Exergy Analysis of Aerothermal and Geothermal Heat Pumps in a Critical Environment Application

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Abstract

Through the last decades, energy consumption presented a continuous increase and became a fundamental asset in every sector. Considering heating, ventilation, and air-conditioning (HVAC), improvements have been progressively required, mainly when circumstances are also influenced by geopolitical and economical aspects. The present work discusses an exergy analysis of two existing heat pump (HP) technologies, air-source and ground-source for heating and cooling operations. These may be used for the replacement of the system of a critical environment, a bioterium, which currently comprises chillers for cooling and boilers for heating to provide environmental conditions that must be uninterruptedly maintained, thus requiring substantial energy consumption. With the purpose of exploring less demanding alternatives, an exergy analysis is performed in this work to establish a comparison between the two aforementioned HP technologies using an algorithm executed in Python. For both equipment exergetic analyses, six different types of refrigerants are considered as well. In all scenarios, the ground-source HP presented a smaller exergy, alongside a considerably higher exergetic efficiency due to a smaller exergy destruction and a higher coefficient of performance (COP).

Keywords
Air-Source Heat Pumps, Ground-Source Heat Pumps, Exergy, Python, Critical Environment.

1. Introduction

Despite the improvements regarding HVAC equipment energy efficiency in the last 60 years, energy consumption increased more than 60% per person worldwide, from 12976 kWh in 1965 to 20902 kWh in 2021 (Ritchie et al. 2022). According to Delmastro et al (2022), from to 2010 to 2021, the energy consumed worldwide in buildings increased from 31944,4 to 37500 TWh, accounting thus, for about 30% of the total global energy consumption. In regard to this consumption, HVAC corresponds to a substantial part since from 2020 to 2021 space cooling presented the largest increase in electricity consumption in buildings, higher than 6.5%. Moreover, a more grievous concern in the matter of HVAC is space and water heating, as almost 50% of the consumed energy by buildings in 2021 was used for this effect. As heating demand is still supplied at approximately 64% by fossil fuels, only 42% as natural gas, its usage resulted in the direct emissions of about 2450 Mt of CO_2 in the atmosphere (Goodson et al, 2022). In addition to decarbonisation, another aspect of space and water heating that cannot be neglected is the uncertainty of natural gas supply, since Russia, who once provided more than 50% of the gas in EU, was providing less than 13% by the end of 2022 (European Council, 2022).

A promising solution able to fulfil all the HVAC needs of the buildings is the replacement of the current systems, for both cooling and heating, by HP technologies. Such solution relies on the fact that HPs are a cleaner and more efficient technology (Delmastro et al, 2022). For this reason, their implementation has been progressively supported by several countries. Nevertheless, they supply only 10% of building heating needs in global terms. Consequently, the global market of HPs has presented a notable growth, with an increase that surpasses 13%. At the moment, air-source heat pumps (ASHP) represent the largest portion of the HPs market, with over 60% of the total sales. Meanwhile, ground-source heat pumps (GSHP), despite their higher COP, represent a minor share of the global sales due to their higher costs and more disruptive installation (Delmastro et al, 2022) (Omer, 2008) (Staffel et al, 2012).

In virtue of the continuous growth of this technology, it requires more research and more development. The choice between which HP technology to use must be analysed based on the application, budget, and availability of space for implementation. In the case of the present paper, the application for a critical environment, a bioterium, is considered.

As Barandier and Cardoso (2021) depicted, HPs present a great opportunity for the improvements in the energy efficiency of a university bioterium, a facility for raising and maintenance of laboratory animals used for research and teaching activities. This facility, to ensure the maintenance of the environmental conditions at 21 ℃ and an air relative humidity of 50%, demands a constant and uninterrupted climatization and requires, consequently, a large amount of energy. The permanent fulfilment of such requirements is even more relevant due to the facility's location. Located in a region of Portugal with a considerable yearly weather variation, Covilhã holds a maximum average temperature that can reach over 34 ºC in summer and a minimum average temperature that can drop to below 0 ºC in winter, as presented in Figure 1, where the red and blue lines represent the maximum and mean average temperatures, respectively.

