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Potential of Energy Saving of Propane Heat Pump as replacement of gas boilers with low and high temperature emitters

Corrado Camponeschi[1], *Maurizio* Goni[1], *Francesca* Cioffi[1], *Matteo* Dongellini[1*], *Claudia* Naldi[1], *Gian Luca* Morini[1], *Luca* Germano[2], *Filippo* Genovese[2], *Andrea* Cervellati[2], *Alessandro* Casolari[2], *Federico* Corsaro[3], *Matteo* Ciancamerla[3], and *Luca* Ballotta[3]

[1]Department of Industrial Engineering, University of Bologna, Viale del Risorgimento 2, 40136, Bologna, Italy
[2]Galletti S.p.A., via L. Romagnoli 12/a, 40010, Bentivoglio, Italy
[3]Danfoss S.r.l., Corso Tazzoli 221, 10137, Torino, Italy

Abstract. This work deals with the analysis of the energy performance and the environmental impact of a Heating, Ventilation and Air Conditioning (HVAC) system based on an innovative Air-to-Water electrical Heat Pump (AWHP) using propane (R290) as the refrigerant. A building of the University of Bologna located in Forlì (North of Italy) is considered for replacing a condensing gas boiler and a conventional chiller with an AWHP using R290. To evaluate the efficiency of the existing heating system and the potential savings linked to the adoption of the propane AWHP, the building energy model was created and calibrated by collecting monthly thermal and electrical consumptions as a function of the actual climate data. In this paper, the main features of the R290-based AWHP are described in detail by emphasising the device performance as a function of the operating conditions (i.e., air and water temperature and speed of the scroll compressor). A series of scenarios have been studied to evaluate the energy performance of the propane AWHP with respect to the reference scenario under various operating conditions. The results show that while the total primary energy demand increases adopting the propane AWHP with respect to the case of a gas boiler, the non-renewable primary energy fraction decreases significantly, with a dramatic increase in the renewable quote. From an economic point of view, lower annual costs are obtained by adopting a propane AWHP coupled to fan coils, mainly when the electrical heat pump is used in a thermally insulated building in which a photovoltaic system is installed.

Keywords: Air-source Heat Pumps, R290 (Propane), Global Warming Potential, Energy Efficiency, Environmental Impact

* Corresponding author: matteo.dongellini@unibo.it

1 Introduction

Nowadays, energy and environmental transition are challenging tasks for the global society. Within this frame, air conditioning, refrigerating, and heat pump systems contribute significantly to global energy consumption and greenhouse gas emissions: about 8% of the total CO2 emissions are related to this sector [1]. Air-source heat pumps (ASHPs) are suitable solutions to reduce the energy demand and the environmental impact related to the climatisation of residential and non-residential buildings. ASHPs can satisfy all energy services (i.e., space heating, space cooling and Domestic Hot Water (DHW) production) required by the coupled building with a single device and can exploit a significant share of renewable energy from aerothermal, geothermal or hydrothermal sources with high thermodynamic efficiency [2].

The performance of heat pumps and air conditioning systems is considerably influenced by the thermo-physical properties of the working fluids. Thermodynamic properties (e.g., latent heat of vaporisation, heat transfer coefficients, density…), toxicity, flammability, environmental impact, cost and availability are crucial to ranking refrigerants and defining the best fluids [3].

Unfortunately, the refrigerants deployed currently in commercial ASHPs are harmful to the environment. In particular, R410A and R134a, the most widespread working fluids for conventional heat pumps, are hydrofluorocarbons (HFCs) characterised by a high Global Warming Potential (GWP) value, equal to 2088 and 1430, respectively. Therefore, in 2016, more than 170 countries agreed on the Kigali Amendment of the Montreal Protocol [4] to phase down HFCs in the upcoming decades.

Before the Kigali Amendment, the European Union (EU) implemented similar actions with Regulation N° 517/2014 [5-6], which introduced a gradual reduction of the consumption of fluorinated refrigerants until 2030. The EU recently reached a provisional agreement to strengthen the existing targets by pointing to the complete phase-out of HFCs before 2050. Additionally, new marketing prohibitions will be set for the refrigerating equipment. From 2030, new products must contain refrigerants with a GWP value lower than 150.

