Performance assessment of a R290 air-to-water heat pump for the HVAC system retrofit in an academic building through numerical simulation validated with monitored data

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Abstract

Propane is expected to be the most widespread refrigerant in the next generation of heat pumps due to its very low GWP value and optimal thermo-physical properties, which guarantee a wide operational range. In this paper, a new reversible Air-to-Water Heat Pump (AWHP) utilizing R290 as the refrigerant and having a rated heating capacity of approximately 60 kW is presented. The main features of the AWHP are discussed in detail, emphasizing the technical characteristics of the heat pump components and the unit performance as a function of the operating conditions. In order to assess the effective performance of the AWHP on a seasonal basis, an academic building located in Forlì (North of Italy) was considered. The HVAC system was based on condensing gas boilers and a conventional air-to-water chiller. The building was renewed during the spring of 2024 by installing two units of the AWHP mentioned before. Each unit is equipped with a datalogger, which enables the real-time monitoring of the HVAC system and heat pumps performance (i.e., heating/cooling capacity, absorbed power input, inlet/outlet water temperature). In this work, numerical models of the building, coupled to both the baseline and the retrofitted HVAC system, were developed. First, the building energy model was calibrated with thermal and electrical energy bills collected every month. Then, the potentially achievable energy savings by adopting the propane heat pumps were assessed through numerical simulations. The results show that the non-renewable primary energy demand of the HVAC system can be reduced strongly, up to 60%, with the refurbished system. Results also indicate that the heat pump performance is significantly influenced by the terminal unit typology.

Keywords: Air-to-water heat pump; R290; On-site monitoring; Seasonal energy performance; Energy retrofit

1. Introduction

Nowadays, the transition to energy and environmental sustainability is a challenging task for global society. Within this framework, air conditioning, refrigeration, and heat pump systems contribute significantly to global energy consumption and, therefore, greenhouse gas emissions. In recent years, these systems accounted for around 14% of worldwide CO_2 emissions, making that sector an important driver of global warming [1]. Air-Source Heat Pumps (ASHPs) are a suitable technology for reducing energy demand and environmental impact related to climate control in residential and non-residential buildings. ASHPs can meet the energy demand linked to all energy services (i.e., space heating, space cooling and Domestic Hot Water (DHW) production) required by a building with a single device. Moreover, this kind of system can deploy a significant share of renewable energy from the aerothermal source with high thermodynamic efficiency [2]. Finally, the installation

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costs of ASHPs are comparable to those of other conventional systems, and the availability of the external heat source (i.e., ambient air) is substantial, making this solution attractive in most cases [3].

However, the energy performance of heat pumps and air conditioning systems is considerably influenced by the refrigerant used as working fluid. Thermodynamic and thermophysical properties (e.g., latent heat of evaporation/condensation, heat transfer coefficients, density, and specific heat), flammability and toxicity, environmental impact, cost, and availability are key elements for ranking refrigerants and selecting the best fluid for a given application [4].

Unfortunately, the working fluids most commonly deployed in ASHPs dedicated to climate control and DHW production in buildings are harmful to the environment. More in detail, hydrofluorocarbons (HFCs) are characterized by high Global Warming Potential (GWP) values. For instance, R410A and R134a, the most widely used working fluids for conventional heat pumps, have a GWP value of 2088 and 1430, respectively.

Therefore, to reduce the carbon footprint of the air conditioning, refrigeration, and heat pump sector, the European Union (EU) implemented a series of actions with Regulation N° 517/2014 [5], aiming at a gradual reduction of the consumption of HFCs and other fluorinated refrigerants until 2030. Furthermore, the EU has recently replaced the aforementioned Regulation with the new Regulation 2024/573 [6]. The law strengthens the previous targets by pointing to achieve “net-zero” emissions from this sector in the next decades. This target will be reached with the complete phase-out of the allowable supply of HFCs by 2050. Additionally, new marketing restrictions were established for the placement of refrigerating and air conditioning equipment on the market. For example, starting in 2030, new monoblock heat pumps must contain refrigerants with a GWP value lower than 150.

