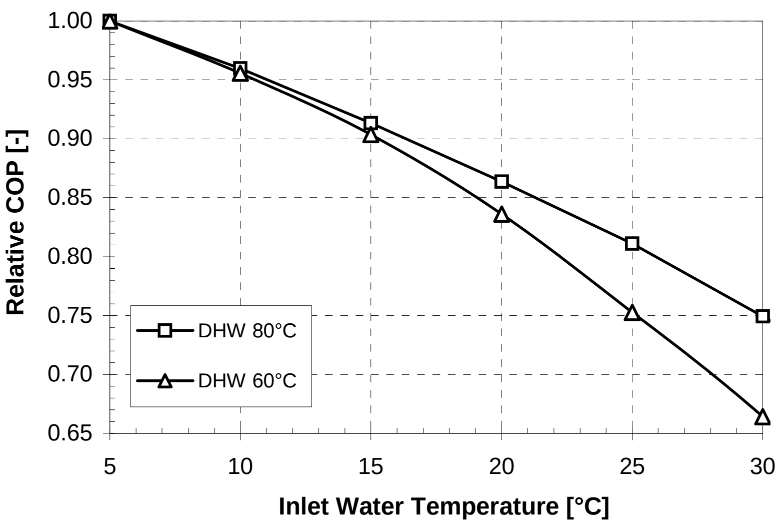

Figure 6 Simulated relative COPs for a CO_2 HPWH as a function of the inlet water temperature to the gas cooler at 60 and 80ºC set-point temperature for the DHW (Stene, 2004).

The DHW storage system for a CO_2 heat pump water heater should preferably use relatively small diameter tanks storage tanks connected in series in order to minimize conductive heat transfer between the DHW and the city water in the tanks. Efficient diffusers are also recommended at the tank inlets in order to minimize the water velocity and consequent mixing of hot and cold water. Figure 7 shows a principle drawing of the DHW system for the 26 kW CO_2 HPWH including four 1,000 litres single-shell storage tanks and an inverter controlled pump (Hjerkinn, 2007).

[3] Design Outdoor Temperature (DOT) – The lowest 3-day temperature during a 30-year period

[4] Average ambient air temperature during the year

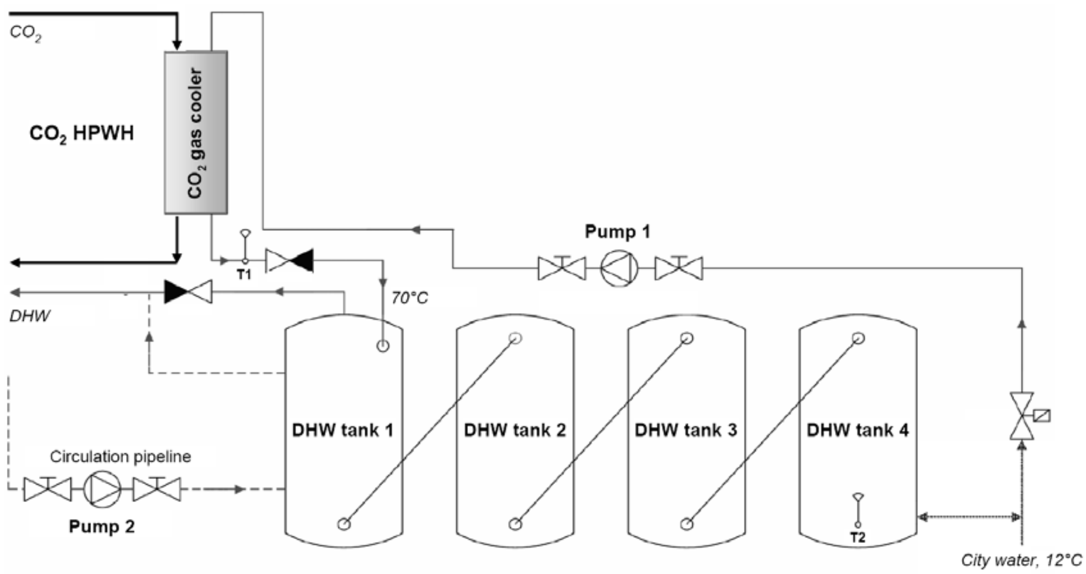

Figure 7 Principle sketch of the DHW system connected to the CO_2 HPWH (Hjerkinn, 2007).

