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Integration of heat pumps with natural working fluids into a neighborhood energy system

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ABSTRACT

Combining heat pumps (HP) with other renewables, e.g. solar thermal collectors, photovoltaics and energy storage systems can contribute to the growth of future zero emission societies. This article investigates HP integration for a real case-study system in Norway, which supplies a small neighborhood with energy for heating and cooling. The main components of the case-study system are heat pumps, plate heat exchangers, flat plate solar collectors, water storage tanks and borehole thermal energy storage. Several possibilities for integrating HPs with natural working fluids into the case-study system were evaluated. Dynamic simulations based on the modelling language Modelica were conducted to analyze the performance of the component and system models for thermal energy supply.

Keywords: Heat pumps, Natural working fluids, Integrated energy system, Modelica.

1. INTRODUCTION

Buildings account for a large share of the world's energy use, with a share of around 40% in Europe, (European Union, 2010). Nearly 55% of this energy is used for space heating, domestic hot water (DHW) heating, and space cooling, (International Energy Agency, 2013). Many efforts have been made to reduce the carbon emissions related to these thermal energy demands. Emissions can be reduced by decreasing the demands themselves, e.g. through better building envelopes and/or advanced control strategies, or by delivering the thermal energy at lower carbon costs, e.g. using more efficient energy systems and/or renewable energy sources. The integration of heat pumps (HP) in energy systems have grown to become a key factor for improvement of energy efficiency and reduction of CO_2 emissions.

An integrated heating and cooling system (IHCS) for a small neighborhood in Oslo, Norway was described and analyzed in a previous study, (Rohde, Andresen, & Nord, 2018). A Modelica model was created and dynamic simulations were performed to analyze the system performance. The goal of this study was to replace the current heating/cooling solutions using synthetic refrigerants with new heat pumps using natural refrigerants, such as Ammonia and CO_2. Thus, reducing the heat pump's ozone depletion potential (ODP) and global warming potential (GWP). Furthermore, integration of new heat pumps should be proposed to liberate or reduce the need of district heating (DH) import for DHW heating.

2. SYSTEM DESCRIPTION

2.1. The integrated heating and cooling system

Vulkan is located in Oslo, Norway and was renewed by implementing an IHCS and several types of buildings. Renovation was finished in 2014 and the IHCS supplied heat for a total floor area of 38,500 m^2. Offices, shops, hotels, apartments, food court and an event location were the building types which were covered by the IHCS, as shown in Table 1.

Table 1: Floor area covered by heating/cooling from the IHCS.

Type	Offices	Shops	Hotels	Apartments	Food court	Event location	Total
Floor area [m^2]	15 000	6 650	7 600	3 900	3 500	1 850	38 500

The main components of the integrated heating and cooling system were heat pumps, solar collectors, heat exchangers, storage tanks, ice thermal energy storage (ITES) and borehole thermal energy storage (BTES). A simplified overview of the IHCS is shown in Figure 1. Space- and DHW heating, space cooling, snow melting for walkways between buildings and product cooling for the food court were all provided by the IHCS. The BTES and heat from product cooling and space cooling operated as heating sources for the heat pumps, which provided heat for space heating, DHW pre-heating and snow melting.

