PAPER ID: 0697
DOI: 10.18462/iir.compr.2024.0697

R290 - 1,8 MW CHILLER AND HEAT PUMP SYSTEM

Ayesha Saher[a], Armin Hafner[a], Øyvind Jordfald[a] Eirik Rødstøl[b]

[a] Norwegian University of Science and Technology, Trondheim, 7491, Norway
[b] Kelvin AS, Sandvika, 1337, Norway
armin.hafner@ntnu.no

ABSTRACT

With the increasing demand for reducing CO_2 emissions, reliable and environmentally friendly energy systems are vital for a green future. Heat pumps offer an efficient option to reduce greenhouse gas emissions caused by heating and cooling. Heat pump units are an excellent way to distribute heat while decreasing electricity consumption. Selecting the right refrigerant is vital to meet the F-gas regulations. Conventional refrigerants have a significant global warming potential and will be banned soon by the F-gas regulation. Hydrocarbons have better thermodynamic properties to increase the efficiency of the system. The energy system in operation at Teknobyen, an office complex located in Trondheim, Norway, uses propane and CO_2 heat pump units to meet the heating and cooling demands of the building. This versatile unit ensures optimal energy usage and maintains a pleasant environment regardless of the season. This paper further explains the energy system; some measured field data are shown for selected days.
Keywords: Hydrocarbons, Carbon Dioxide, Energy Efficiency, Heat Pump

INTRODUCTION

Owing to the increasing awareness of the rise in global temperature and the urgency to reduce the use of fossil fuels and toxic gases, heat pumps are recognised as an efficient option in this context. The installation and usage of heat pumps are predicted to rise globally. According to the International Energy Agency (IEA), more heat pump installations are required worldwide to reach net zero emissions by 2050 (Abergel, 2021). Heat pumps can deliver heat without fossil fuel consumption by using and upgrading renewable energy sources. Heat pumps are significantly more energy efficient than conventional heaters when electricity is applied to operate the vapour compression unit for heating and cooling purposes. Most of the current heat pumps use synthetic chemicals with high global warming potential (GWP).

To diminish greenhouse gas emissions, it is necessary to employ natural refrigerants with low global warming potential (GWP) and no ozone depletion potential (ODP), such as ammonia, CO_2 and hydrocarbons. Neither should these fluids be harmful to human health nor the biosphere. Therefore, a fluid decomposing to PFAS is not an option for new systems either.

Propane (R290) is a hydrocarbon known for its excellent thermodynamic properties and low environmental impact (GWP=3, ODP=0) when applied as a working fluid. Considering the natural existence and favourable properties, a significant number of propane heat pumps and chillers have been deployed in nursery homes, schools, office buildings, hospitals, and universities. Propane has the potential to substitute synthetic refrigerants and compete with their performance in a wide application range, mainly when indirect loops are applied to distribute the heat and cold. It has been a common refrigerant in heat pumps, chillers, and industrial refrigeration systems since the 1930s. Propane is also interesting due to its large volumetric cooling capacity and well-suited working pressures (Huber 2016). It is categorised as an A3 refrigerant due to its flammability. However, to ensure safe operation, propane heat pumps and operators must follow current safety standards like conventional systems (Corberán et al. 2008). A potential solution to lessen the risk associated with flammable refrigerants is charge reduction. If leakage occurs in a system with a reduced charge, the refrigerant loss is significant as compared to a system with a larger refrigerant charge. Therefore, it is essential to identify leaks to eliminate the risks, performance losses and component damage. CO_2 cooling systems are the preferred technology for commercial refrigeration and supermarket applications in many countries, as well as hot water heat pumps. These CO_2 systems perform very well in moderate or cold climates but can be challenging to operate in warmer climates because of the low critical temperature of approximately 31 °C. However, CO_2 heat pumps can provide a large temperature lift on the hot water side and hot water temperatures from 85 to 95 °C can be achieved. CO_2 heat pump water heaters do have a higher COP than normal hot water heat pumps.

This paper is focused on the building project of Teknobyen, a complex of office buildings located in Trondheim, Norway. It has an integrated air source heat pump unit with propane as the working fluid for space heating and cooling of the buildings and a CO_2 heat pump for the domestic hot water demand. Field data of the propane heat pump for space heating and cooling on a typical winter- and summer day are collected for analysis. The study's objective is to investigate the actual demand and performance while ensuring the comfort of the occupants and fulfilling their energy / thermal comfort requirements. The building complex is still under expansion, the investigated energy system is designed to supply for the entire complex, ready in the coming years.

