CO_2 Heat Pump System for Space Heating and Hot Water Heating in Low-Energy Houses and Passive Houses

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Low-energy and passive houses are superinsulated and air-tight buildings where the space heating demand is considerably lower than that of buildings constructed in accordance with prevailing buildings codes. Due to the low space heating demand, the annual heating demand for domestic hot water (DHW) typically constitutes 50 to 85% of the total annual heating demand for the residence.

A heat pump system can be used to cover the heating demands in low-energy houses and passive houses. The heat pump can be designed as a stand-alone system, i.e. a heat pump water heater in combination with a separate unit for space heating, or be an integrated unit for combined space heating and hot water heating. Due to compact design, the latter system is most likely to achieve the lowest investment and installation costs and with that the best profitability.

Integrated residential heat pump systems using carbon dioxide (CO_2, R744) as a working fluid can achieve a high Coefficient of Performance (COP) due to the unique characteristics of the CO_2 heat pump cycle. Integrated CO_2 heat pumps for combined space heating and hot water heating can be designed to utilize different heat sources such as ground, exhaust ventilation air, ambient air or a combination of exhaust ventilation air and ambient air.

Different integrated CO_2 heat pump systems have been investigated, focusing on the design of the heat rejection heat exchanger (gas cooler) and the DHW system. It was found that a counter-flow tripartite CO_2 gas cooler in combination with an external single-shell DHW tank and a low-temperature heat distribution system would enable production of DHW from 60 to 85ºC without electric reheating, and contribute to the highest possible COP for the CO_2 heat pump system. The Seasonal Performance Factor (SPF) for a prototype brine-to-water CO_2 heat pump was calculated on the basis of extensive laboratory measurements and compared with the performance of a state-of-the-art high-efficiency brine-to-water heat pump. At DHW heating demand ratios above approx. 50%, the CO_2 heat pump outperformed the state-of-the-art heat pump. Consequently, an integrated CO_2 heat pump system equipped with a tripartite gas cooler represents a promising, high-efficiency system for combined space heating and DHW heating in low-energy and passive houses. The results presupposes the use of a low-temperature space heating system and optimized design of the DHW tank in order to minimize thermodynamic losses caused by mixing of hot/cold water and conductive heat transfer inside the tank.

1. Heating Demands in Low-Energy and Passive Houses

In low-energy houses and passive houses the space heating demand and the ventilation loss have been greatly reduced compared to houses constructed in accordance with prevailing building codes. This has been made possible by better insulated and more air-tight building envelopes, advanced ventilation systems with high-efficiency heat recovery and utilization of passive solar heating. Since the DHW heating demand remains more or less constant, the annual heating demand for DHW typically constitutes 50 to 85% of the total annual heating demand in Scandinavian residences. I.e. the annual DHW heating demand ratio ranges from *0.50 to 0.85* [Breembroek and Dieleman, 2001].

Figure 1 shows, as an example, the calculated monthly space heating demand and DHW heating demand [kWh/month] for a 104 m^2 semi-detached house of different standards in Oslo, Norway [Dokka and Hermstad, 2006]. The different standards of the building envelope correspond to a house constructed according the Norwegian building codes of 1997 (*BF97*), a low-energy house (Energy rating *B*), a passive house (Energy rating *A*) and a passive house+ (Energy rating *A+*). The average monthly DHW heating demand is about *335 kWh/month* (*4,000 kWh/year)*, which is the estimated average value for Norwegian homes [Breembroek and Dieleman, 2001].