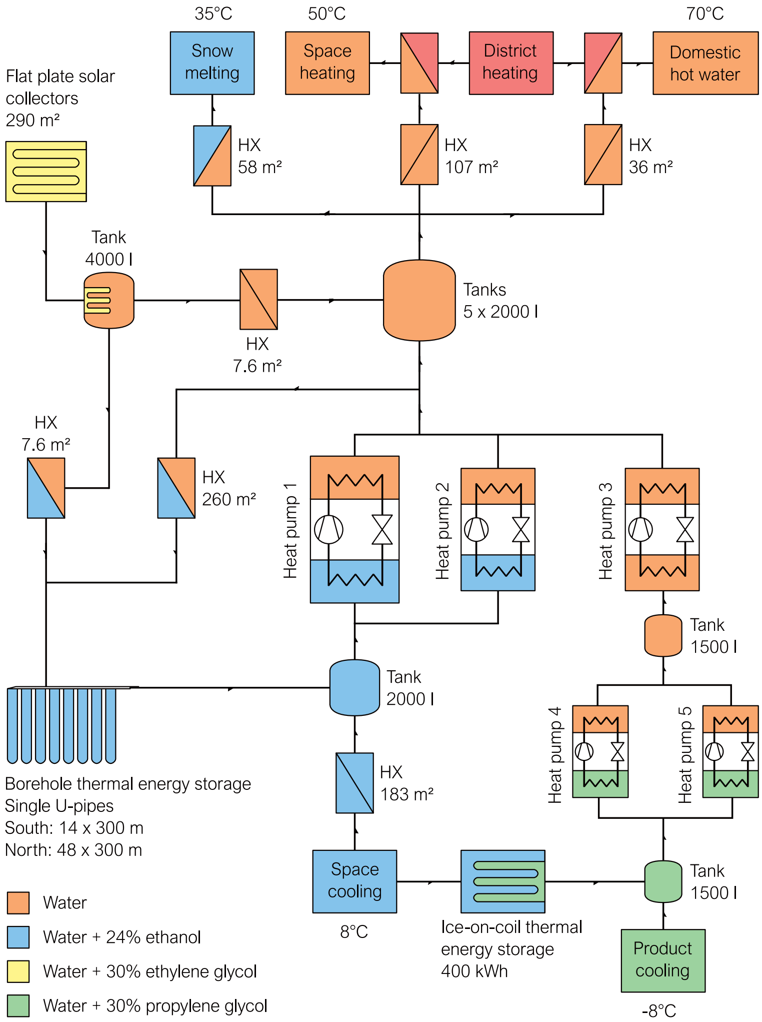

Figure 1: Simplified schematics of the integrated heating and cooling system.

During the cooling season, surplus heat from the cooling systems and solar collectors was sent to the BTES. Thus, the BTES operated as heat source during heating season and as a heat sink during cooling season. In the summer when the demand of space cooling was high, the ITES was used for peak shaving. The IHCS could supply heat at 50-55 °C and was connected to the local DH system, mainly to lift the temperature for DHW heating up to 70 °C which was the set-point. At peak demands the DH system could also work as backup. A basic control system was used for the IHCS. Step-wise control signals were sent to the heat pumps, which could activate or deactivate their compressor stages and parallel circuits. The storage tanks worked as buffers and the temperature in the tanks were used for the step signals. Temperature- or pressure difference set-points were used to control the circulation points.

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2.2. Heating mode

During the heating season the heat supply temperature was equal to the outlet temperature on the condenser side of heat pump 1 and 2 (55 °C). The BTES supplied the evaporator side of heat pump 1 and 2 with a supply temperature of 6 °C. Heat pump specifications are listed in Table 2. Heat from solar collectors was stored in a solar storage tank. Depending on the temperature in the storage tank, heat could be used to feed the heat pumps, or injected back to the BTES. As the ambient temperature and cooling demand increased, the amount of heat extracted from the BTES decreases. This resulted in a temperature increase in the cooling storage tank. If the average temperature in the cooling tank exceeded 10 °C a mode was activated so the system would be able to provide space cooling if needed, Rohde et al. (2018).

Table 2. Specifications for the currently used heat pumps.

	HP 1	HP 2	HP 3	HP 4&5
Type	WSA2802X	WSA1602X	WSA0701X	NXW0600X
Working fluid	R134a	R134a	R134a	R410a
Compressor	Screw (2)	Screw (2)	Screw	Scroll
Design data (evaporator/condenser)				
Temperatures [°C]	0/50	0/50	20/55	-8/25
Capacities [kW]	473/652	264/365	224/283	87/119
COP [-]	3.64	3.61	4.8	4.78

2.3. Cooling mode

The outlet temperature on the condenser side of heat pump 1 and 2 was reduced to 51 °C as setpoint during cooling mode, which was controlled by a BTES pump. On the evaporator side, the temperature was equivalent to the space cooling temperature (6 °C). During the cooling season the BTES was charged by the solar collector, the ITES was used at daytime to reduce peak loads and was charged at nighttime by heat pump 4. Increasing heat demands, causes a reduction in storage tank temperature. Similar to the heating system, a mode was activated when the average storage tank temperature was lower than 47 °C to secure heat demand coverage.