SYSTEM AND METHODS

2.1 Description of the system

The propane system of the Teknobyen consists of two heat pump units with four individual circuits within each unit. One cycle includes an evaporator, a compressor, a condenser and an expansion valve, as illustrated in Figure 1. In the inlet of the evaporator, the propane is in two-phase and has a lower temperature than the secondary medium it extracts heat from, in this case a 37% ethylene glycol mixture. The propane evaporates and is transported by the compressor, resulting in a high-pressure, high-temperature propane gas. The propane enters the condenser, releases heat to another medium, water, and condenses into a liquid state.

(A) **(B)**

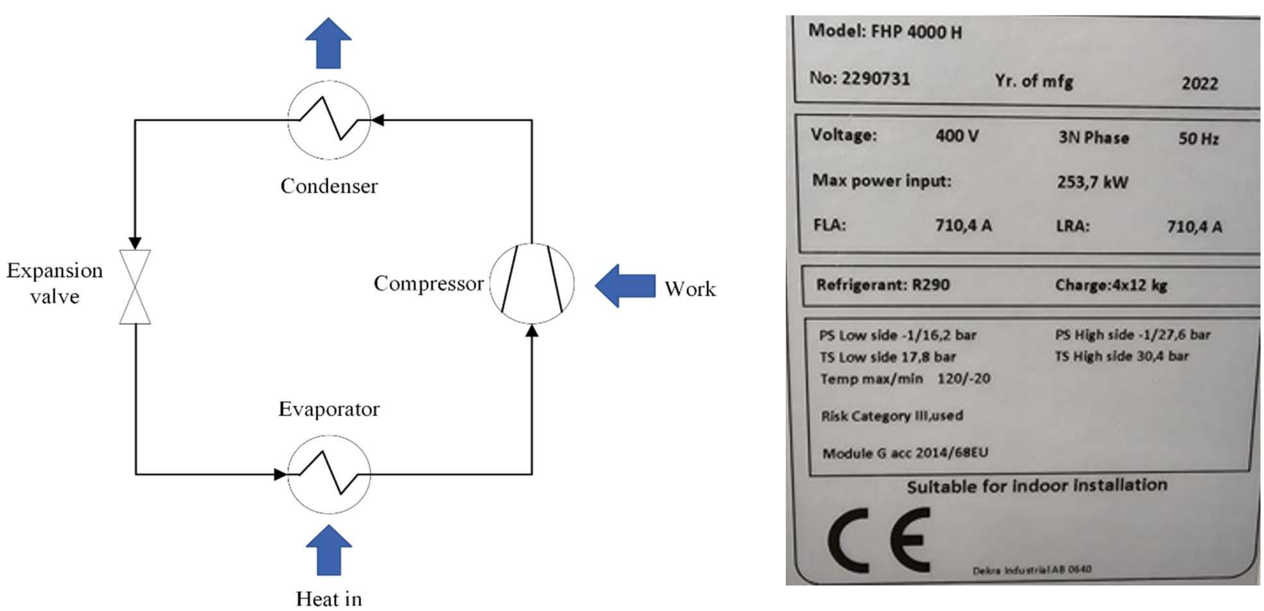
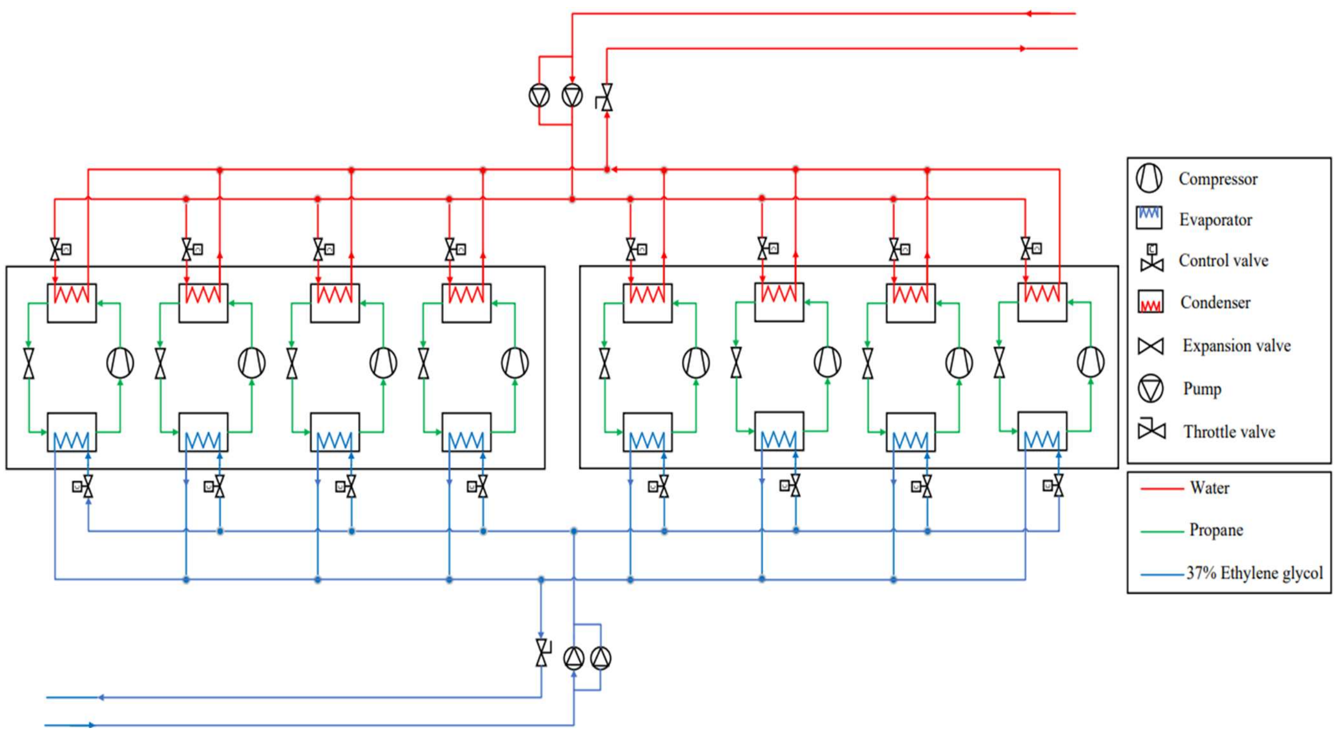