Within this framework, manufacturers and academic researchers need to identify the next generation of working fluids for heat pumps and air conditioning units. Among the others, propane (R290) is one of the most suitable fluids for replacing HFCs in HVAC systems. Propane is an environmentally-friendly natural refrigerant, causing no impact on the ozone layer (Ozone Depletion Potential, ODP, equal to 0) and having a very low GWP value (equal to 3), making R290 the most promising working fluid for the following years. Table 1 summarizes the main thermo-physical properties of propane. Furthermore, R290 exhibits favourable thermodynamic properties, such as no temperature glide, high latent heat of vaporization, and low viscosity, which result in the efficient operation of heat pumps and air conditioning systems, as well as a reduction in indirect greenhouse gas emissions [8].

Table 1. Main thermo-physical properties of R290 [7]

Chemical formula	Boiling point (°C)	Critical temperature (°C)	Critical pressure (bar)	Latent heat of vaporization (kJ/kg)
$CH_3CH_2CH_3$	-42.12 (at 1.013 bar)	96.7	42.51	374.9 (at 0°C)

Despite the aforementioned optimal characteristics, the primary challenge in boosting the diffusion of propane in commercial units is its high flammability. The R290 safety level is categorized as A3 due to several factors: flammability range between 2.1% and 9.5%, very low values of ignition energy and auto-ignition temperature (equal to 0.25 mJ and 10°C, respectively), and a maximum flame speed of approximately 45 cm/s [9].

Several recent studies have focused on propane-based heat pumps and water heaters in residential and non-residential buildings, examining this topic in depth. Nawaz et al. [10] compared the performance of natural refrigerants, such as propane and isobutane (R600a), to replace R134a in heat pump water heaters using a numerical model validated against experimental data. Both fluids proved to be efficient alternatives to R134a, but R290 demonstrated to be the best drop-in replacement refrigerant. More recently, Tang et al. [11] optimized the components of a new AWHP based on R290 to reduce the refrigerant charge. Particular effort was made to investigate the risk after a leakage, measuring the propane concentration within the heat pump and in its surroundings under different scenarios. The experimental results showed that an explosive environment appears only inside the heat pump and in the region immediately surrounding the unit on the ground. Byrne and Ghoubali [12] developed a prototype of an air-source heat pump capable of simultaneously meeting heating and cooling energy demands for large buildings, using propane as the working fluid. Experimental tests were carried out in a climate chamber according to the European Standard EN 14511, yielding Coefficient of Performance (*COP*) values ranging from 2.50 to 3.00 in heating mode. A review paper by Zou et al. [13] reported the most recent studies on R290-based AWHPs for replacing high-GWP refrigerants in water heater systems. Several works detailed in that review article demonstrate that a significant enhancement in the heat pump COP can be achieved, and values of the outlet water temperature up to 80°C can be reached thanks to the use of propane.

In this paper, a reversible Air-to-Water Heat Pump (AWHP) using propane as the refrigerant is presented. In order to evaluate the unit effective energy performance on a seasonal basis, the HVAC system of an academic building located in northern Italy was renewed during the spring of 2024 by installing two of the aforementioned heat pumps. Numerical models of the building, coupled to both the baseline and the retrofitted HVAC system, were developed and calibrated with monitored data. The potential energy and environmental savings achievable with the propane AWHPs were then assessed through numerical simulations.

2. Methodology

2.1. Description of the building

In this work, a building owned by the University of Bologna, located in Forlì (Northern Italy), was considered as an application case study. The facility houses the headquarters of the Department of Industrial Engineering at the Forlì Campus, and comprises two distinct sections. A historic complex, built in 1920, houses mainly faculty offices, a virtual laboratory, and a computer lab. A modern building, constructed in 1998, includes large classrooms and offices. Both sections feature two storeys and large windows, with a total area of 462 m². The facility total net floor area and gross heated volume are approximately equal to 2767 m² and 13472 m³, respectively. The building surface-to-volume ratio (i.e., the ratio between the dispersing surface and the gross heated volume) is 0.46 m⁻¹, a value typical of compact and energy-efficient structures.

However, the opaque elements of the building envelope are poorly insulated. In particular, the historic section features a load-bearing structure made of solid bricks and a pitched roof constructed from brick-cement slabs. On the other hand, the more recent section of the complex is characterized by better thermal performance. Its envelope features a vertical load-bearing face-reinforced concrete structure, internal brick and prestressed concrete floors, and a roof structure of glulam beams with an overlying reinforced concrete slab. The values of the average thermal transmittance of the envelope components are summarized in Table 2 and compared to the actual limits stated in the current Italian Regulation for new buildings [14]. Reported data indicate that, on average, the U-value of each envelope component is not compliant with the required limits; therefore, the building exhibits low energy performance.