3. METHODS

3.1. New heat pumps using natural refrigerants

Environmental impacts from working fluids used in the past combined with new restrictions have put more attention on the natural refrigerants water, ammonia, CO_2 and hydrocarbons. Ammonia was found to be the best suited working fluid for HP 1*-6 and CO_2 for HP 7. The selected heat pumps for this study are shown in Table 3. An asterisk in the name indicates that the heat pump will replace an existing heat pump.

Table 3: Specifications for the suggested heat pumps with natural working fluids.

	HP 1*	HP 2*	HP 3*	HP 4&5*	HP 6	HP 7
Type	GEA RedAstrum LL	GEA RedAstrum HH		GEA BluAstrum 400	GEA RedAstrum HE	TVVP80
Working fluid	R717	R717		R717	R717	R744
Compressor	Screw	Screw		Screw	Screw	
Design data (evaporator/condenser)						
Temperatures [°C]	6/65	6/65	6/65	-8/25	35/70	6/70
Capacities [kW]	650/890	560/770	560/770	246/306	760/1000	118
COP [-]	5.85	5.75	5.75	4.6	3.85	7.2

The theoretical Lorentz cycle was used as basis for the heat pump model. The Lorentz cycle could be compared to the Carnot cycle. However, the heat sink and heat source are not assumed to be isothermal. In a Lorentz cycle they have a finite heat capacity. This results in a temperature change during heat release/extraction,

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(Zehnder, 2004). This was the case for the fluid flows in the IHCS. Thus, the Lorentz COP (COP_L) was based on the outlet and inlet temperatures on the secondary sides, which were used to define the Lorentz temperature (T_L) for both the evaporator and condenser. Eq. 1 and Eq. 2. from (Rohde, Andresen, & Nord, 2018) was used to calculate and find COP_L and T_L. A manufacturer database was used to extract part load performance for the five new heat pumps which could replace the current heat pumps. An existing heat pump model created in previous work was used as baseline and was further extended to deliver a varying Lorentz efficiency (η_L) based on the part load data. Further, the Lorentz efficiency was used to calculate the heat pump's COP (COP_{HP}) as shown in Eq. 3. (Rohde, Andresen, & Nord, 2018).

3.2. Scenarios created for simulation

Three different case scenarios have been created, while the base case scenario from the existing system was also included. In Scenario 1 the five heat pumps from the base scenario were replaced with the new ”greener” heat pumps using natural working fluids. For the second scenario a ”booster” heat pump was integrated into the system to lift the DHW temperature even further and in the third scenario a heat pump using CO_2 as refrigerant was used instead of the heat exchangers currently used, see Figure 1. The results were examined and compared with each other to find the best solution for the IHCS. The base scenario represents the currently used IHCS at Vulkan without any changes. The base case was included to compare the results from the other three scenarios to find potential improvements or deterioration of the system performance. The currently used system is dependent on DH import to achieve high enough DHW temperatures.

Table 4: Overview of the simulated scenarios.

	Scenario information	Heat pumps	DHW heating
Base scenario	Current system	See Table 2	Heat exchangers & DH import
Scenario 1	Replacing HPs with new “green” HPs	See Table 3 (HP 1*-5*)	Heat exchangers & DH import
Scenario 2	Replacing HPs with new “green” HPs and HP 6 for DHW temperature lift	See Table 3 (HP 1*-5* & HP 6)	Heat exchangers & HP 6
Scenario 3	Replacing HPs with new “green” HPs and HP 7 for DHW heating	See Table 3 (HP 1*-5* & HP 7)	HP 7

In Scenario 1, the five heat pumps from the base scenario were replaced with new heat pumps using natural refrigerants. The details of the new heat pumps are shown in Table 3. The capacities and temperature ranges were set to be as identical as possible to the currently used heat pumps. The main reason of simulating this scenario was to establish if the system could perform at the same level as the existing IHCS system. However, the IHCS would still be reliant on DH import.