Figure 1: Heat pump cycle with main components (A) Picture of the plate on one of the two R290 units (B)

Following this, the propane passes through the expansion valve and is expanded to the same pressure as in the evaporator, and the cycle repeats. The total eight circuits are shown in Figure 2. One cycle has a maximum heating capacity of 310 kW, resulting in a maximum heating capacity of 1240 kW for each heat pump section. Consequently, this configuration allows a total capacity of 2480 kW per cycle (Naemi, 2023).

Because of the varying temperatures in the ambient environment, the propane system must operate in both cooling and heating modes. For the heating mode, the 37% ethylene glycol mixture is passed through the four outdoor air-glycol heat exchangers and absorbs heat from the ambient air. It is also used for energy recovery by absorbing heat from data rooms and other cooling rooms. This absorbed heat is further augmented by the propane system and transferred to the water circuit. The water circuit serves multiple purposes, including space (floor) heating and ventilation air heating. However, tap water is heated by a separate the CO_2 heat pump. Additionally, it is used to heat up the ethylene glycol mixture to defrost dry coolers, utilising the remaining temperature level of the returning water to reduce the return water temperature further. For cooling, the ethylene glycol mixture is cooled by the heat pump/chiller, absorbs heat from the building (ventilation units), and rejects heat via the outdoor dry coolers. For this mode, the required heat is extracted from the heat exchanger connected to the water circuit (Carrillo, 2023).



2.2 Defrosting system
When the fin surface temperature is below 0° C, frosting occurs on the fins of the four outdoor heat exchangers. This frost buildup leads to various consequences, such as reduced heat transfer at increasing temperature differences between the heat source and the circulated fluid, resulting in increased energy demand for the entire unit and further frost buildup. Therefore, a defrosting system consisting of an accumulator tank (15 m^3) with a warm 37% ethylene glycol mixture is utilised in the energy system, as shown in Figure 3.

The mixture is reheated by the return flow from the circulated hot water and is stored in the tank, which is to be utilised when defrost is required. The mixture defrosts each dry cooler sequentially (Carrillo, 2023) without disturbing the main circuit, as the accumulated heat delivers several hundred kW of heating capacity in the first part of the defrost cycle.

2.3 Capacity
As stated previously in section 2.1, the propane system consists of two heat pumps with four separate cycles each. Each cycle has a maximum heating capacity of 310 kW. Consequently, the two heat pumps have a maximum heating capacity of 1240 kW each, resulting in a total capacity of 2480 kW. The cooling capacity of the entire system is 1800 kW. The system can be used for auxiliary heating, using an electric heater or district heating if necessary. Additionally, storage tanks are integrated into the water circuit, ensuring optimal temperature control

(Naemi, 2023) and a continuous smooth operation of the heat and cold distribution system.