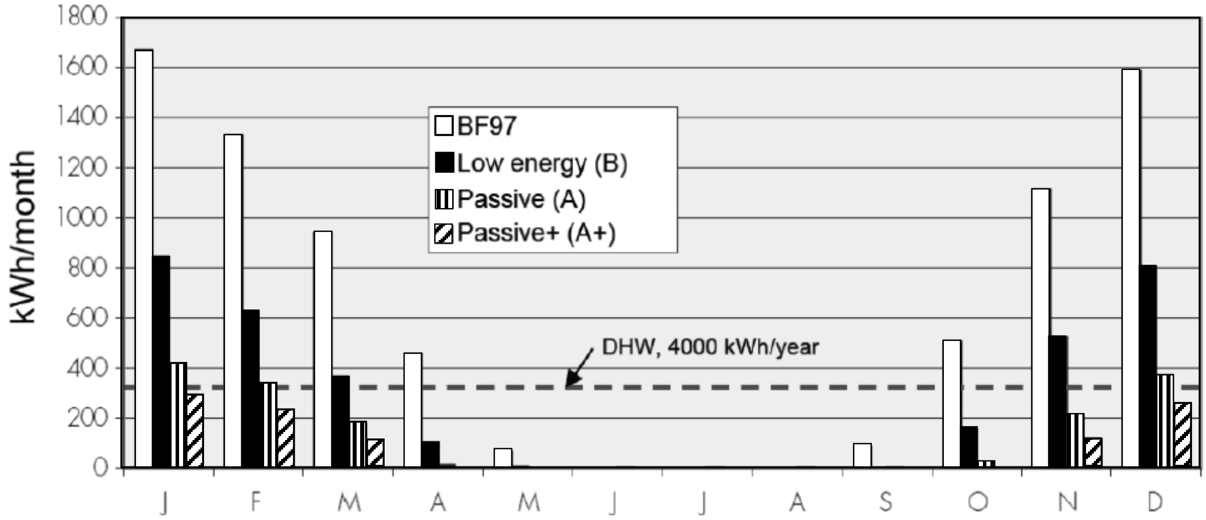


Figure 1 Example – Calculated monthly space heating demand and DHW heating demand for a 104 m^2 semi-detached house in Oslo, Norway constructed according to different building standards [Dokka and Hermstad, 2006].

The house constructed according to BF97 has an annual space heating period of 9 month/year, while the space heating periods for the low-energy house (B), the passive house (A) and the passive house+ (A+) are about 7, 6 and 5 months, respectively. The monthly heating demand for DHW is equal to or higher than the monthly space heating demands during the entire year for the passive houses (A and A+), while the monthly space heating demand is higher than the average DHW heating demand during roughly 4 month per year for a low-energy house (B). Consequently, it is important that heat pump systems for low-energy and passive houses are designed for high energy efficiency in DHW mode.

2. Analysis of Integrated Residential CO_2 Heat Pump Systems

A heat pump system can be used to cover the heating demands in low-energy houses and passive houses. The heat pump system can be designed as a stand-alone system, i.e. a heat pump water heater in combination with a separate unit for space heating, or be an integrated unit for combined space heating and hot water heating. Due to compact design, the latter system is most likely to achieve the lowest investment and installation costs and with that the best profitability. There exists a large number of designs for integrated heat pump systems with conventional working fluids, and the main differences are related to the design and operation of the DHW system. The most common systems are double-shell tank system, desuperheater system, shuttle-valve system and two-stage DHW system.

2.1 Main Characteristics of CO_2 Heat Pumps

Carbon dioxide (CO_2, R744) is one of the few non-toxic, non-flammable working fluids that neither contributes to ozone depletion nor global warming. CO_2 therefore represents an interesting long-term alternative to the commonly used HFC working fluids. CO_2 has excellent thermophysical properties, and by utilizing these properties by means of optimized component and system design for the heat pump unit, the DHW system and the heat distribution system, high energy efficiency can be achieved.

CO_2 has an especially low critical temperature (31.1ºC) and high critical pressure (73.8 bar). As a consequence, the operating pressure in CO_2 heat pump systems will typically be 5 to 10 times higher than that of standard heat pumps, i.e. 20 to 40 bar in the evaporator and 80 to 130 bar during heat rejection. Due to the low critical temperature most CO_2 heat pumps operate in a so-called *transcritical cycle* with evaporation at subcritical pressure and heat rejection at supercritical pressure (p>73.8 bar). Unlike a subcritical heat pump cycle, heat is not given off by means of condensation of the working fluid in a condenser but by cooling of high-pressure CO_2 gas in a heat exchanger (gas cooler). The temperature drop for the CO_2 gas during heat rejection is denoted the *temperature glide*. Figure 2 shows the principle of the transcritical CO_2 heat pump cycle in a Temperature-Enthalpy (T-h) diagram.