This scenario forces heat pump manufacturers to outline the next generation of environmentally friendly refrigerants. The natural refrigerant R290 (propane) is expected to be one of the most promising and competitive candidates for replacing HFCs. The optimal environmental characteristics of R290, such as no impact on the ozone layer (ODP, Ozone Depletion Potential, equal to 0) and a very low GWP value (equal to 3), have attracted the attention of researchers and manufacturers (see Table 1). Even though propane has good thermodynamic properties, its high flammability is still challenging for manufacturers [7]. Therefore, many studies about using R290 in heat pumps have been published in the last few years.

Some recent works focused on adopting R290 in heat pump water heaters, i.e., heat pumps for DHW production. For instance, Nawaz et al. [8] compared the performance of R290 and R600a (isobutane) to replace R134a in heat pump water heaters using a component-based model calibrated against experimental data. Both fluids proved to be valid alternatives, but R290 demonstrated to be more convenient as a drop-in-replacement refrigerant, whilst R600a showed performance similar to R290, only with an increased compressor size to provide the same heating capacity.

Tang et al. [7] tried to optimise the devices of a prototype air-to-water heat pump to reduce the charge of R290. The Energy Efficiency Ratio (EER) and Coefficient Of Performance (COP) values obtained experimentally reached 2,80 and 3,27 in the rated refrigerating and heating conditions, respectively. The authors investigated the risk after an R290 leakage, measuring the R290 concentration distribution in the heat pump's surrounding and internal areas in different scenarios. Their results show that the explosive zone appears inside the heat pump during the leakage, but in the outside area, it only appears in the region around the heat pump close to the ground.

Table 1. Main properties of R290 (propane).

Chemical formula	$GWP_{100years}$ [$kg_{eq}CO_2\ kg^{-1}$]	ODP	Lower flammable limit [% volume]	Upper flammable limit [% volume]	Auto-ignition temperature [°C]
$CH_3CH_2CH_3$	3	0	0,29	2,2	10

2 Materials and methods

2.1 Building data

The subject of this study is a building of the University of Bologna located in Forlì, North of Italy, which serves as the headquarters for the Department of Industrial Engineering and General Administration at the Forlì Campus. This complex comprises two distinct sections: a historical building constructed in 1920, housing mainly faculty offices, a virtual laboratory, and a computer lab, and a modern building erected in 1998, which includes large classrooms and offices. Figure 1 shows a 3D model of the building developed using Edilclima EC 700 software [9]. The building's total net floor area is approximately 2767 m², and the gross heated volume is 13472 m³, with a surface-to-volume ratio (S/V) of 0,46 m⁻¹. Lastly, the total window area is equal to 462 m².

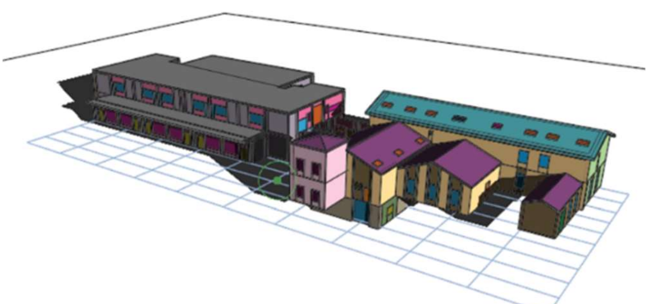

Fig. 1. Building 3D model.

The historical building's opaque elements are poorly insulated. Its structure comprises load-bearing solid bricks and a pitched roof in brick-cement slabs. In contrast, the newer building boasts adequately insulated envelopes. It 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, formworked with prepainted corrugated metal sheets. The main thermal characteristics of the building complex object of study are summarised in Table 2.

The mean transmittance of each component is not compliant with the required values indicated by the current regulation of the Emilia Romagna region [10], listed in Table 2 as ULst.

Table 2. Average U-value of the main building envelope components.

Envelope component	Average U-value [W m-2 K-1]	ULst [W m^{-2} K^{-1}]
External wall	1.24	0.29
Floor	1.17	0.26
Roof	0.86	0.29
Windows	2.67	1.80

The heating system serves the entire complex using two conventional gas boilers with a nominal thermal power of 290 kW and 230 kW, respectively, oversized compared to the thermal demand of the building. An air-to-water electrical chiller is used as cooling unit for a total installed cooling power of about 170 kW (EER 2.58 A35/W7). The air conditioning emitters are mainly fan coils with some radiators in bathrooms. Domestic hot water is provided by electric boilers installed in the bathrooms with a total capacity of 7,2 kW. A mechanical ventilation system ensures air exchange in the largest classrooms.