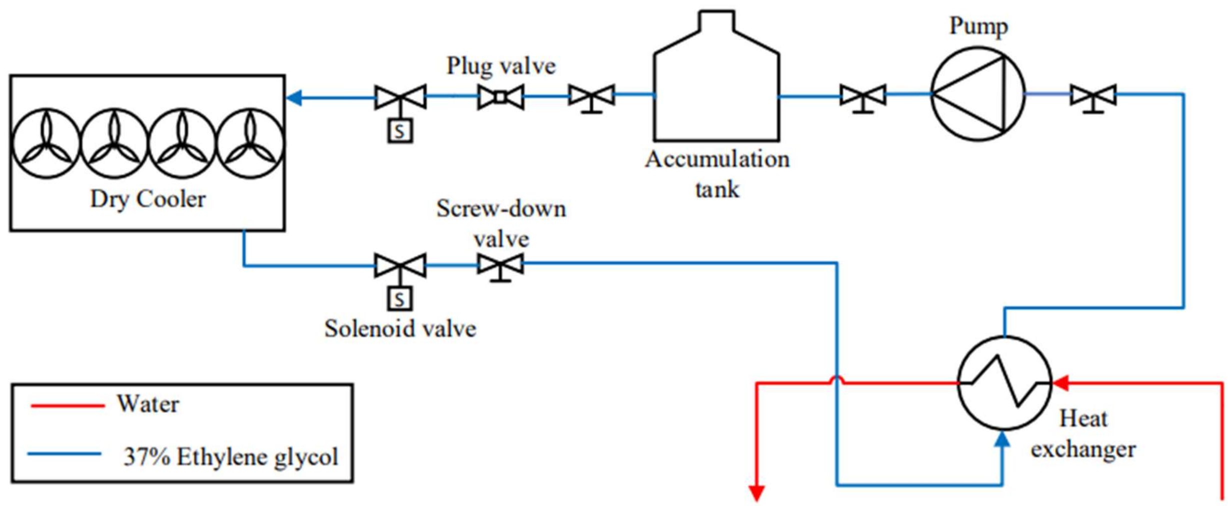


Figure 2: Defrosting system of the dry coolers

2.4 Safety measures
Propane is the most suitable natural refrigerant for this heat pump / liquid chiller system due to its compactness, availability, and low compressor discharge temperature, which still needs to achieve sufficient water supply temperatures from the condenser for the heating purpose of the building. Charge reduction is a promising option to improve the operation of heat pumps when applying A3 flammable refrigerant. The flammability risk can be reduced by modifying the design and components to reduce the refrigerant charge (Ghoubali et al.2017). As shown in Figure 1B, the charge of each R290 circuit, located inside a dedicated ventilated cabinet, is 12 kg and the entire installation is commissioned, tested and approved according to the relevant standards. The entire machine room with restricted access, containing a total of 8 of these R290 cabinets, is also ventilated in accordance to current standards. Besides these measures are additional gas detectors, exhaust fans, and differential pressure sensors are implemented.

RESULT AND DISCUSSION

This work presents results from Teknobyen, a complex of office buildings located in Trondheim, Norway. This energy system provides the heating and cooling requirements for all the buildings in the quarter owned by a single real estate company. The measured data from the different sub-systems are applied to evaluate the overall system's performance under various scenarios. These data are logged by a '*Teknostallen Piscada portal*' system. In this study, there are three relevant operational cases: the typical coldest day- the warmest day- and a defrosting case. The extracted data are plotted as a function of time for the compressors, condensers, evaporators, and pumps.
Figure 4 shows the ambient temperature data for an entire day with the minimum recorded ambient temperature of -13.7 °C. The ambient temperature data for the selected days has been downloaded from the '*Meteorologisk institutt*' database for this part of Trondheim.

For the winter case, the selected coldest day was the 10th of February 2024, with a minimum ambient temperature of -13.7 °C. Figure 5 shows the result of capacity variation with time ranging from 00:00 to 23:55 hours for the coldest day for the compressors, condensers, and evaporators of all heat pumps. The plotted data indicates that the total compressor power demand for the heat pumps had the highest value of approximately 250 kW at 11:00 am with the ambient temperature –9.5 °C.