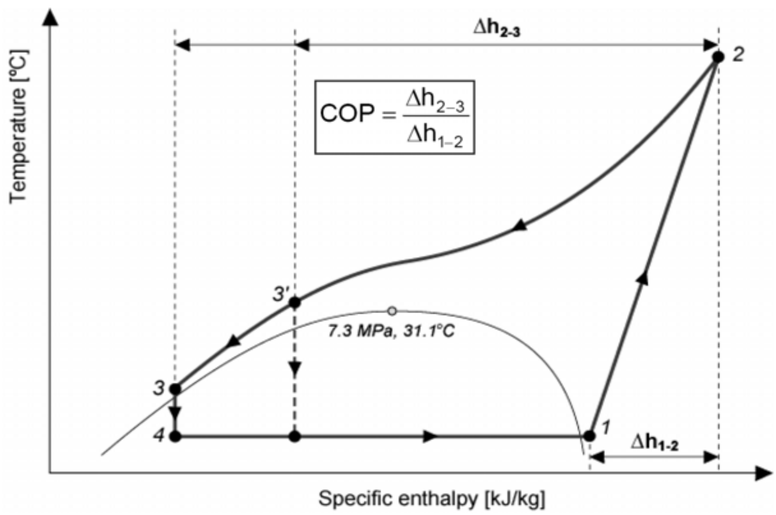


Figure 2 The transcritical CO_2 heat pump cycle in a T-h diagram. 1-2: Compression, 2-3: Heat rejection in a gas cooler, 3-4: Expansion/throttling, 4-1: Evaporation.

The main factors that determine the Coefficient of Performance (COP) for a single-stage CO_2 heat pump are the evaporation temperature, the overall isentropic efficiency for the compressor, the optimum gas cooler pressure, the CO_2 outlet temperature in the gas cooler, and possible recovery of expansion energy by means of an ejector or an expander.

Since the discharge gas temperature from the compressor in a CO_2 heat pump cycle is relatively high (>80ºC), a CO_2 heat pump can meet high-temperature heating demands. However, in order to achieve a high COP for a CO_2 heat pump system, it is essential that *useful heat* is rejected over a large temperature range, resulting in a large enthalpy difference for the CO_2 in the gas cooler (h_2-h_3) and a relatively low CO_2 temperature (t_3) before the expansion/throttling valve. This in turn presupposes a relatively low inlet water temperature in the gas cooler, i.e. a low return temperature in the (hydronic) heat distribution system and/or a low inlet water temperature from the DHW tank.

The input power to the compressor is more or less proportional to the gas cooler pressure, i.e. the higher the gas cooler pressure, the lower the COP. Consequently, CO_2 heat pumps should preferably be designed for a moderate optimum gas cooler pressure.

Integrated heat pump systems (IHPS) provide both space heating and hot water heating, and the heat is normally rejected to a hydronic heat distribution system. An integrated heat pump system can be designed for high energy efficiency, but in the design process there will always be a trade-off between technical solutions that reduce the thermodynamic losses in the system, and first costs.

The main operating modes of an integrated CO_2 heat pump system are:

- *DHW mode* – heating of domestic hot water (DHW)
- *SH mode* – space heating
- *Combined mode* – simultaneous space heating and DHW heating

2.2 Testing and Evaluation of a Prototype CO2 Heat Pump System

A 6.5 kW prototype brine-to-water CO_2 heat pump system for space heating and DHW heating has been extensively tested and analyzed (Stene, 2004/2006). A large number of different gas cooler configurations were evaluated, and it was found that *an external counter-flow tripartite gas cooler for preheating of DHW, low-temperature space heating and reheating of DHW,* would enable production of DHW in the required temperature range from 60 to 85ºC, and contribute to the highest possible COP for the heat pump unit. Figure 3 shows the principle of the integrated CO_2 heat pump system.