2.2 Model calibration

A complete energy model of the building was built with EC 700 after an accurate energy audit, in which all the consumption centres of the site were selected. Electricity and natural gas consumption were derived from monthly energy bills. For reference, consumption data from the pre-pandemic years of 2018-2019 were selected for the energy model calibration; the years after 2020 are considered non-significant because, after the pandemic period, the building has been less used. After all, teaching activities were shifted to another location. Table 3 presents the energy consumption derived from the billing audit for 2018 and 2019. It is possible to observe how the building's average yearly electricity consumption was about 124 MWh/year. The average annual natural gas consumption was approximately 26.600 Sm^3 due to space heating.
Thermal consumption during the heating season was de-seasonalized using heating degree days (HDD in Table 3) from the Dext3r [11].

Table 3. Consumption data for 2018-2019 and heating degree days.

	Natural gas [Sm^3]		Electric energy [kWh]	
	2018	2019	2018	2019
Total	26.465	26.781	131.032	116.286
January	5.738	7.708	9.410	9.573
February	5.587	4.295	8.677	8.061
March	5.021	2.613	10.095	8.656
April	1.984	2.477	8.976	7.281
May	-	-	11.483	8.085
June	-	-	14.114	10.443
July	-	-	16.086	15.857
August	-	-	10.315	8.948
September	-	-	12.258	10.779
October	-	-	10.346	9.663
November	3.728	4.247	9.898	9.734
December	4.406	5.441	9.374	9.206
HDD	2.060	1.861	-	-

For the thermal model's calibration, the actual heating operation of the building was considered, maintaining the heating system operational for 12 hours a day from Monday to Friday and off on weekends. Adjustments were made to the winter internal set point temperature value (19 °C). Closing periods due to national holidays (e.g., during the Christmas period) were also simulated in the numerical model.
Figure 2 compares the theoretical energy signature (black dashed curve, black dots) and the data derived by the actual gas consumption (red dots 2018 and blue dots 2019).

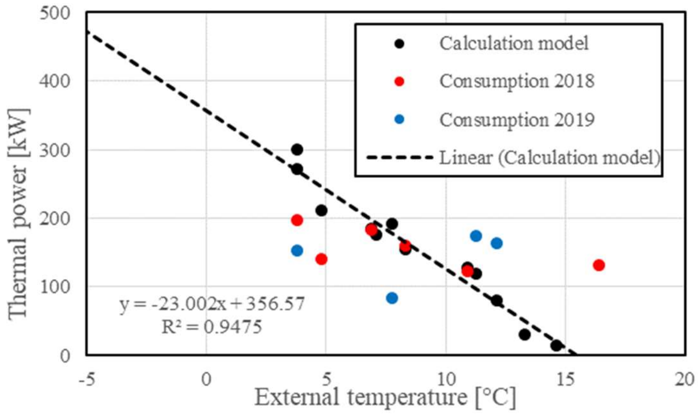

Fig. 2. Comparison of the calculated energy signature (black dashed curve, black dots) and actual gas consumption (red dots 2018 and blue dots 2019).

The comparison between the theoretical energy signature and the points derived by the actual consumption shows a deviation between the effective and the theoretical consumptions, especially in December (winter holidays), October and April (starting and ending of the heating season). However, the standard energy model overestimates natural gas consumption by only 1% after calibration. At the same time, the calibration of the electrical model required assessing the consumption of electrical devices, which is not considered in the energy model in agreement with the standard UNI TS 11300 [12-15]. The energy consumed by electronic devices in offices, laboratories, classrooms, and study halls was calculated assuming an average installed power of 7,5 W m^{-2}. After calibration, the model's estimation of annual electricity consumption compared with bills evidenced an overestimation of 3,4%.
The calibrated complete energy model was used for subsequent modelling of different scenarios described in the following sections.