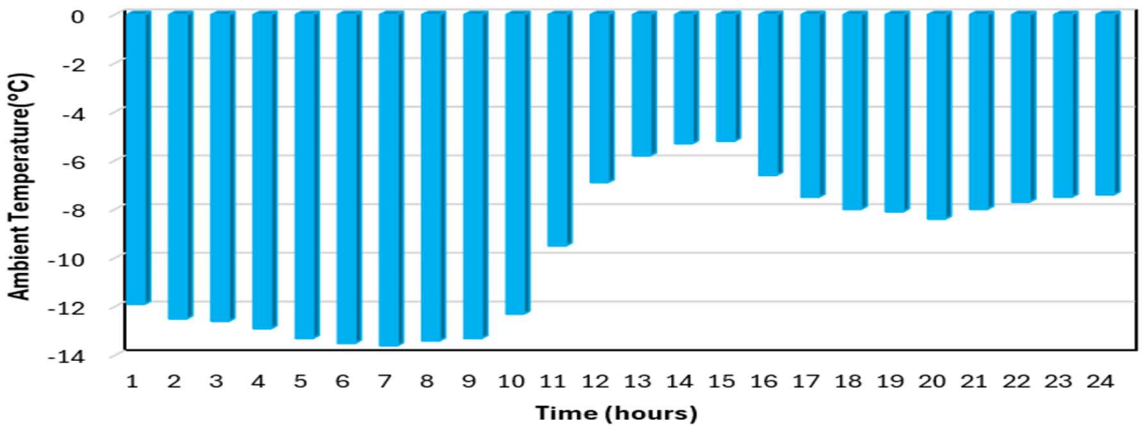


Figure 4: Ambient temperature, hour by hour, 10th of February

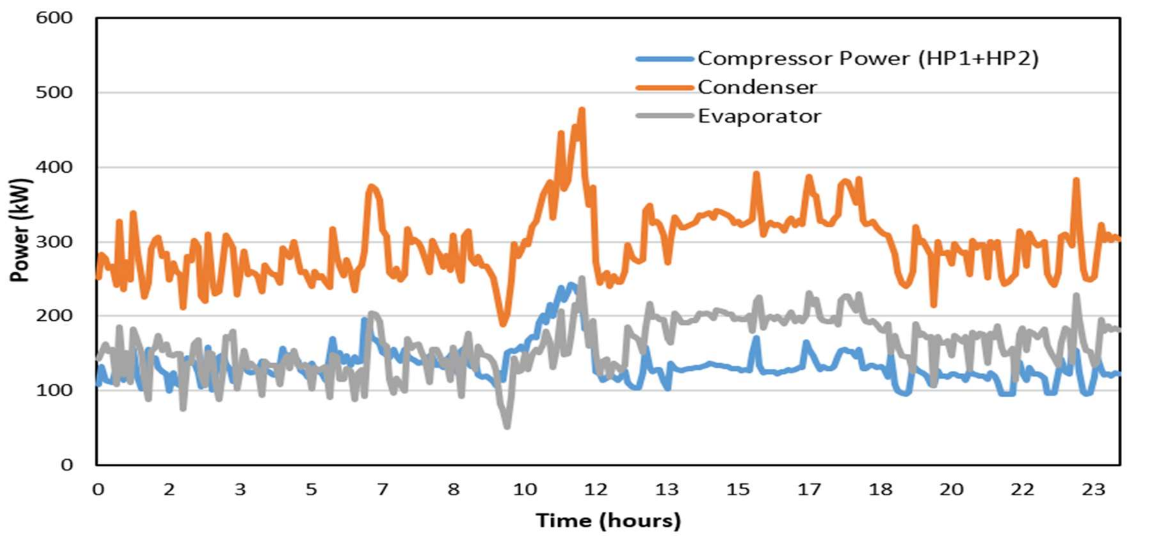


Figure 5: Power demand and capacities during the coldest day/ winter case

The 27th of June 2024 has been selected for warmer summer conditions. Figure 6 shows the hourly values of the ambient temperature with the maximum recorded ambient temperature of 29.4 °C.