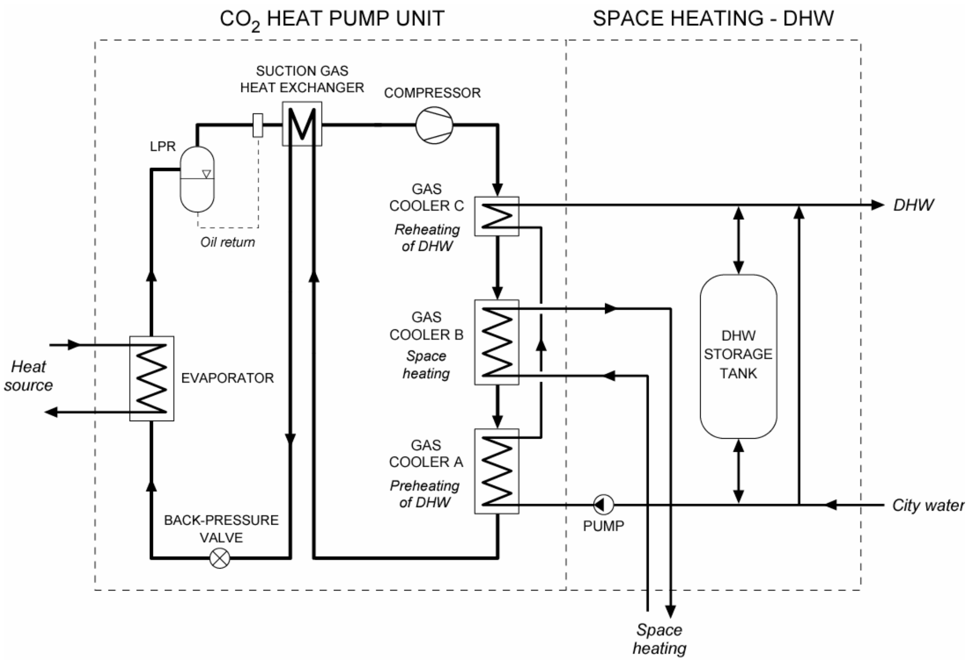


Figure 3 Principle design of the prototype brine-to-water integrated CO_2 heat pump system.

The prototype CO_2 heat pump unit was equipped with a hermetic rolling piston compressor, a tripartite counter-flow tube-in-tube gas cooler and a counter-flow tube-in-tube suction gas heat exchanger. An expansion valve (back-pressure valve) and a low-pressure liquid receiver (LPR) were used to control the pressure in the tripartite gas cooler. Gas cooler units A and C were connected to an unvented single-shell DHW storage tank and an inverter controlled pump by means of a closed water loop. Gas cooler unit B was connected to a low-temperature hydronic heat distribution system.

The integrated CO_2 heat pump unit was tested in three different operating modes. 1) Simultaneous space heating and DHW heating (*Combined mode*), 2) Hot water heating (*DHW mode*) and 3) Space heating (*SH mode*). During tapping of DHW, hot water was delivered at the tapping site, while cold city water entered the bottom of the DHW tank. During charging of the DHW tank in the Combined and DHW modes, the cold city water from the bottom of the DHW tank was pumped through gas cooler units A and C, heated to the set-point temperature, and returned at the top of the tank. The CO_2 system was tested at *40/35ºC*, *35/30ºC* or *33/28ºC* supply/return temperature in the SH system, and *60ºC*, *70ºC* or *80ºC* in the DHW system.

The heat rejection processes in the three different operating modes are illustrated in temperature-enthalpy diagrams in Figure 4. The supply/return temperature for the floor heating system were 35/30ºC, while the city water temperature and the set-point for the DHW were 6.5 and 70ºC, respectively. In the Combined mode, the so-called *DHW heating capacity ratio* was about 45%, which means that 45% of the total heating capacity of the tripartite gas cooler was used for hot water heating.

