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THEORETICAL EVALUATION OF DISTRICT HEATING AND COOLING NETWORKS CONNECTED TO HEAT PUMPS

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Abstract: *This article conducts a comprehensive theoretical analysis containing operational, carbon footprint, and economic aspects of a medium-high temperature heat pump (HP) employing R-1234ze(E). The study contains a total of three scenarios, where the first (single stage/two stage (SS/TSC)) scenario uses waste heat for district heating. The second (SS/TSC) scenario produces heating and cooling for district heating and cooling. The third (TSC) scenario uses heat from the district heating network (DHN) for conventional boiler applications. Regarding the energy analysis, the internal heat exchanger (IHX) presents a positive impact across all scenarios. Moreover, the TSC configuration exhibits a lower coefficient of performance (COP) than SS for scenario 1, and higher for scenario 2. The first scenario (SS) results in the highest COP (4.1), due to presenting the lowest compression ratio among the three scenarios. From a carbon footprint perspective, compared to a natural gas boiler, the first scenario achieves the highest reduction in emissions. Regarding the economic analysis, TSC configurations exhibit higher costs than SS ones. The first (SS) and second (SS) scenarios present the lowest capital expenditure (CAPEX), 35134 € and 44371 €, respectively. Economic viability analysis reveals that only the first and second scenarios with SS configuration are feasible.*

Keywords: sustainable cities, vapor compression, low GWP, carbon footprint analysis, energy performance.

1. INTRODUCTION

District heating and cooling (DHC) technology has been acknowledged as a viable solution to reduce primary energy consumption due to its capacity of the decarbonization heating and cooling sector using renewable energies, the same as local emissions, allowing the use of local resources. Therefore, this system adapts to the heating and cooling requirements of buildings. [1]. The fundamental operation of DHC consists of a centralized building (generation system) that, through a network pipeline (distribution system), provides heating for domestic hot water (DHW), process heating (PH), and space heating (SH) (consumption system), there are a total of five generations of this technology, being the focus in the 4G that operate within a range of temperatures of 35-70 ºC and the 5G with range of 10-35 ºC [2]. Additionally, it offers cooling for space cooling (SC) and process cooling (PC). The thermal fluid circulating inside the pipeline is water.

A few papers have investigated district heating and cooling networks with heating and cooling production methods and connected to different consumptions under several assumptions. Also, they compared the emissions to conventional natural gas boilers, such as [3]. The sustainability of the district heating network (DHN) and district cooling network (DCN) can be improved by connecting high-efficiency electrically driven heat pumps that can be optimized for different scenarios. This way, these scenarios need to be explored and compared, depending on the generation, the type of integration of the heat pumps, their configuration, and the fluid refrigerant to be used.

The paper aims to explore and compare various scenarios of integrating heat pumps into DHC networks, assessing their operational, carbon footprint, and economic feasibility. It proposes a comprehensive analysis of three distinct scenarios, considering different applications of heat pumps in DHC, aiming to promote higher energy efficiency, lower carbon footprint, and greater economic feasibility. Furthermore, it seeks to advance research integrating heat pumps into DHC networks. It provides insights into potential replacements for conventional boilers and less efficient heating systems, particularly in decarbonizing heating and cooling infrastructure.