2.3 The Air-to-Water Heat Pump

The reversible air-to-water heat pump using R290 (propane) as refrigerant considered for the refurbishment of the existing HVAC system is a prototype developed by the manufacturer Galletti utilising a series of components from the other manufacturer Danfoss. Due to the flammability of propane, the prototype is ATEX-certified. Figure 3 shows the air-to-water heat pump (AWHP) operating envelope in heating mode; the same figure compares the typical operating envelope of a conventional heat pump using R410A as refrigerant. It is possible to appreciate how the R290 unit's envelope is significantly larger than that of a conventional AWHP, indicating a broader range of operational conditions that can be satisfied using R290 regarding outlet water temperature. For instance, the R290 unit can produce hot water at 80 °C in a wider range of outdoor conditions by guaranteeing values higher than 60 °C even at low values of the ambient temperature (e.g., -20 °C).

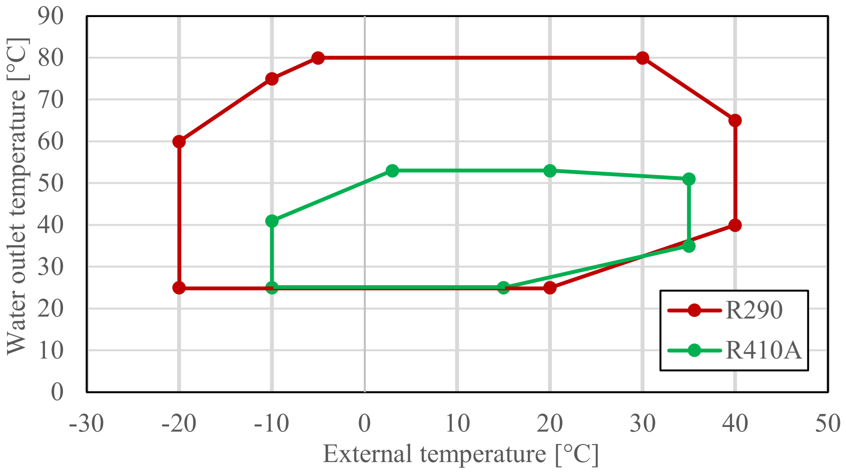

Fig. 3. Operating envelope of the R290 heat pump in heating mode (red line) compared to a traditional R410A-based heat pump envelope (blue line).

A key feature of the heat pump presented in this paper is its variable-speed scroll compressor, designed explicitly for propane use. Compared to equivalent models using synthetic refrigerants, this compressor is slightly larger because of propane's lower density, requiring it to rotate at a higher speed. Therefore, additional soundproof insulation is needed to mitigate noise. The inverter, tailored for this application, operates between 1800 and 8400 rpm, with a maximum speed limit at nominal working conditions to enhance the overall efficiency. The pump uses an electric expansion valve (EEV) driven by a stepper motor to control fluid flow over a wide range. The EEV is designed with a high maximum operative pressure difference (MOPD) to accommodate the broad operating envelope of the R290 compressor. The valve's bi-flow model and S-shaped characteristic ensure compatibility across all working conditions.

The prototype includes four brushless direct current (EC) fans, enabling precise control over the evaporation/condensation temperature. These fans' rotational speeds are continuously adjustable, ensuring optimal air mass flow rates for various operational conditions. Additionally, a variable-speed motor, controlled by another inverter, is installed on the water side of the heat pump. This setup allows modulation of the water flow rate on the user's side, maintaining a consistent temperature difference and improving seasonal energy efficiency.

The prototype features two distinct heat exchangers operating as condenser or evaporator. The user side's heat exchanger handles water and refrigerant and is a stainless steel micro-plate model. This micro-plate technology reduces the refrigerant charge by approximately 20% compared to traditional brazed plate heat exchangers while maintaining a similar efficiency. As a result, the total propane charge in this unit is significantly lower than the limit specified in the UNI EN 378-1 [16] standard for machines located outdoors with supervised access.

On the air side, the heat exchanger is divided into two parallel circuits, each featuring three-row corrugated aluminium copper tubes of 8 mm diameter. These tubes are fitted with corrugated fins treated with a hydrophobic coating, facilitating easy rejection of condensing water droplets when operating in heat pump mode.