Scenario 2 builds on Scenario 1 by adding an additional new heat pump. The current system only provides heat at temperatures up to 50-55 °C. Therefore, DH import is necessary to achieve the DHW set-point temperature at 70 °C. The main reason to integrate a new heat pump is thus to reduce the dependency of the DH import for DHW heating. HP 6 should be able to provide heat at temperatures exceeding 70 °C independently, by using heat at 30-40 °C.

In the last scenario the use of heat exchangers and DH import should be eliminated for DHW heating, by integrating another heat pump, HP 7. HP 7 should be able to singlehandedly deliver heat at temperatures above 70 °C, by using heat from the BTES. Thus, HP 7 should use the heating loop at temperatures around 50 °C as heat source to achieve a temperature lift from 10 °C to 70 °C on the condenser side.

3.3. KPIs for system performance evaluation

Two COP-values COP_{system} and $COP_{system+storage}$ defined in the previous study were used to measure and evaluate the IHCS performance. COP_{system} was the ratio of delivered heating and cooling to the total electricity use of the IHCS system. $COP_{system+storage}$ was similar to COP_{system}, but it included the annual heat balance of the BTES. The annual heat balance of the system was the difference between heat injected and heat extracted from the BTES. The calculation of the two COPs can be found in Eq. 3 and 4 in (Rohde, Andresen, & Nord, 2018).

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4. RESULTS AND DISCUSSION

This chapter displays the results from the analysis performed for each case scenario. The base case scenario is analyzed first since it is used as basis for the other three scenarios. For the first scenario, the results are primarily compared with the base scenario to establish if the new heat pumps using natural refrigerants can perform as well as the heat pumps using synthetic refrigerants. Results from the second and third case scenarios focus on reduced DH import dependency by integrating new heat pumps into the existing DHW heating system.

4.1. Annual electricity use of the system

Figure 2 displays the total accumulated annual electricity use for each scenario, which includes the electricity use of all the heat pumps, the circulation pumps used in the IHCS and the constant use found in the previous study. The electricity use per individual heat pump for the different scenarios are also shown in Figure 2. Scenario 1 proved to be slightly less electricity consuming than the base case scenario, with an energy reduction of 26 MWh. The energy reduction was mainly because of the new HP 1*&2*, while HP 3* proved to be more energy consuming and HP 4&5* were in total a bit more efficient than in the base case. Scenario 3 was found to be the most electricity consuming, with a total accumulated electricity use of 1455 MWh. However, the total DH import was reduced from 572 MWh from the base case and Scenario 1 to 0 MWh in both Scenario 2 and 3, which explains the increased electricity use.