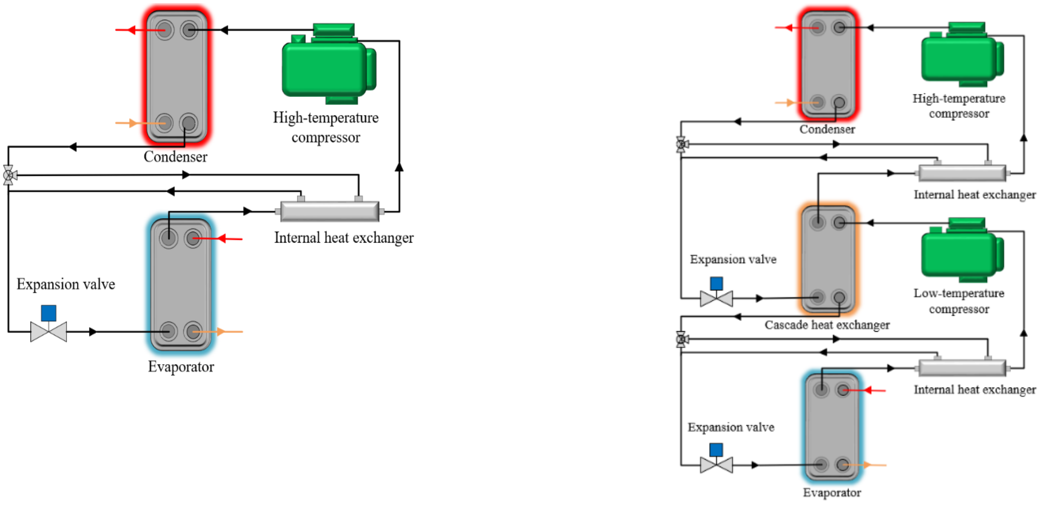
2. SYSTEM DESCRIPTION

2.1. Research scenarios

For this study, the single-stage (SS) cycle and two stage cascade (TSC), both with an internal heat exchanger (IHX), will be considered; in the SS configuration, the main components are the evaporator, the condenser, the compressor, and the expansion valve. In the TSC configuration, the main components are the evaporator, the condenser, two compressors, two expansion valves, and a cascade heat exchanger (CHX). Figure 1a) shows the scheme of the heat pumps for SS, and Figure 1b) for TSC. There will be three primary scenarios of integrating heat pumps (HPs) into the DHC systems.

The first scenario consists of cooling dissipation water (30 ºC of the evaporating point) and heat supply to 4G DHN (80ºC of the condensing point); the temperature conditions were established considering the waste heat temperature and the 4G DHN range temperatures. The second scenario is the Simultaneous production of heating for DHN (65 ºC for condensing point) and cooling for DCN 4G (2 ºC for evaporating point); in this case, the temperature conditions were established to supply simultaneous heating and cooling for DHC 4G considering its temperatures range. The third scenario process is heating production (conventional boiler substitute) sourced from DHN 5G, as the temperature range of the 5G is low; in this case, the HP boosts the temperature for the final supply, which means the evaporating temperature is 10ºC due to the range of the 5G network. The condensing temperature is 90 ºC to supply heat instead of the boiler, respectively. The first and second scenarios will be assessed using SS and TSC configurations to study and compare their operational results. However, the third scenario will only be tested with the TSC configuration due to its high-pressure ratio.

R-1234ze(E) has been chosen as the primary working fluid for the three scenarios due to its favorable thermodynamic and safety properties, particularly in DHN. Additionally, its potential in HPs as an alternative to conventional boilers is notable. For TSC, in this case, the working fluid for the high-temperature circuit is R-1234ze(E), and for the low-temperature circuit, R-1234yf.



a) b)

Figure 1. Scheme of SS and TSC configuration.

3. METHODOLOGY AND MODELLING

The system modeling strategy, assumptions, and boundary conditions are presented in this section.

3.1. System modeling

Refrigerant specifications, boundary conditions, and assumptions will be input parameters in the Engineering Equation Solver (EES) [4]This software contains all the necessary equations to simulate the thermodynamic cycle. Once the output parameters are obtained, a commercial component will be chosen for each constituent of the cycle. The results obtained for each component guide the criteria for selecting commercial components.

3.2. Calculation method and compressor modeling

The calculation methodology of the operational parameters, such as coefficient of performance (COP) and compressor efficiency, is based on manufacturer data. [5]. The simulation is made using the manufacturer's software. The conditions of each scenario are applied to the software to obtain the operational parameters of each scenario and develop the paper. To calculate the COP, the load at the condenser is set at 100 kW for each scenario. Consequently, the COP depends directly on compressor power consumption.

3.3 Assumptions and boundary conditions

Two parameters, evaporating and condensing temperatures, are primarily employed to simulate the operating conditions. Additionally, the following boundary conditions are considered: (i) Neglecting pressure losses in the pipes and internal components of the circuit. (ii) Ignoring heat losses from the system compared to other energy changes. (iii) Assuming isenthalpic flow through the expansion valve in the compression cycle. (iv) The actual power consumption of the compressors is determined based on the data provided by the manufacturer, specifying the condensation, evaporation, subcooling, and superheat conditions of each scenario [6]. The superheating and subcooling degrees considered are 10 and 5 K, respectively. The cascade heat exchanger temperature difference is 5 K.