Figures 4a and 4b) depict the unit's energy performance trends in heating mode, demonstrating how thermal power and Coefficient of Performance (*COP*) vary with different operating conditions, such as ambient air temperature, water outlet temperature, part load factor (25%, 60%, 100%), maintaining a fixed water temperature difference (ΔT = 5 K, inlet and outlet water temperature (T_{win} and T_{wout}, respectively) equal to 40 and 45°C. Figure 4a reports the heating capacity, while Figure 4b details the *COP*.

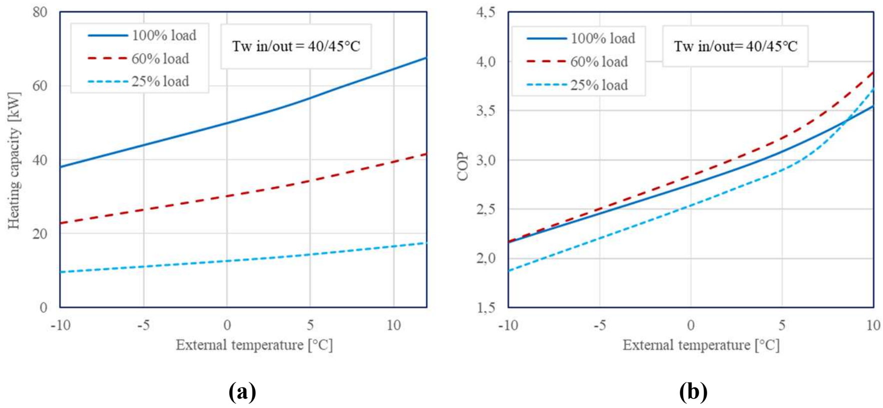

Fig. 4. Trends of the heat pump heating capacity (a) and *COP* (b) as functions of the external air temperature and load conditions.

Figures 5a and 5b present the characteristic curves of the AWHP's energy performance in heating mode, showing variations in thermal power and *COP* under different operating conditions such as water outlet temperature, load, and ambient conditions (outdoor air temperature and relative humidity equal to 7 °C and 87%, respectively). Figure 5a reports the heating capacity, while Figure 5b details the *COP*.

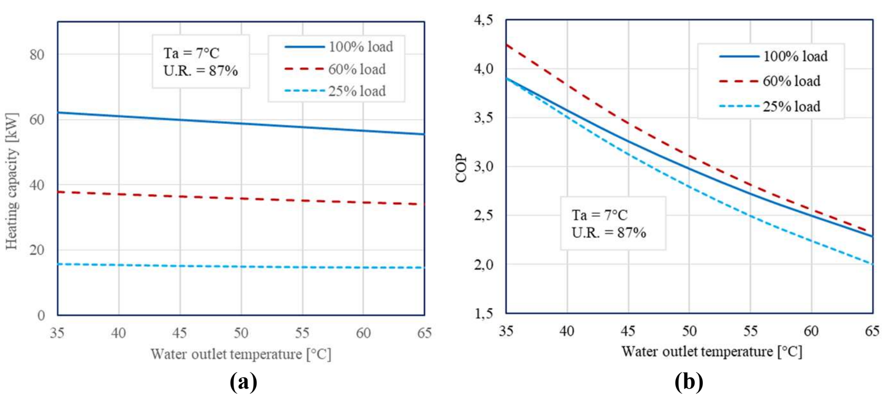

Fig. 5. Trends of the heat pump heating capacity (a) and *COP* (b) as functions of water outlet temperature and load conditions.

3 Results and discussion

3.1 Scenarios analysed

To evaluate the behaviour of the prototype described in the previous section, various scenarios were analysed using the software EC 700, summarised in Table 4.
The “Baseline” scenario represents the actual building, plant and use situation. In all other scenarios, the space heating/cooling heat generator is the propane air-to-water heat pump described in Section 2. The prototype was appropriately sized in each case analysed using

the energy signature method to cover the building's total energy demand without backup systems. The heat pump sizing was carried out considering a continuous heating profile.
Scenarios “A” and “B” are different due to the considered emission subsystem: for scenario “A”, fan coils are considered as low-temperature emitters. For scenario “B”, the emitters are radiators to evaluate the heat pump performance coupled with high-temperature terminal units.
For both project scenarios, three sub-cases are analysed:

- “1”: scenario considering the actual building envelope;
- “2”: scenario considering the actual building envelope and the presence of a 66 kWp photovoltaic system (sized according to the available installation area) serving all electrical uses of the building;
- “3”: scenario considering an energy refurbishment of the building envelope components imposing the U-values associated with the reference building following the current regulation DGR. n.1275/2015 [10] (ULst in Table 2).