Table 2. Average thermal transmittance of the building envelope components and actual limits for new buildings.

Envelope component	Average transmittance (W/m^2K)	Transmittance limit for new buildings (W/m^2K)
External walls	1.24	0.29
Floors	1.17	0.26
Roofs	0.86	0.29
Windows	2.67	1.80

The heating energy demand of the entire complex is met by two conventional natural gas boilers with a nominal heating capacity of 290 kW and 230 kW, respectively, which are significantly oversized compared to the building peak load. During the cooling season, an air-to-water vapor-compression chiller is used to meet the building cooling energy demand. The rated cooling capacity and Energy Efficiency Ratio (EER) are approximately 170 kW and 2.58, respectively, for the following source/sink temperature values: 7°C (i.e., cold water temperature) and 35°C (i.e., ambient air temperature). The terminal units of the HVAC system are primarily fan coils, with some radiators located in bathrooms. The energy demand for DHW production is low and is provided by single electric boilers with a total electric capacity of 7.2 kW. An air handling unit ensures the air renewal in the largest classrooms.

2.2. Building simulation model and calibration of thermal and electric energy consumption


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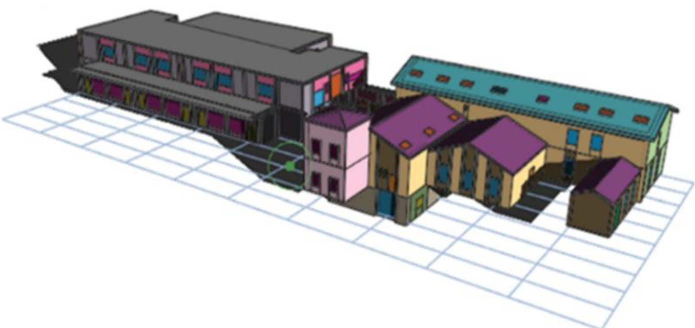
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Figure 1. Picture of the facility (a) and 3D model of the buildings implemented within EC 700 software (b).

The energy simulation model of the building and HVAC system was implemented using the Edilclima EC 700 software [15] following an accurate energy audit. Fig. 1 shows a picture of the facility, featuring both historic and modern buildings, as well as the 3D model of the complex developed using EC 700 software.

Table 3. Natural gas and electric energy consumption data for 2018 and 2019.

Month	Electric energy (kWh)		Natural gas (Sm^3)	
	2018	2019	2018	2019
January	9410	9573	5.738	7.708
February	8677	8061	5.587	4.295
March	10095	8656	5.021	2.613
April	8976	7281	1.984	2.477
May	11483	8085	-	-
June	14114	10443	-	-
July	16086	15857	-	-
August	10315	8948	-	-
September	12258	10779	-	-
October	10346	9663	-	-
November	9898	9734	3.728	4.247
December	9374	9206	4.406	5.441
Total	131032	116286	26465	26781

The facility electric energy and natural gas consumptions were collected from the monthly energy bills. In order to analyze reliable statistics, consumption data from the pre-pandemic years of 2018 and 2019 were selected to calibrate the energy simulation model. Table 3 presents the facility electric energy and natural gas requirements. The reported data highlight that the building average electric energy consumption was approximately 124 MWh per year. Moreover, the average annual natural gas demand was almost equal to 26.600 Sm^3. In order to normalize the gas consumption with respect to the severity of the heating season, Heating Degree Days (HDDs) for the years 2018 and 2019 were calculated using the Dext3r database [16].

In order to calibrate the energy simulation model, the effective operation of the HVAC system was taken into account. In particular, the heating system operates for 12 hours per day, from Monday to Friday, during the winter, while it is switched off on weekends. Moreover, adjustments were made to the internal set point temperature value, which was decreased from 20°C to 19°C according to an in-situ survey. Facility closing periods due to national holidays (e.g., Christmas period) were also simulated in the model.

Figure 2 compares the building energy signature calculated using the calibrated energy simulation model (black dashed curve) with the actual natural gas consumption of the years 2018 and 2019 (red and blue dots, respectively).