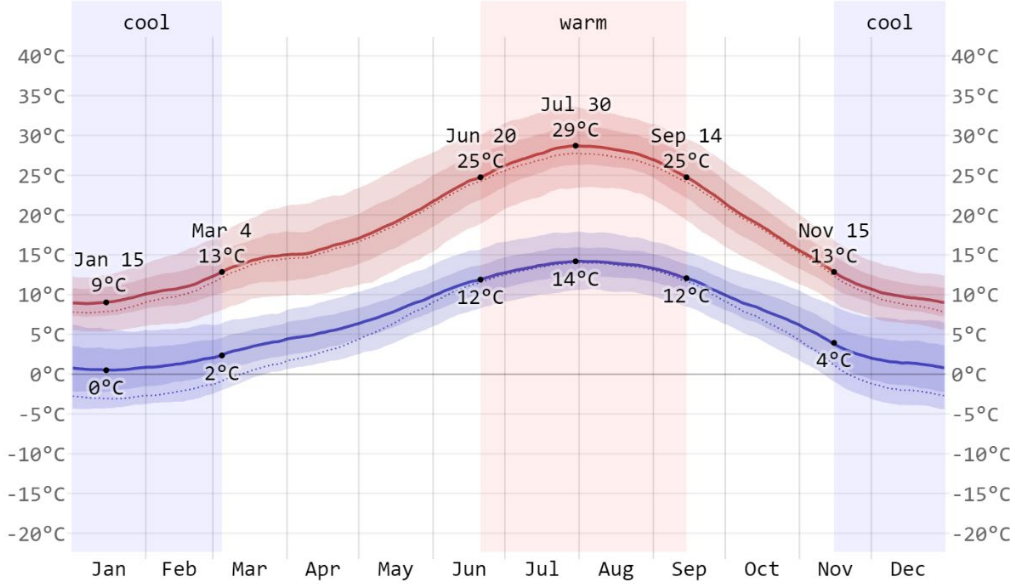

Figure 1. Weather Variation in Covilhã, (Weather Spark, 2023).

GSHP present a COP considerably higher when compared to ASHP. Therefore, in order to provide a more detailed analysis between the two HP types and an assessment tool to support the decision process for the current equipment replacement associated to the bioterium, in order to achieve higher system energy and exergy efficiencies, this work performs an exergy analysis of both ASHP and GSHP in cooling and heating modes with six different types of refrigerants. The analysis is executed in Python language through TESPy library (Witte and Tuschy, 2020).

This paper is structured in 5 sections. Section 2 provides a brief literature review of the addressed subject, section 3 provides, with more detail, the employed methods, in section 4 the results are presented and discussed, and, finally, in section 5, the work is concluded.

2. Literature Review

2.1 Heat Pumps

In comparison to other systems, HP technology present economical and efficient advantages for both cooling and heating that may be employed in several applications. Additionally, various studies revealed the great potential of this technology for the reduction of greenhouse gases emissions (Chua et al, 2010). As stated by Osterman and Stritih (2021), HPs can be classified into three types: chemical, absorption and vapour compression. The first two, chemical and absorption, provide only cooling whereas vapour-compression devices can provide either cooling or heating. Since the present work considers systems capable of providing both functions, only vapor-compression HPs shall be accounted for.

A basic vapour-compression cycle consists of 4 main components: the compressor, two heat exchangers working as condenser and evaporator, and an expansion device, as presented in Figure 2 (Staffel et al, 2012). In addition to the main components, other items such as liquid receivers, accumulators, oil separators and others may also be employed in a circuit although they are used only to increase the system efficiency, safety, and/or reliability (Rajapaksha and Suen, 2003) (Cremaschi et al, 2004) (Kim et al, 2016) (Cavallini et al, 2010).