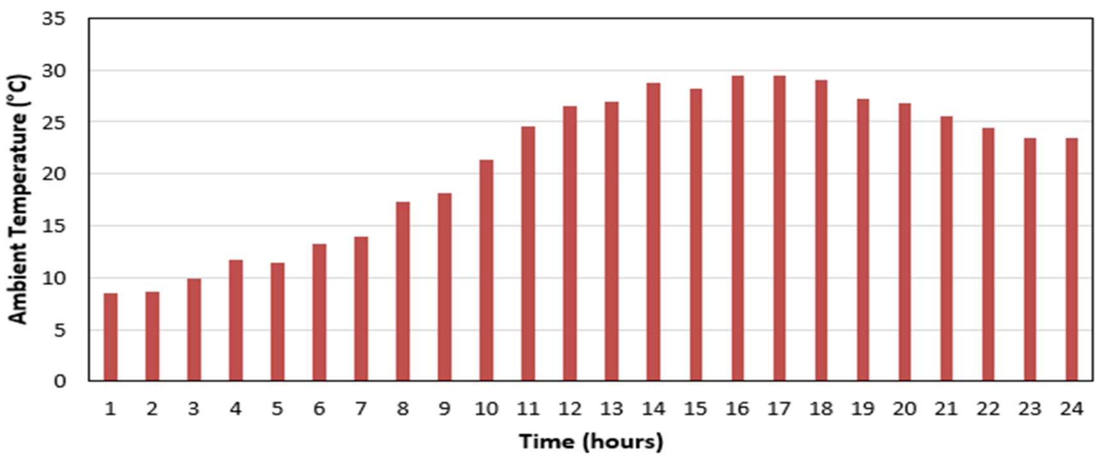


Figure 6 : Ambient temperature data of a summer day, 27th of June

Figure 7 shows the power demand of all R290 compressors for the selected warmest day. The maximum recorded power consumption by the R290 compressors was 234 kW at 17:00 in the evening with a maximum ambient temperature of 29.4 °C. The lowest compressor power demand for the heat pumps is 2.5 kW at night when the ambient temperature drops to 8.5 °C.

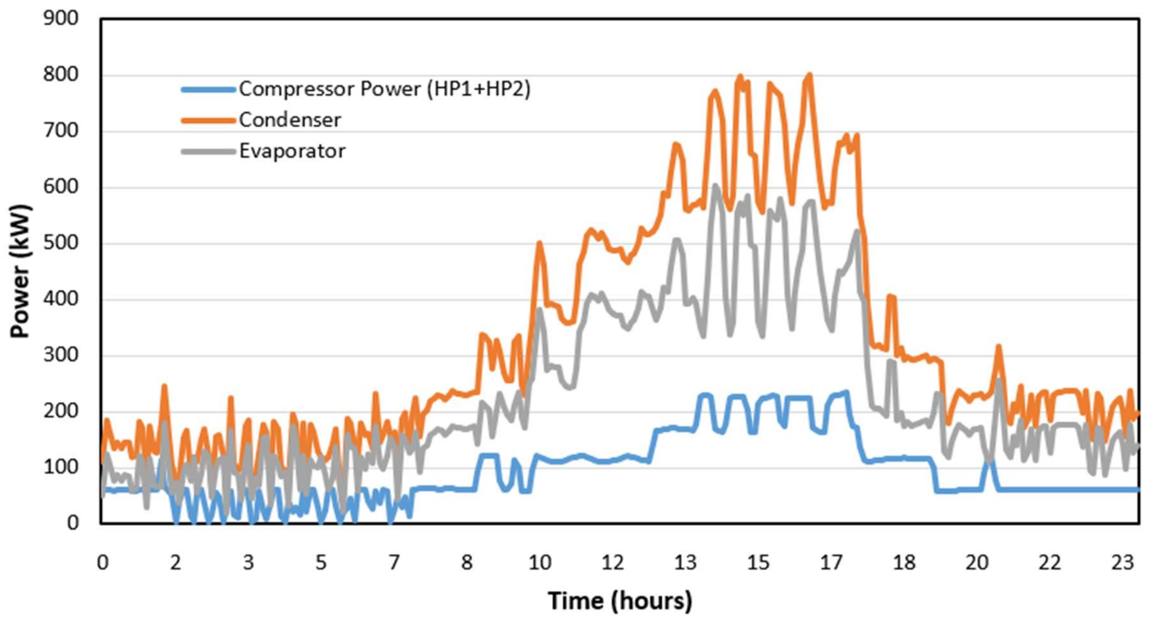


Figure 7: Power demand of the warmest day

Figure 8 shows the coefficient of performance (COP) of both heat pumps, the ratio of capacity divided by the power demand. The COP has been plotted against time for the coldest and warmest day of the year. The highest COP recorded for the warmest day is 5.6 at 5:00 am in the morning, and the lowest COP value is 2.09 at 1:00 am at night. When considering the energy efficiency ratio for the entire day (delivered cooling energy/energy to compressors), a value of 2.41 has been achieved.

For the winter day case, the maximum COP was 2.75, and the lowest COP was 1.47. Considering the energy efficiency ratio for the entire winter day (delivered heating energy/energy to compressors), a value of 2.19 has been achieved.