The climate data used in all energy models are derived from the standard UNI 10349-1:2016 [17].

Table 4. Description of the scenarios analysed.

Scenario	Building	Emitters	Heat generator	Heating capacity [kW]	Heating profile	Photovoltaic system
Baseline	Real	Real	Real	520	Real	No
A1	Real	Fan coils	Galletti HP R290	371 (A7/W35)	24/7	No
A2	Real	Fan coils	Galletti HP R290	371 (A7/W35)	24/7	Yes
A3	Reference building	Fan coils	Galletti HP R290	248 (A7/W35)	24/7	No
B1	Real	Radiators	Galletti HP R290	320 (A7/W65)	24/7	No
B2	Real	Radiators	Galletti HP R290	320 (A7/W65)	24/7	Yes
B3	Reference building	Radiators	Galletti HP R290	248 (A7/W35)	24/7	No

It is essential to highlight that for the modelling of the heat pump performance in the case of high-temperature emitters (“B1” and “B2” cases), the analytical calculation of declared performance is not in agreement with UNI/TS 11300-4 [15], but according to a simplified method proposed by the software EC 700. This introduces an approximation in the model, but it turns out to be the best solution for defining the *COP* and the useful thermal and absorbed electrical power for very high values of the water outlet temperature. This situation highlights how this kind of propane heat pump, characterised by an extended range of working temperatures, forces to modify the reference temperature values reported in the standards for calculating the main heat pump parameters.

3.2 Primary energy

In Figure 6, a comparison between the different scenarios in terms of primary energy consumption (non-renewable, renewable and total) is shown. The focus is on the behaviour of the propane heat pump during the heating season. Therefore, the results presented below refer to the heating service only. Figure 6 shows that the “Baseline” scenario has a total primary energy demand of approximately 310 MWh per year. This value is lower than in the other scenarios where the total primary energy is significantly higher, except for the scenarios “A3” and “B3”. The increase in the total primary energy demand depends on the fact that with the heat pump, the consumed energy vector is changed from natural gas (needed to feed the boilers) to electric energy.

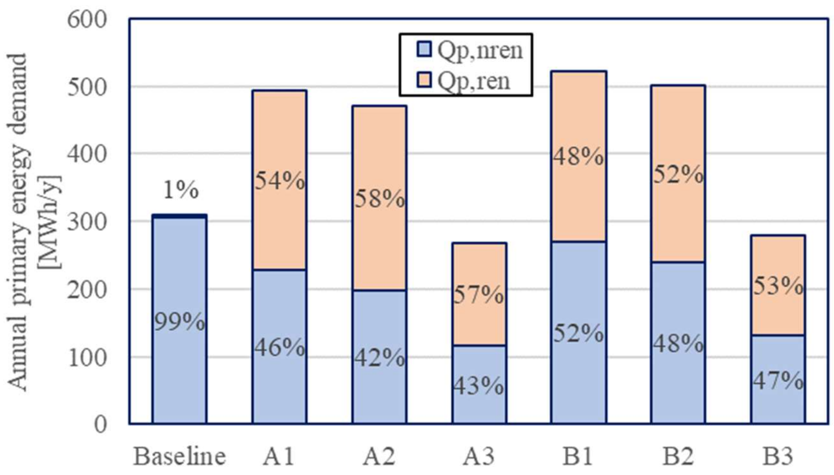

Fig. 6. Annual non-renewable, renewable and total primary energy demand for the various scenarios.

Nevertheless, the energy label of a building depends on the non-renewable primary energy demand. In that case, it is evident that the non-renewable energy consumption is lower in all the analysed scenarios than in the “Baseline” scenario. Consequently, an increase in the renewable quote is assessed, which, among the scenarios, assumes values between 48% (case “B1”) and 58% (case “A2”) of the total primary energy demand.
Comparing the “A” and “B” scenarios, the performance of the system improves in the presence of fan coils as emitters (“A” cases). This is due to the lower water temperature required by fan coils with respect to radiators. (“B” cases). It is important to stress how the propane heat pump can completely satisfy the thermal energy demand, even in the case of a non-insulated building and high-temperature emitters such as radiators (“B1” case).