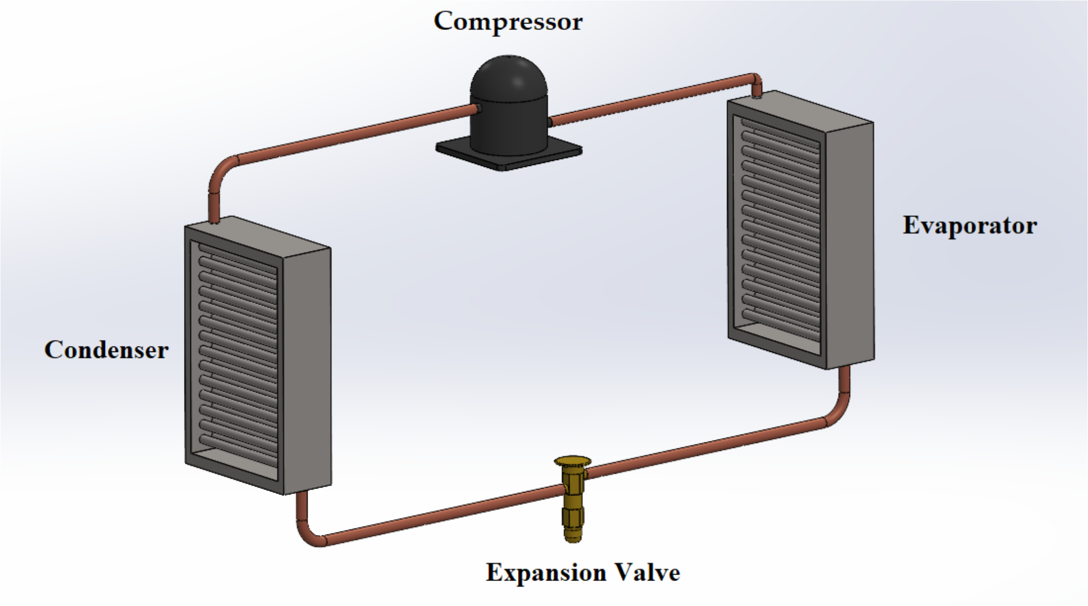

Figure 2. Vapor-Compression Cycle

The vapour-compression HPs can be classified according to their heat source and heat sink. ASHP, the most common type, use the outside air as heat source or heat sink during heating and cooling operations, respectively. Its setup can be either packaged, where all the components are located outdoors inside a single unit, or split, where a heat exchanger is located indoors and the rest of the components outdoors (Wu, 2009). The main drawback of these systems is that their performance is affected by the greater variability of the outside air temperatures. Therefore, in heating mode, with the increase in the temperature difference between the heat source and heat sink, commonly denominated as temperature lift, the COP deteriorates. The same behaviour is observed when the temperature lift increases during cooling mode (De Swardt and Meyer, 2001).

GSHP exploit the ground, whether soil or underground water, instead of outside air, as heat source or heat sink. Since it demands more space and is more expensive to implement, it happens to have a less common application. This type of HP is composed of three main sub-circuits: the geothermal circuit, the HP circuit, and the distribution circuit (Omer, 2008). When the underground water is exploited as heat source/sink, the earth connection can be either through an open loop or a closed loop. In these systems, lakes, ponds, and wells can be employed. When the ground is used as the heat source/sink, the connection is exclusively a closed loop (Omer, 2008) (Atam and Helsen, 2016). The main advantage of the GSHP is the higher invariability of ground temperatures, mainly at greater depths, which result in a higher HP COP (De Swardt and Meyer, 2001).

Additionally, in all types of HP, whether ASHP or GSHP, the COP in heating mode is always higher than cooling mode. That occurs due to the fact that in heating mode, the thermal power comprises the heat absorbed in evaporator plus the heat generated by the compressor. Meanwhile, the thermal power in cooling comprises only the heat absorbed in the evaporator (Barandier, 2023).