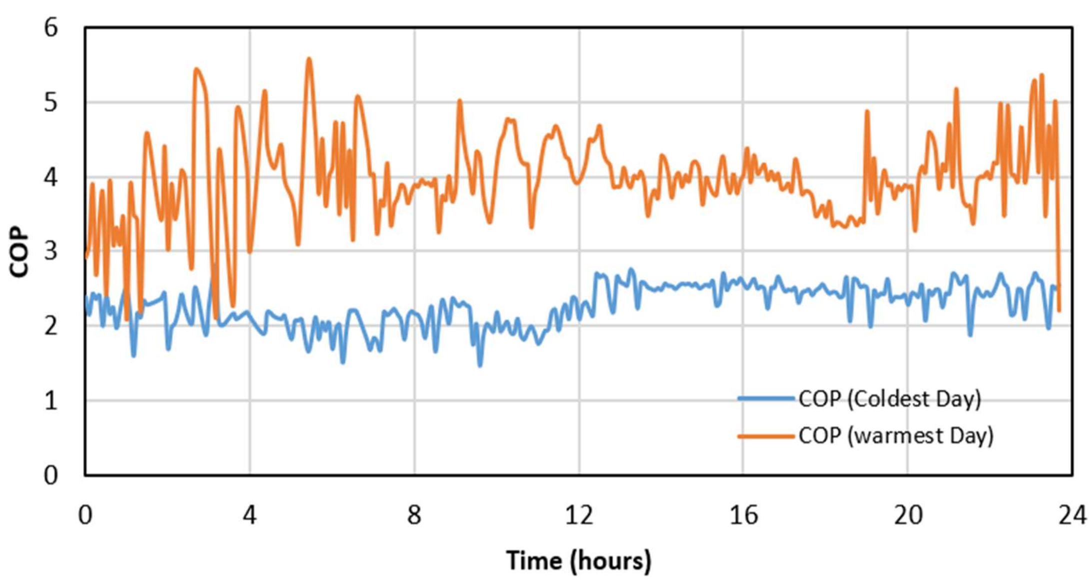


Figure 8: Coefficient of performance (COP) of the heat pumps

Adding the pump power, COP for the warmest and coldest day becomes 3.1 and 2.1, respectively. The average pump power for the cold day is 6.0 kW, and the warmest day is 9.2 kW. The part load compressor capacity utilization of 18 % (2234 kWh) was measured and calculated for the day and compared to the total available energy if all compressors would have been operated 24h (12177 kWh) for the warmest day (27^{th} June 2024). 26.5 % (3221.23 kWh) of the available capacity was utilized on the coldest day (10^{th} of February 2024).
For the defrosting case, as an example, the 18^{th} of January 2024 has been selected. Figure 9 shows the hourly values for the ambient temperature data for the defrosting case. The minimum ambient temperature recorded for the defrosting case was -15 °C.

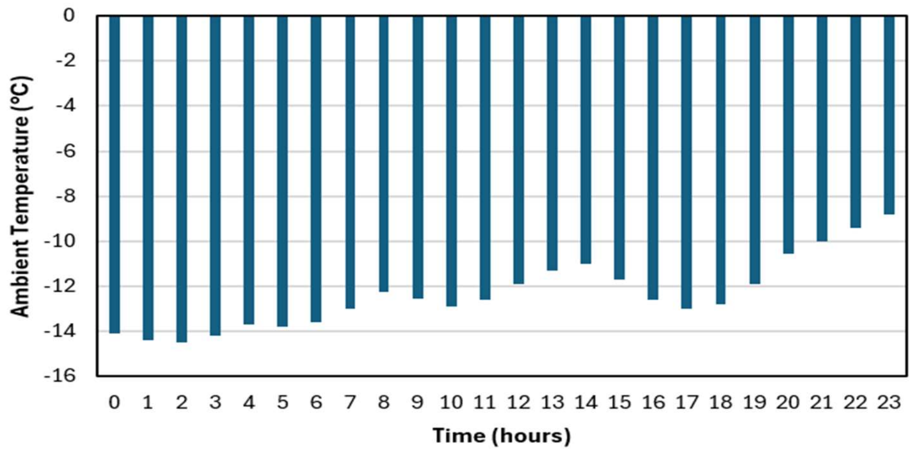


Figure 9: Ambient temperature data of defrosting case

Figure 10 shows the measured defrosting cycle data. The extracted data are plotted for the four dry coolers located on the rooftop of the building. The corresponding bar graphs show the duration of the defrosting cycle, with a minimum duration of 1 minute and a maximum duration of 10 minutes, with different defrosting cycles for the four dry coolers.