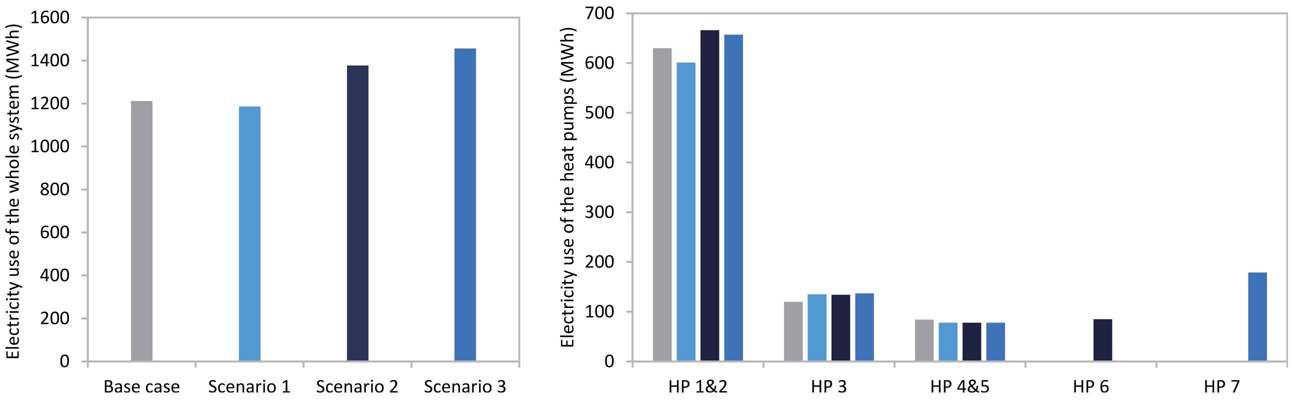

Figure 2: Accumulated annual electricity use for each scenario (left) and individual electricity use per heat pump (right).

4.2. Annual energy results

The overall results from the simulations are shown in Table 5. The results show that the heat pumps using natural refrigerants from Scenario 1 were able to provide equivalent amount of heating and cooling as in the base case scenario. However, the annual heat balance of the BTES was found to be lower in Scenario 1 compared with the base case, meaning that more energy from the BTES was extracted. This could further explain the lower total IHCS electricity use in the same scenario. The delivered cooling was constant for all the four scenarios since the case study was focused on the DHW heating. In Scenario 2 and 3 with the integration of the new heat pumps, HP 6 and HP 7 the amount of heating delivered increased with approximately 570 MWh compared to the base case, which is equivalent to the DH import from the base scenario. The annual heat balance of the BTES decreased drastically, as expected due to the increased BTES heat extraction. However, the “booster” HP 6 from Scenario 3 was found to have the biggest impact on the BTES, ending the annual heat balance at -919 MWh. Furthermore, the electricity uses for Scenario 2 and 3 also increased compared to the base case, because of the integration of new heat pumps using electricity for compressor work.

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Table 5: Results of the simulated scenarios.

	Base scenario	Scenario 1	Scenario 2	Scenario 3
Cooling delivered [MWh]	1583	1583	1583	1583
Heating delivered [MWh]	2985	2985	3557	3556
BTES heat balance [MWh]	-467	-495	-919	-830
Electricity use [MWh]	1212	1186	1375	1455
DH import [MWh]	572	572	0	0
COP_{system}	**3.77**	**3.85**	**3.74**	**3.53**
$COP_{system+storage}$	**3.38**	**3.43**	**3.07**	**2.96**

4.3. System performance

For the base scenario, COP_{system} and $COP_{system+storage}$ were found to be 3.77 and 3.38, respectively. However, the "green" heat pumps replacing the existing heat pumps in Scenario 1 were able to achieve an increase in system performance, as shown in Table 5. Suggesting that heat pumps using natural working fluids can outperform the existing heat pumps using non-natural refrigerants and increase the IHCS COPs. The system performance excluding the BTES in Scenario 2 was almost identical to the base case. The $COP_{system+storage}$ on the other hand experienced a decrease, because of the increased BTES heat extraction. Likewise, in Scenario 3 which had the lowest system performance of all the scenarios. The $COP_{system+storage}$ is the most important performance value when comparing the scenarios.

5. CONCLUSIONS

Dynamic models created in Modelica were successfully used to modify and suggest expansions of the existing integrated heating and cooling system in Oslo, Norway. Scenario 1 was found to give the best system performances and results from simulations proved that heat pumps using natural refrigerants can perform at the same rate as HPs using synthetic refrigerants. Due to the rapid evolution of new and more efficient "green" HPs, they should be considered instead of HPs using synthetic refrigerants for future energy systems. R744 and R717 were found to be the best fitting refrigerants for the case scenarios. R717 was well suited for medium- to high temperature lifts and R744 for low- to high temperature lifts. Integration of new HPs to replace DH import was found to be not sustainable due to the increased amount of heat extracted from the BTES. However, increasing the number of solar collectors for more heat injection to the BTES could be a solution to maintain an equivalent system performance as the base case.

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