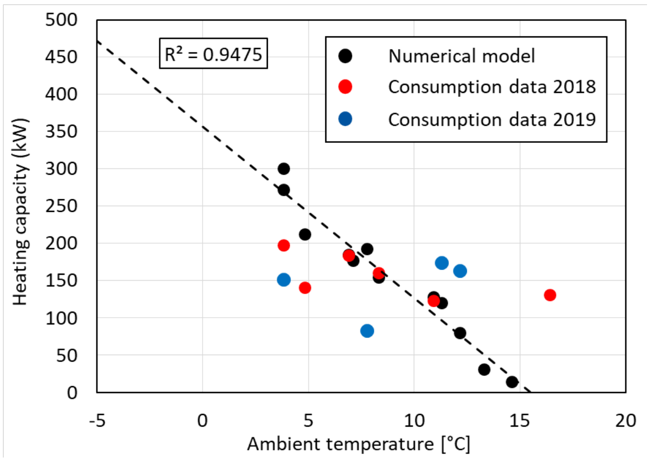

Figure 2. Comparison of the building energy signatures assessed from natural gas consumption for the years 2018 and 2019, and calculated with the energy simulation model.

The comparison between the numerical model results and the natural gas consumption data reveals a significant deviation in correspondence with the winter holidays (December) and the extremes of the heating season (October and April, which are the months characterized by the highest values of the ambient temperature). However, the calibrated energy simulation model overestimates the natural gas consumption by only 1% on a seasonal basis.

Regarding the validation of the electric energy demand calculated using the numerical model, the effective consumption of electrical devices is required. The electric energy absorbed by equipment in offices, laboratories and classrooms was calculated assuming an average electric power of the installed devices equal to 7.5 W/m^2 [17]. After the numerical model calibration, the deviation in the annual electric energy consumption with respect to the bills data is below 4%.

2.3. Description of the R290 air-to-water heat pump

A reversible AWHP using R290 as refrigerant was considered for the refurbishment of the building HVAC system. The heat pump presented in this paper is based on a variable-speed scroll compressor, specifically designed for propane, and is coupled to an inverter. Compared to compressors of equivalent units using synthetic refrigerants, such as HFCs, this device is slightly larger due to propane lower density, which requires a higher rotational speed to guarantee the same heating capacity (for a fixed displacement). The compressor electric motor operates between 1800 and 8400 rpm, with a maximum speed limit at nominal working conditions to enhance the overall efficiency. An Electronic Expansion Valve (EEV) driven by a stepper motor is used to control the heat pump operation over a wide range of working conditions, ensured by the valve S-shaped characteristic.

Four brushless direct current fans enable precise control of the refrigerant evaporation/condensation temperature within the finned-tube heat exchanger on the air-source side of the unit. The fans rotational speed can be adjusted continuously, ensuring the optimal air mass flow rate for all operating conditions. Additionally, a variable-speed motor is also installed on the circulating pump on the water side of the unit. Due to the deployment of the ambient air and the HVAC system water as heat source/sink, respectively, two different heat exchangers are installed in the heat pump. On the user side, a stainless steel micro-plate heat exchanger operates as the evaporator/condenser during the cooling/heating season, respectively. Thanks to this technology, the refrigerant charge can be reduced by approximately 20% compared to traditional brazed plate heat exchangers while maintaining a similar efficiency. On the external source/sink side, a finned-tube exchanger featuring three rows of copper tubes with a reduced diameter of 8 mm is used. Corrugated aluminium fins treated with a hydrophobic coating to facilitate the rejection of water droplets are used to increase the overall heat transfer area. As a result of the aforementioned features, the propane charge in the heat pump is significantly lower than the limit specified in the UNI EN 378-1 standard [18] for units located outdoors with supervised access (i.e., 5 kg).

Fig. 3 illustrates the AWHP operating envelope in heating mode, comparing it with the typical envelope of an equivalent conventional heat pump using R410A as the refrigerant. It is essential to emphasize that the R290 heat pump envelope is significantly larger than that of a traditional AWHP, indicating a broader range of working conditions that can be satisfied. For instance, the R290 unit can produce hot water at 80°C across a wide range of ambient air temperatures, extending from -5°C to 30°C. Moreover, the heat pump can supply hot water at 60°C even at low ambient temperatures, down to -20°C. Therefore, the propane-based heat pump presented in this paper is a suitable solution for retrofitting high-temperature HVAC systems.