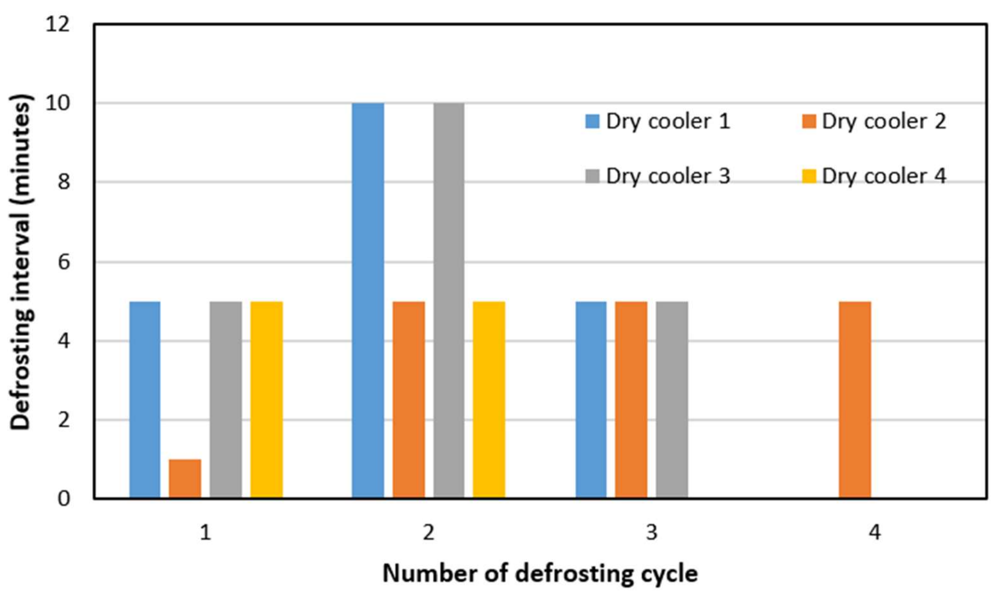


Figure 10: Defrosting cycles of the four outdoor air/glycol heat exchangers

SUMMARY

The novel R290, based on the energy system with a total cooling capacity of 1,8 MW implemented at the Teknobyen office complex, demonstrates a durable and energy-efficient solution for meeting the building's heating and cooling demands. Even though only a small part of the building complex is refurbished and connected to the energy system, these initial part load operation cases indicate that the system can operate during all seasons.

The implemented natural refrigerant-based heat pump chiller unit can deliver high performance and demonstrate that such an energy system can significantly reduce greenhouse gas emissions and eliminate health / environmental threads related to currently applied F-gasses.

Propane is considered to be a favourable option and an alternative to R744 (CO_2). High energy efficiency makes these compact propane systems an economical choice for end-users. The maximum compressor power demand of the selected coldest day was 250 kW, and the maximum recorded coefficient of performance was 2.75 at an ambient temperature of -13.5 °C. The highest recorded coefficient of performance for the hottest day is 5.6 at a power demand of 234 kW.

The end-user is very satisfied with the energy system's performance and primary energy demand and is currently preparing refurbishment projects for other properties to phase out F-gas-based heat pump chillers as soon as possible.

ACKNOWLEDGEMENTS

The authors acknowledge and are grateful to KLP Eiendom for sharing the measured data of the Teknobyen energy system.

NOMENCLATURE

GWP	Global warming potential	IEA	International energy agency
ODP	Ozone depletion Potential	COP	Coefficient of performance
GHG	Greenhouse gases	R290	Propane
R744	Carbon Dioxide	CO_2	Carbon Dioxide

REFERENCES

Abergel, T. (2021). IEA Reports, Heat Pumps. Retrieved from IEA: https://www.iea.org/reports/heat-pumps

Carrillo, D. (2023). Optimising the heating and cooling system at Teknostallen: Master’s thesis in Sustainable Energy Heat Pumping Processes and Systems [Master thesis], Norwegian University of Science and Technology.

Naemi, Sanaz. (2023). Improving the new heating and cooling system with R290 at Teknostallen: Master’s thesis in Sustainable Energy (Energy use in Buildings) [Master thesis], Norwegian University of Science and Technology.

Huber, Karl (2016): R290- Refrigeration System with optimised filling quantity. TK cold with redundant propane system (5).

Corberán, Jose M.; Segurado, Jacobo; Colbourne, Daniel; Gonzálvez, José (2008): Review of standards for using hydrocarbon refrigerants in A/C, Heat pump and refrigeration equipment. In International Journal of Refrigeration 31 (4), pp. 784-756. DOI: 10.1016/j.ijrefrig.2007.12.007

Ghoubali, R., Byrne, P., Bazantay, F., 2017 Refrigerant charge optimisation for propane heat pump water heaters, Int. J. Refrigeration 76, 230–244.