4. RESULTS AND DISCUSSION

This section contains three analyses. Firstly, an operational analysis will be conducted on the three scenarios, comparing their COP and examining the influence of the IHX. Secondly, a carbon footprint analysis will be performed utilizing the Total Equivalent Warming Impact (TEWI) (Eq(1)) to compare heat pump emissions with those of conventional boilers. This analysis aims to provide observations into the environmental implications of adopting heat pumps compared to traditional boiler systems. Finally, an economic analysis will be executed to compare the feasibility of HP with conventional boilers. This economic evaluation aims to comprehensively understand the economic viability of using heat pumps instead of traditional boiler systems.

$$TEWI = GWP\, m\, L_a\, n + GWP\, m\, (1-\alpha) + (E_a\, \beta\, n) \qquad (1)$$

4.1. Operational analysis

Figure 2 illustrates a comparison between scenarios with and without an IHX. Scenario 1 SS exhibits the highest COP among the six scenarios. This outcome is attributed to scenario 1 having the smallest difference between the condensing and evaporating temperatures compared to the other scenarios, signifying a lower power demand for the compressor. Additionally, the IHX impacts positively across all scenarios.

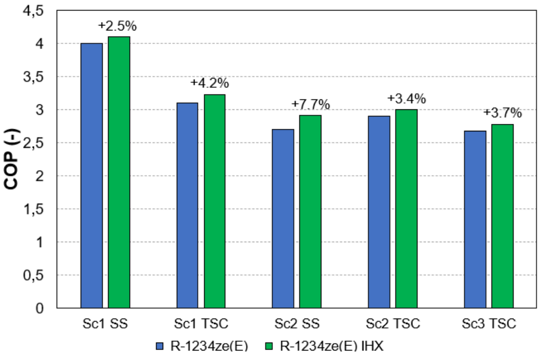


Figure 2. COP comparative with and without IHX.

4.2 Carbon footprint analysis

To compare scenarios and conventional boilers. In the case of HPs, the TEWI method will be used to obtain the tCO_2e generated by the HPs for a 15-year life cycle. In the case of the boiler, a boiler within the range of application of the HPs is selected; therefore, the efficiency for each scenario will be selected based on the curve given by the manufacturer; consequently, the efficiencies are 92% for scenarios 1 and 3 and 94% for scenario 2, then the emission factor of the natural gas will be considered to obtain the tCO_2e of the boiler, and also the life cycle is 15-year for the boiler. The investigation will be conducted in Spain, specifically in Valencia. Valencia was selected as the study location to represent one of the three European climates, specifically the warmer climate. Figure 3 shows the carbon footprint comparison. As scenario 2 is for simultaneous heating and cooling production, it will also be compared with the chiller. This chiller was developed considering scenario 2 conditions and Valencia's climate data. Therefore, in Figure 3, the emissions of the chiller will be added to those of the boiler for scenario 2. As observed in Figure 3, all scenarios represent a significant emission reduction compared to the boiler or boiler plus chiller for scenario 2.

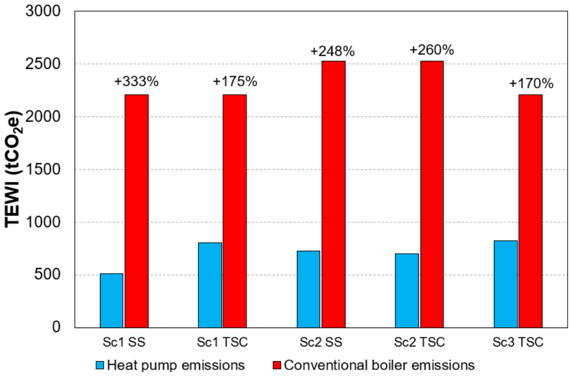
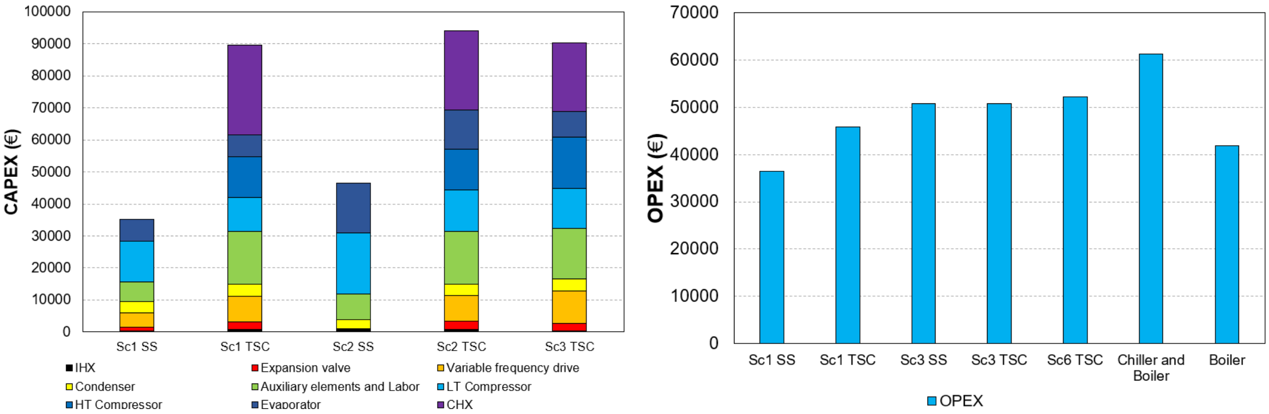