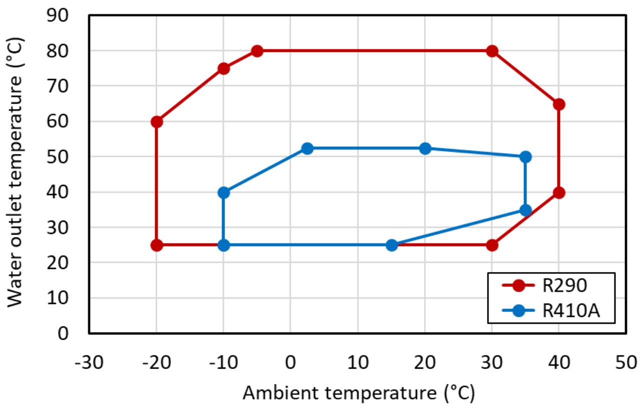

Figure 3. Operating envelopes of the propane heat pump and a conventional R410A-based heat pump in heating mode.

Fig. 4 and 5 depict the heat pump characteristic curves in heating and cooling modes, respectively, as functions of ambient air temperature and load conditions (i.e., 25%, 60%, 100%). The reported performance curves are based on manufacturer data, which were validated with experimental measurements conducted in the producer's climatic chamber. More in detail, Fig. 4 reports the heat pump heating capacity and *COP* considering inlet and outlet water temperatures equal to 40°C and 45°C, respectively. On the other hand, the heat pump cooling capacity and *EER* for inlet and outlet water temperatures of 12°C and 7°C, respectively, are shown in Fig. 5.

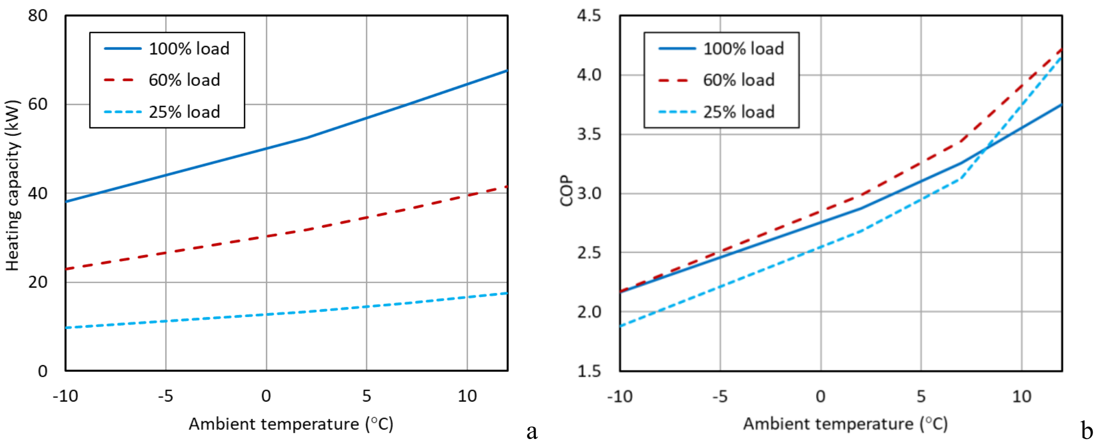

Figure 4. Trends of the R290 heat pump heating capacity (a) and *COP* (b) as functions of the ambient air temperature at full and partial load conditions.

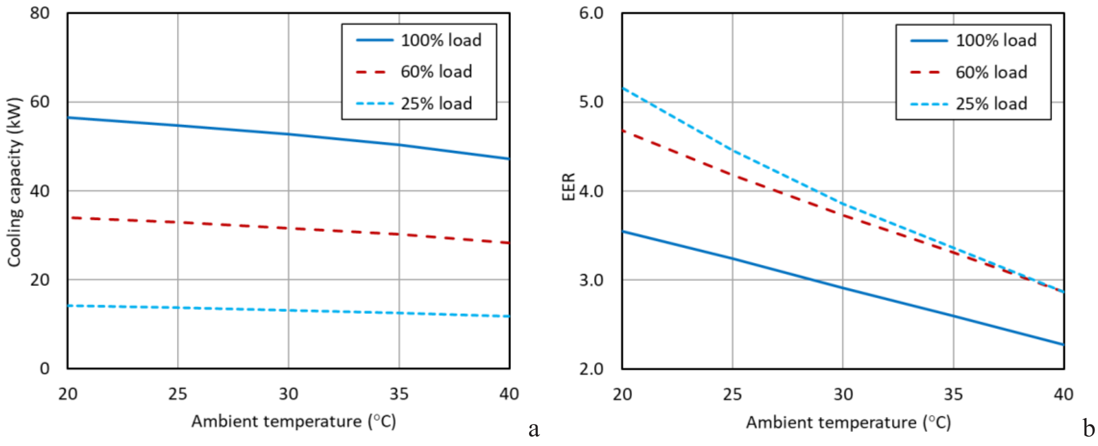

Figure 5. Trends of the R290 heat pump cooling capacity (a) and *EER* (b) as functions of the ambient air temperature at full and partial load conditions.