3.2 Control Strategy

The DHW system was designed as a closed unvented (pressurized) system, where DHW tank 4 was connected to the city water supply (cold mains) and DHW tank 1 was connected to the tapping sites.

During the tapping periods, cold city water flows into the bottom of DHW tank 4 whereas the same amount of hot water is flowing from the top of DHW tank 1 to the tapping sites. The CO_2 heat pump will normally run during the tapping periods. An inverter controlled pump (Pump 1) circulates the cold city water to the gas cooler, where the water is being heated to the set-point temperature (T1) before it enters the top of DHW tank 1. When the tapping period has ceased the CO_2 heat pump will be running as long as the water temperature (T2) at the bottom of DHW tank 4 is lower than the set-point temperature (70ºC). The gas cooler pressure for the CO_2 heat pump unit is continuously optimized in order to achieve the maximum COP for the heat pump at varying operating condition.

3.3 Simulations – COP and Profitability

The 26 kW CO_2 heat pump water heater (HPWH) was simulated in CSIM (Skaugen, 2002), which is an advanced computer programme developed at NTNU-SINTEF for optimization of CO_2 heat pumps.

When using groundwater at 7ºC as the heat source, the calculated COP for the CO_2 HPWH was approx. 3.8. This corresponds to an *energy saving of about 70-75%* compared to a conventional DHW system with electric immersion heaters, and it is roughly 20-25 percentage points higher that that of a DHW system based on solar collectors and electric heaters for supplementary heating.

The maximum permissible investment cost (MPI) for the CO_2 HPWH system was calculated using the following boundary conditions:

- Annual heating demand: 170,000 kWh/year
- Heat pump, average COP: 3.5 – conservative value
- Real interest rate: 6%
- Economic lifetime: 15 years
- Electricity price: 0.1 €/kWh (0.75 NOK/kWh)
- Reference DHW system: Electric immersion heaters

The calculated maximum permissible investment cost was about €[5]125,000 or 4,800 €/kW. It was therefore concluded that the CO_2 HPWH system will be a very profitable installation.

3. SUMMARY AND CONCLUSION

"Bergen og Omegn Boligbyggelag" is about to construct a number of apartment buildings of passive house standard at Damsgårdssundet in Bergen, Norway. The total energy demand for hot water heating for one of the buildings with 40 flats has been estimated to be about 170.000 kWh/year, i.e. 4,250 kWh/year for each flat.

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An in-depth analysis was carried out for a 26 kW CO_2 heat pump water heater system. Four different heat sources were evaluated, including ambient air, sea water, ground water and grey water (waste water). The CO_2 heat pump unit was simulated with CSIM, which is an advanced simulation tool for design and optimization of CO_2 heat pump and air conditioning systems. The calculated COP for a CO_2 heat pump water heater using 7ºC groundwater as heat source was about 3.8 when supplying 70ºC hot water. This corresponds to a *net energy saving of about 70-75%* compared to state-of-the-art electric immersion heaters in single-shell hot water tanks. This is roughly 20-25 percentage points higher that that of Norwegian/Nordic DHW systems based on solar collectors and electric heaters for supplementary heating.

The calculated maximum allowable investment cost for the CO_2 heat pump water heater system was about €125,000 when assuming an average COP of 3.5, 6% real interest rate, 15 years system lifetime and an electricity price of approx. 0.1 €/kWh. Due to the high energy efficiency, the excellent profitability and the favourable environmental properties of CO_2, CO_2 heat pump water heaters are regarded as a very promising alternative for centralized hot water heating in apartment buildings and block of flats of low-energy and passive house standard. Air-to-water CO_2 heat pump water heaters in the capacity range from about 5 to 30 kW are now available from several Japanese manufacturers.

4. REFERENCES

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[5] 100 NOK = approx. 8.0 € (February 2008)