3.3 Environmental performance and TEWI

To assess the environmental efficiency of the HVAC system based on the propane heat pump, the Total Equivalent Warming Impact (*TEWI*) index has been calculated for both a propane and an R410 heat pump coupled to the building. According to the standard UNI EN 378-1:2021 [16], *TEWI* accounts for both direct greenhouse gas emissions from the refrigerant fluid and the indirect impact from the electric energy consumption of the unit by means of the following equation:

$$TEWI = n \cdot m \cdot Pt \cdot GWP \cdot L + m \cdot Pt \cdot GWP \cdot (1-\alpha_{rec}) + n \cdot Eel \cdot \beta \quad (1)$$

Here, n is the standardised operating life of the heat pump (15 years); m is the refrigerant load (in kg/kWt), set approximately equal to 0,10 kg/kWt for R290 and approximately equal to 0,23 kg/kWt for R410A; Pt is the nominal thermal power of the heat pump (in kWt); L is the annual refrigerant leakage factor (7%) [18]; α_{rec} is the end-of-life refrigerant recycle/recovery factor (70%); E_{el} is the total electric energy consumption of the system; and β is the emission factor of the grid electricity. Following [19], the emission factor for electric energy from the Italian grid is equal to 245,7 gCO2/kWh.

It is important to note that the impact of indirect emissions on the TEWI value can be mitigated in various ways. For example, integrating photovoltaic (PV) panels to power the heat pump directly can substantially reduce grid electricity consumption, thus lowering indirect emissions. Advances in heat pump technology that minimise electric energy requirements will also help decrease indirect greenhouse gas emissions.

The indirect impact linked to the electric energy consumption generally has a much greater weight than the direct component. However, with the ongoing energy transition towards a decarbonised electric power system, which is expected within 2050 [20], it is supposed that the direct fraction will become increasingly important to the detriment of the indirect emissions.

Therefore, to assess the environmental impact of the analysed heat pump system, the direct refrigerant gas emissions were calculated for the scenarios described previously (Figure 6). This outcome was then compared to what would be achieved with a similarly sized unit using R410A as refrigerant.

Figure 7 reveals a notable difference between R410A and R290 regarding direct emissions. More specifically, R410A exhibits significantly higher direct emissions than R290 of three orders of magnitude due to the considerably higher GWP value of R410A (2088) with respect to R290 (3).

Considering the crucial role that direct emissions will continue to play in the future, a shift toward environmentally friendly refrigerants with low global warming potential, such as R290, emerges as an imperative step to reach the targets imposed by the EU.

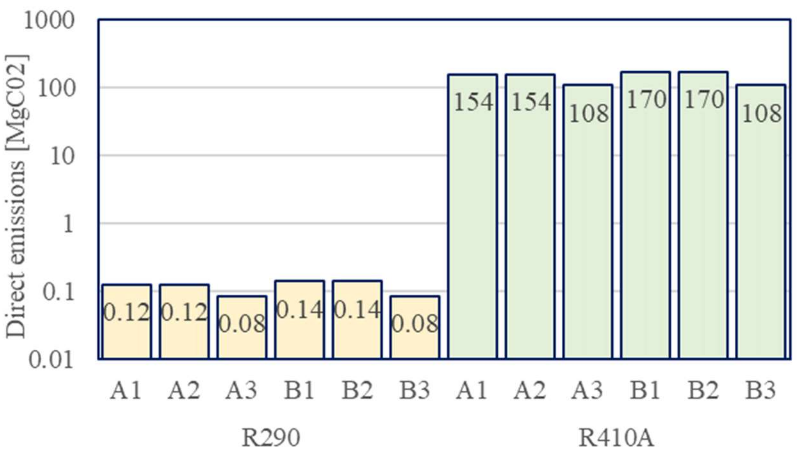

Fig. 7. Contributions of direct emissions for the AWHP-based system operating with R290 (yellow columns) and R410A (green columns).

3.4 Energy costs for space heating

In addition to the energy and environmental analyses, it is also essential to make some economic evaluations of the yearly costs associated with the building's space heating for each scenario. A price for natural gas of 1.22 €/Nm3 and 0.26 €/kWh for electricity from the national grid is assumed. These values represent the average incurred cost by the University of Bologna in 2023 on its complete building stock.