2.4. Analyzed scenarios

The calibrated energy simulation model was used to evaluate the seasonal energy performance of the heat pump during the heating season. Several scenarios were considered to simulate the refurbishment of both the building envelope and the HVAC system at different levels. Table 4 summarizes the scenarios analyzed in this study.

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Table 4. Features of the considered scenarios.

Scenario	Building envelope	Terminal units	Heat generator	PV system
Baseline	Actual	Actual	Natural gas boilers	No
A1	Actual	Fan coils	Propane heat pump	No
A2	Actual	Fan coils	Propane heat pump	Yes
A3	Refurbished	Fan coils	Propane heat pump	No
B1	Actual	High-temperature radiators	Propane heat pump	No
B2	Actual	High-temperature radiators	Propane heat pump	Yes
B3	Refurbished	High-temperature radiators	Propane heat pump	No

The “Baseline” scenario simulated the performance of the actual building envelope and HVAC system. In all other scenarios, the facility heating/cooling energy demands were met by the propane AWHP described previously. Since the heat pump heating capacity is significantly lower than the building peak load, the unit characteristic curves were appropriately scaled in each analyzed case to meet the building energy demand without requiring backup systems. More specifically, the heat pump heating capacity was increased according to the building heating peak load, while the *COP* curves remained unchanged.

Different terminal units were simulated in scenarios “A” and “B”. In configurations “A”, low-temperature emitters, such as hydronic fan coils, were considered. For scenario “B”, high-temperature terminal units, i.e., radiators, were simulated to evaluate the heat pump performance coupled with this kind of emitter.

For both configurations “A” and “B”, three sub-scenarios were analyzed:

- Case “1”: actual building envelope components (i.e., no renovation of the envelope);
- Case “2”: actual building envelope components and inclusion of a PV field with a peak power equal to 66 kW. The PV system size was determined according to the available installation area on the complex roofs;
- Case “3”: complete renovation of the building envelope. The thermal transmittance limit values for new buildings, as specified in the current Italian regulation (see Table 2), were imposed for each component of the building envelope.

3. Results and discussion

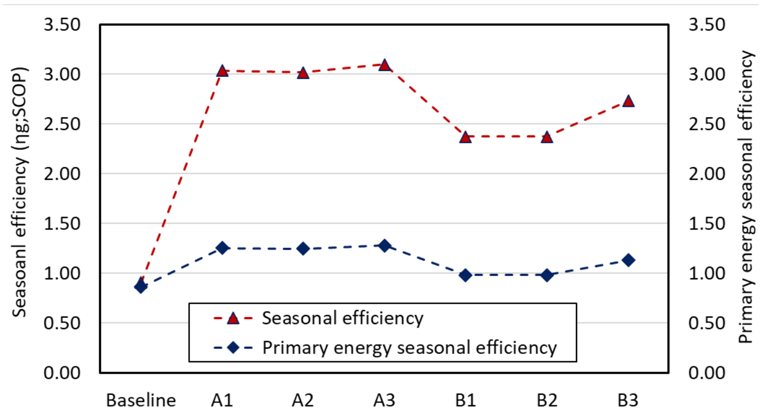

Figure 6. Seasonal energy performance figures of the HVAC system for all considered scenarios.

In Fig. 6, the seasonal performance figures of the HVAC system are reported for all simulated scenarios. Two Key Performance Indicators (KPIs) were calculated. The system seasonal efficiency is defined as the ratio between the useful thermal energy supplied to the emission subsystem and the energy input of the heat generator (i.e., natural gas for the Baseline and electric energy for the other configurations) during the heating season. It is worth mentioning that for scenarios “A” and “B”, this KPI corresponds to the heat Seasonal Coefficient of Performance (*SCOP*). More in detail, the heat pump *SCOP* was calculated using the methodology described in the Italian Standard UNI/TS 11300-4 [19]. That procedure is based on the bin method, following the same approach outlined in the European standard EN 14825, but considering the specific climatic data of the location where the heat pump is installed (i.e., Forlì). In order to compare the seasonal energy performance of all scenarios, the primary energy seasonal efficiency was introduced. It is calculated as the ratio between the useful thermal energy supplied to the emission subsystem and the total primary energy input of the heating system. The primary energy conversion factors for natural gas and electric energy from the national grid, as defined by the current Italian regulation [20], are 1.05 and 2.42, respectively.