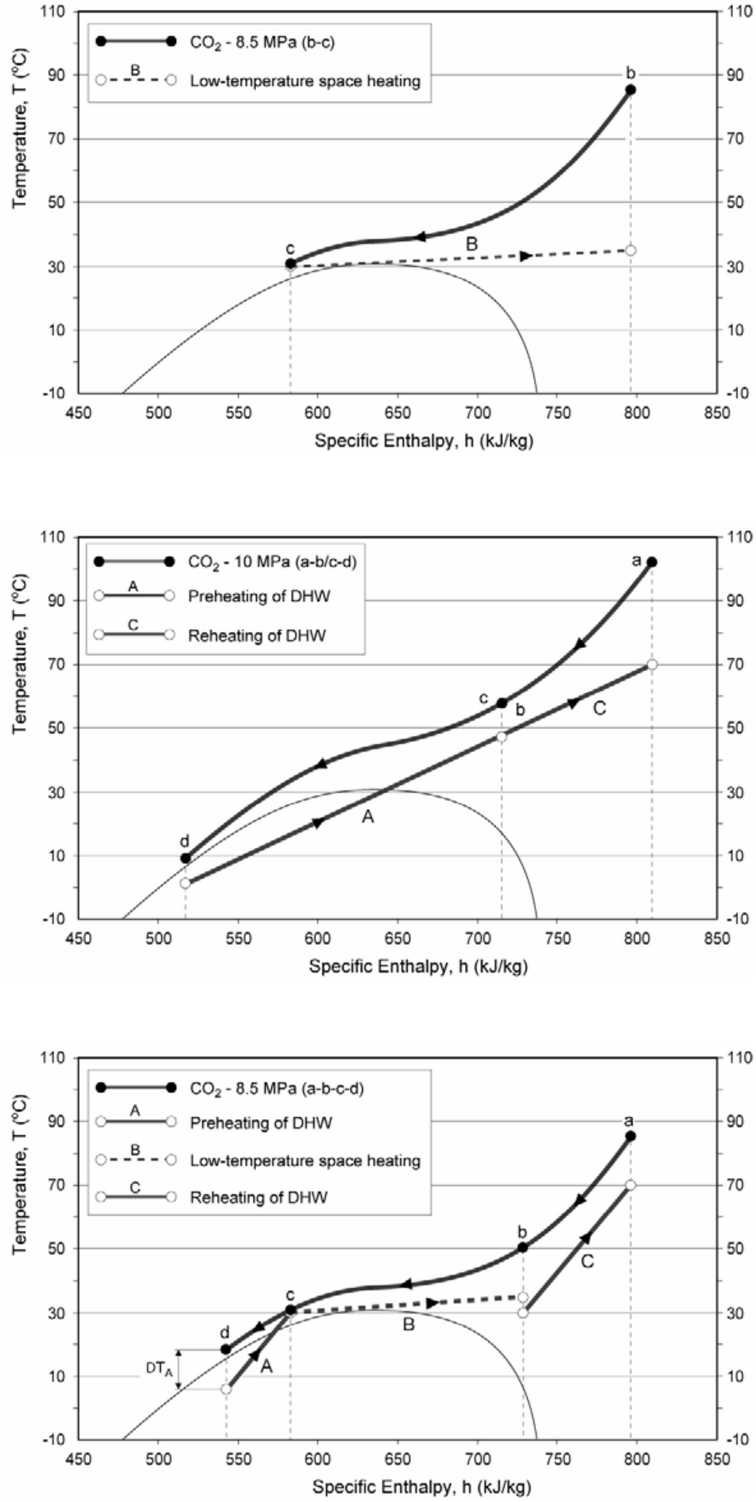


Figure 4 Example – Illustration of the heat rejection process for an integrated CO_2 heat pump in Space heating (SH) mode (35/30ºC), DHW mode (70ºC) and Combined mode (35/30ºC, 70ºC). The optimum gas cooler pressures were 85 and 100 bar.

The COP in the Combined mode was 2-10% higher than that of DHW mode due to the moderate optimum gas cooler pressure (85-95 bar) and the relatively low CO_2 outlet temperature from the tripartite gas cooler caused by the excellent temperature fit between the CO_2 and the water.

The COP in the SH mode was 20-30% lower than that of the Combined mode. This was a result of the poor temperature fit between the CO_2 and the water, and the fact that the CO_2 outlet temperature from the gas cooler was limited by the relatively high return temperature in the space heating system.

2.3 Comparison of Seasonal Energy Efficiency

The Seasonal Performance Factor (SPF) for the prototype CO_2 heat pump unit and a state-of-the-art high-efficiency brine-to-water heat pump was calculated, assuming constant inlet brine temperature for the evaporator (0ºC) and constant temperature levels in the space heating system (35/30ºC) and the DHW system (10/60ºC). An improved CO_2 heat pump unit with 10% higher COP than the prototype system was also investigated in order to demonstrate the future potential of the CO_2 system. Higher COP can be achieved by using a more energy efficient compressor, optimizing the tripartite gas cooler or replacing the throttling valve by an ejector. The latter is capable of increasing the COP by typically 10 to 20% (Stene, 2004). For the CO_2 heat pump systems, the thermodynamic losses in the DHW tank due to mixing and internal conductive heat transfer were not included when calculating the SPF.

Table 1 shows the measured COPs for the heat pump systems at the selected operating conditions.

Table 1 Measured COPs for the brine-to-water heat pump systems.