Figure 3. Emission comparative between HP and conventional boiler and chiller.

4.1. Economic analysis

In this section, an economic analysis of the HPs for all three scenarios, each with its distinct configurations, will be done in Spain. The HP and boiler are compared, and in scenario 2, a chiller is also compared. The economic evaluation of the HPs is divided into capital expenditure (CAPEX) and operating expenditure (OPEX). Figure 4a) shows the CAPEX, and Figure 4b) shows the OPEX. The CAPEX represents the cost of each component of the HPs and boiler and labor for its construction, whereas the OPEX represents the operating cost of the HPs and boiler. The economic analysis is done considering the 15-year life cycle. Therefore, for HPs, the electricity price for band IB (range power of the HP) in Spain and the boiler, as well as the price of natural gas, is considered band I2 (range power of the boiler).



a) b)

Figure 4. CAPEX and OPEX of the scenarios.

As can be observed in Figure 4a), the TSC's CAPEX surpasses the SS due to its additional components. Scenario 1 achieves the lowest CAPEX. Regarding the OPEX, scenario 1 also achieves the lowest cost, as observed in Figure 4b).

4.2. Global analysis

Table 1 comprehensively summarizes the operational, carbon footprint, and economic analyses. Scenario 1 is the most promising of the three. It presents the highest COP, the lowest emissions, and a favorable PBP indicator. Eq (2) shows the calculation of the PBP; for this case, the boiler and chillers' CAPEX is zero because it's assumed to exist already.

$$PBP = \frac{CAPEX_{HP} - CAPEX_{boiler/chiller}}{OPEX_{boiler/chiller} - OPEX_{HP}} \tag{2}$$

Table 1. Summary of the analysis results for each scenario.

Scenario	Configuration	COP (-)	Emissions in Spain (tCO_2e)	PBP (years)
Scenario 1	SS	4.11	517.47	4.70
	TSC	3.28	648.57	-
Scenario 2	SS	2.95	719.82	3.67
	TSC	3.07	693.52	-
Scenario 3	TSC	2.87	740.36	-

5. CONCLUSION

In summary, the paper shows that scenario 1 is a viable solution for industrial processes in district heating, and scenario 2 is a viable solution for the simultaneous production of heat and cooling for district heating and cooling networks. All scenarios are viable environmentally and economically compared to natural gas boilers (except 6 in the economic case). The role of HPs in the DHC networks is crucial to achieve higher energy efficiency and reduce the environmental impact, especially in the building, as those networks allow the integration of renewable energy. Therefore, combining the HPs with DHC that use renewable energies reduces the dependency on fossil fuels and improves the sustainability of the networks. Additionally, this combination is cost-effective over time, and the HPs help balance the energy load in DHC networks.

This paper is limited to a theoretical simulation using manufacturer data and boundary conditions considered. In practice, conditions may differ from simulated results. In practical applications, factors such as compressor efficiency, pressure drop, heat transfer to the surroundings, and operational limitations can introduce differences that are not fully captured in theoretical models. Consequently, the scenarios considered in this paper will be experimented with a prototype heat pump for future work.

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