The results indicate that the boiler seasonal efficiency for the baseline scenario is 0.91. On the other hand, the heat pump *SCOP* is significantly influenced by the terminal unit typology. More specifically, the best seasonal efficiency is achieved in scenarios A1-A3, with *SCOP* values exceeding 3. Conversely, the lowest energy performance is obtained for scenarios B1 and B2, with the heat pump seasonal efficiency of 2.37. Moreover, numerical results point out that the primary energy seasonal efficiency of configurations based on the heat pump is higher than that achieved in the baseline scenario. Due to the higher heat pump efficiency, the system primary energy seasonal performance factor can be improved by up to 50% if the R290 heat pump is considered as the heat generator.

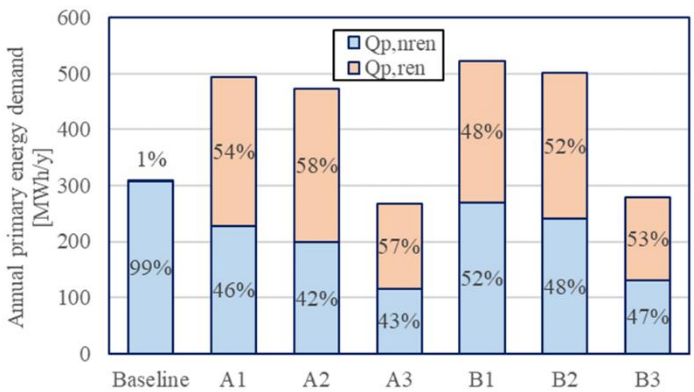

Figure 7. Annual non-renewable, renewable and total primary energy demand of the HVAC system for the simulated scenarios.

In Fig. 7, the annual non-renewable, renewable, and total primary energy consumption of the HVAC system is illustrated. It is worth mentioning that the Italian renewable and non-renewable primary energy conversion factors for electricity taken from the national grid were considered to assess the heat pump performance in scenarios “A” and “B”. More specifically, the current Italian regulation sets the before-mentioned parameters equal to 0.47 and 1.95, respectively.

The reported data indicate that the Baseline scenario presents a total primary energy demand of approximately 310 MWh per year. This value is lower than in the other analyzed configurations, where the total primary energy is significantly higher, except for the scenarios “A3” and “B3”. That increase depends on the fact that with the heat pump, the energy vector consumed changes from natural gas to electric energy. Nevertheless, in Italy, the energy label of a building depends on the non-renewable primary energy demand. In that case, the non-renewable primary energy consumption is lower in all configurations based on the heat pump than in the Baseline scenario. Consequently, an increase in the renewable quote is assessed, which, among the scenarios, assumes values ranging from 48% (case B1) to 58% (case A2) of the total primary energy demand.

Finally, it is essential to emphasize that the propane heat pump can fully meet the building thermal energy demand, even in cases where the envelope is non-insulated and high-temperature emitters, such as radiators, are used (B1 case).

4. Conclusions

This paper presents a comprehensive study on the potential energy savings linked to the refurbishment of the HVAC system of an academic complex located in Forlì (Northern Italy) with a new air-to-water electrical heat pump using R290 (propane) as working fluid. The numerical model of the facility was implemented in the Edilclima EC 700 software and calibrated using the effective energy consumption data from 2018 and 2019. Different scenarios, characterized by low- and high-temperature emitters, the renovation of building envelope components, and the installation of a PV field, were considered.

The results highlight how non-renewable primary energy consumption is significantly reduced by adopting a propane AWHP with respect to the baseline scenario (based on conventional gas boilers), with a substantial increase in the renewable quote. The renewable energy quote in scenario A2 (where the propane heat pump is coupled to low-temperature terminal units and a photovoltaic system) reached 58% of the total primary energy demand, demonstrating a substantial increase in the deployment of renewable energy. Moreover, the system seasonal energy performance factor, referred to the primary energy, can be enhanced by up to 46% if the heat pump is considered as heat generator.

In conclusion, the transition to R290-based heat pumps in HVAC systems can be considered a promising solution to enhancing energy efficiency and environmental sustainability, while ensuring economic viability.

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