Prototype CO_2 heat pump	• COP = 3.0 – SH mode at 35/30ºC • COP = 3.8 – DHW mode at 10/60ºC – no electric reheating • COP = 3.9 – Combined mode at 35/30ºC and 10/60ºC
Improved CO_2 heat pump	• COP = 3.3 – SH mode at 35/30ºC • COP = 4.2 – DHW mode at 10/60ºC – no electric reheating • COP = 4.3 – Combined mode at 35/30ºC and 10/60ºC
State-of-the-art heat pump	• COP = 4.8 – SH mode at 35/30ºC • COP = 3.0 – DHW mode at 10/60ºC – no electric reheating

Table 1 shows that the integrated CO_2 heat pumps and the state-of-the-art heat pump have reversed COP characteristics, i.e. the CO_2 units achieve the highest COP during operation in the DHW mode and the Combined mode, whereas the state-of-the-art unit achieves the highest COP in the SH mode.

Figure 5 shows the calculated SPFs for the three residential heat pump systems during monovalent operation presented as a function of the seasonal DHW heating demand ratio.

At low DHW heating demand ratios, the state-of-the-art heat pump was more efficient than the CO_2 systems due to their poor COP during operation in the SH mode. At increasing DHW heating demand ratios, the SPFs of the CO_2 systems were gradually improved, since an increasing part of the heating demand was covered by operation in the Combined mode and the DHW mode. On the other hand, the SPF for the state-of-the-art heat pump dropped quite rapidly with increasing DHW heating demand, since the COP during operation in the DHW mode was about 35% lower than that of the SH mode.

At the actual operating conditions, the break-even for the prototype CO_2 system occurred at a DHW heating demand ratio around 60%, whereas the break-even for the improved CO_2 system was about 10 percentage points lower.

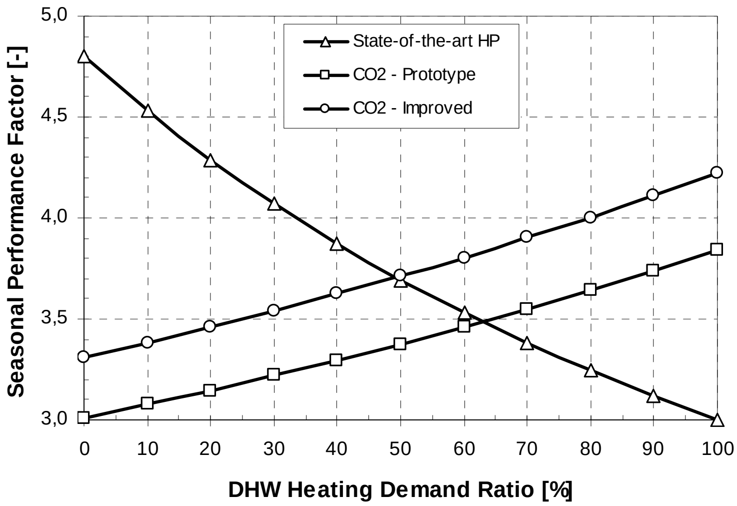


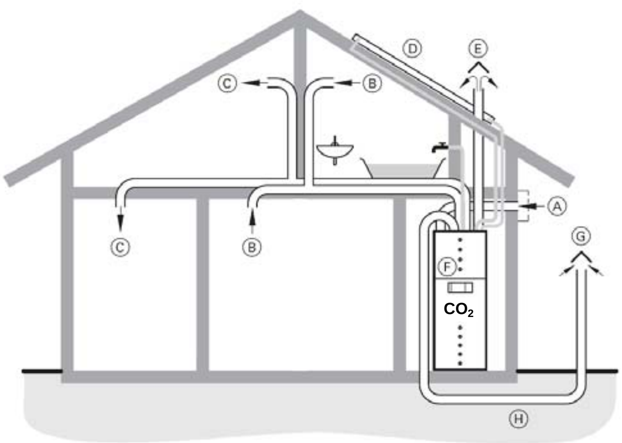
Figure 5 Calculated SPF during monovalent operation for a high-efficiency state-of-the-art heat pump, the prototype CO_2 heat pump and an improved CO_2 heat pump.

In existing houses where the DHW heating demand ratio typically ranges from 10 to 30%, a state-of-the-art high-efficiency heat pump system will be more energy efficient than an integrated singe-stage CO_2 heat pump system. However, *in low-energy houses and passive houses, where the DHW heating demand ratio ranges from 50 to 80%, an integrated CO_2 heat pump system with a tripartite gas cooler will outperform the most energy efficient heat pump systems on the market*.

At 70% DHW heating demand ratio, the COP for the improved CO_2 heat pump is about 3.9. This corresponds to a *net energy saving of about 75%* compared with a direct electric heating system.