Observing Figure 8, it can be noted that the annual cost for space heating for the “Baseline” scenario shows a value of 36.2 k€ linked to the energy consumption of natural gas (96%) and electricity from the grid (4%).

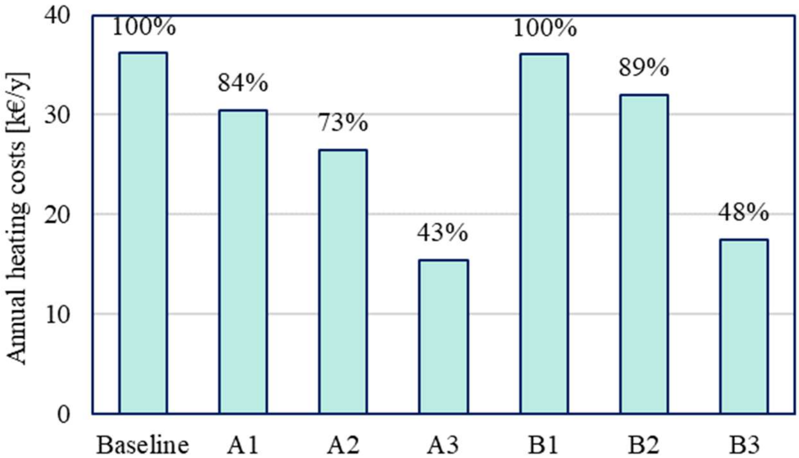

Fig. 8. Annual costs for space heating needs for the various scenarios.

Replacing the gas boiler with the propane AWHP means a lower cost for the building’s climatisation during the winter, especially when the heat pump is coupled to fan coils (“A” cases). When high-temperature radiators are selected as emitters (“B1” scenario), an annual cost of 36 k€, just below the actual running costs, is obtained; this data puts in evidence that the propane heat pump can be considered, from an economic point of view, equivalent to the case of a heating system based on condensing gas boilers.

The scenarios “2” (i.e., with the installation of a 66 kWp PV system) allow a reduction in costs compared to the respective sub-cases “1” (without PV system) of about 11%, depending on the self-consumption of electricity produced by the photovoltaic panels.

A reduction of annual costs for the supply energy of around 55% can be obtained with an intervention in the thermal insulation of the building envelope components (scenarios “3”); in these cases, the difference between “A” and “B” scenarios becomes lower and lower depending on the increase of the thermal insulation of the buildings.

4 Conclusions

This paper presented a comprehensive study on the implementation of an innovative air-to-water electrical heat pump (AWHP) using R290 (propane) in an academic building located in Forlì, North of Italy. The results highlight how non-renewable primary energy consumption is significantly reduced by adopting a propane AWHP with respect to the baseline scenario (using a conventional gas boiler and a chiller) with a substantial increase in the renewable quote. The renewable energy fraction in scenario A2 (in which the propane AWHP is coupled to fan coils and a photovoltaic system) reached 58% of the total primary energy demand, demonstrating a substantial increase in the exploitation of renewable energy. The results presented in this paper highlight the environmental advantages of using R290 in heat pumps, primarily in reducing direct greenhouse gas emissions. The Total Equivalent Warming Impact (*TEWI*) analysis revealed that R290's very low Global Warming Potential (GWP) of 3 significantly minimises the direct emissions in the atmosphere compared to conventional refrigerants like R410A (GWP=2088). From an economic point of view, replacing a gas boiler with a propane ASHP can only reduce costs if the heat pump is coupled

to low-temperature emitters. In the presence of radiators, propane AWHP ensures yearly running costs of the same magnitude as a gas boiler. A reduction in running costs can be obtained in buildings with improved thermal insulation and photovoltaic systems.
In the future, the energy performance of the building coupled with the propane ASHP will be monitored both during the winter and summer seasons starting from the first months of 2024. In addition, it will be evaluated the role of a dynamic balancing system on the yearly energy consumption in the presence of a partial use of the building during the season.
In conclusion, the transition to R290-based ASHPs in HVAC systems can be considered a promising approach to increase energy efficiency and environmental sustainability by guaranteeing economic viability.

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