2.4 CO_2 Heat Pumps in Passive Houses – Application Example

A CO_2 heat pump system with a tripartite gas cooler for heating of low-energy houses and passive houses can be designed to utilize different heat sources. In Germany 40-50% of all passive houses are using an integrated heat pump system for space heating and hot water heating [Bühring, 2005]. The most common heat source is ventilation air, often in combination with ambient that is preheated in a ground heat exchanger (GHE[1]). Figure 6 shows a principle sketch of a residential CO_2 heat pump system for a passive house using ventilation air and ambient air as heat sources (Viessmann, 2008).



A) Fresh air supply to the house
B) Exhaust air from the rooms
C) Fresh air supply to the rooms via a balanced ventilation system
D) Solar collector (optional) for heating of domestic hot water
E) Discharge air outlet
F) CO_2 heat pump unit and domestic hot water tank
G) Ambient air to the heat pump evaporator preheated by the GHE
H) Ground heat exchanger (GHE)

Figure 6 Example – CO_2 heat pump installation in a passive house (Viessmann, 2008).

[1] GHE – Approx. 15 meter long OD 200 mm plastic tube located around the house at about 1 meter below ground level

Ground (soil) is also a heat source of current interest for CO_2 heat pumps in low-energy and passive houses. In these systems the evaporator tubes (direct system) or a OD 40 mm PE tube with circulating anti-freeze fluid (indirect system) is installed horizontally in the ground about 0.8-1.5 meter below the ground level. Due to the relatively low heating capacity of the heat pump unit in a passive house (2-3 kW), a relatively small ground space is required for the ground-heat exchanger.

3. CONCLUSION

Integrated residential heat pump systems using carbon dioxide (CO_2, R744) as a working fluid can achieve high energy efficiency due to the unique characteristics of the CO_2 heat pump cycle. Different integrated CO_2 heat pump systems have been investigated, focusing on the design of the heat rejection heat exchanger (gas cooler) and the DHW system. It was found that a counter-flow tripartite CO_2 gas cooler in combination with an external single-shell hot water tank and a low-temperature heat distribution system, would enable production of DHW from 60 to 85ºC without electric reheating and contribute to the highest possible COP for the CO_2 heat pump system. The Seasonal Performance Factor (SPF) for a prototype brine-to-water CO_2 heat pump was calculated on the basis of laboratory measurements and compared with the performance of a high-efficiency state-of-the-art brine-to-water heat pump unit. At DHW heating demand ratios above approximately 50%, the CO_2 heat pump system outperformed the state-of-the-art heat pump system. Consequently, integrated CO_2 heat pump systems equipped with a tripartite gas cooler represent a promising, high-efficiency system for combined space heating and DHW heating in low-energy houses and passive houses. In passive houses the most interesting heat sources includes ground (direct expansion system), ventilation air or a combination of ventilation air and ambient air.

4. REFERENCES

Breembroek, G., Dieleman, M., 2001: *Domestic Heating and Cooling Distribution and Ventilation Systems and their Use with Residential Heat Pumps*. IEA Heat Pump Centre Analysis Report HPC-AR8. ISBN 90-72741-40-8.

Bühring, A., 2005: Bühring, A., 2005: *Development and Measurement of Compact Heating and Ventilation Devices with Integrated Exhaust Air Heat Pump for High-Performance Houses*. Proceedings fra 8. IEA Heat Pump Conference, Las Vegas, USA, May 30 – June 2, 2005.

Dokka, T.H., Hermstad, K., 2006: *Energieffektive boliger for framtiden – en håndbok for planlegging av passivhus og lavenergihus (Energy Efficient Houses for the Future – A Handbook for Planning of Passive Houses and Low-Energy Houses)*. Norwegian final report from ECBCS Annex 38, Sustainable Solar Housing. SINTEF Building and Infrastructure.

Stene, J., 2004: *Residential CO_2 Heat Pump System for Combined Space Heating and Hot Water Heating*. Doctoral Thesis at the Norwegian University of Technology and Science, Dept. of Energy and Process Engineering, 2004:53. ISBN 82-471-6316-0.

Stene, J., 2006: *Residential CO_2 Heat Pumps for Combined Space Heating and Hot Water Heating – System Design, Test Procedures and Calculation of SPF*. Report no. TR A6102. SINTEF Energy Research, Norway.

Viessmann, 2008: *Compact Energy Tower für das Passivhaus – Vitotres 343*. Information from Viessmann Werke GmbH&Co KG, Germany