2.2 Exergy

Exergy is an extensive property that can be defined as the maximum theoretical work that can be performed by a system as it comes into thermodynamic equilibrium with a reference environment. It is only conserved when the process of the system and the environment is reversible. For this reason, exergy is generally destroyed, and not conserved, as energy. While some aspects of energy, such as its balance and efficiency, are related to the first law of thermodynamics, the aspects of exergy are also related to the second one. That can be explained by the fact that destroyed exergy is proportional to the generated entropy and, consequently, responsible for the lower real system efficiency when compared to its theoretical one (Dincer and Cengel, 2001) (Moran and Sciubba, 1994).

According to Wall (1986), this concept is essential for efficiency and cost accounting studies and economic analyses, thus becoming the only reasonable way for the evaluation of fuels, resources, processes, systems efficiencies, dissipations, and outputs, as well as their inherent costs. In this manner, an exergetic analysis is an indispensable tool to determine the effectiveness of energy production and the inexorable thermal losses of a given process (Ozturk, 2014). Consequently, proper exergy analysis may result in a considerable reduction rate in the use of natural resources and the environmental pollution with the decrease of the rate of discharge of waste products (Dincer and Cengel, 2001).

According to Bayrakçi and Özgür (2009), the exergy can be estimated through equation 1 and the irreversibility of the system through equation 2, where ψ is the exergy, Δh is the specific enthalpy variation, T0 is the surrounding temperature, Δs is the specific entropy variation, and I the irreversibility, that is, the exergy destruction. The exergetic efficiency can be calculated through equation 3, where ε represents the exergetic efficiency.

$$\psi = (\Delta h) - T_0(\Delta s) \qquad (1)$$

$$I = \psi_{in} - \psi_{out} \qquad (2)$$

$$\varepsilon = \psi_{out} \,/\, \psi_{in} \qquad (3)$$

The current available literature in the field of exergy analysis for vapor compression systems already presents some remarkable achievements, as by Ahamed and Masjuki (2011). According to the authors, the evaluation of energy performance of HVAC systems usually relies on the first law of thermodynamics. Nevertheless, exergy analysis, based on the second law of thermodynamics, is a relatively new method that is able to provide a better insight of the process by pointing out more accurately the location of the thermodynamic losses and thus, enabling the optimization of a system's performance. One of the pioneers in this area were Akau and Schoenhals (1980) who, motivated by the fact that the so far established analyses relied on the first law of thermodynamics, applied the second law efficiency in a water-to-water HP.

Bilgen and Takahashi (2002), developed a program in Matlab to simulate a domestic HP. Through the simulations, the exergy destructions were estimated for further research and improvement of the equipment's COP. The authors verified and determined exergy destruction in the compressor, heat exchangers, expansion device, and even in the piping system. Badescu (2002) also reached the same findings, concluding that the compressor presents the largest exergy destruction, by testing the first and second law in a solar assisted ASHP.

Hepbasli and Akdemir (2002) performed an energy and exergy analysis of a vertical closed loop GSHP through thermodynamical equations and concepts. It was concluded that the highest exergy losses, approximately 56% of the total, occur in the compressor, due to electrical, mechanical, and isentropic efficiencies. The second, third, and fourth largest exergy losses occurred in the condenser, expansion device, and evaporator, respectively.

Kabul et al (2008) analysed the COP and exergy efficiency of a vapor compression system with R600a. It was concluded that the temperatures in the heat exchanger have a significant effect on the COP and exergy. With higher temperatures in the condenser, COP and exergy decrease. Meanwhile, with higher temperatures in the evaporator, such parameters increase.

Ozturk (2014) analysed both energy and exergy efficiencies of a GSHP combined with a photovoltaic-thermal (PVT) collector, which works as the evaporator, for space heating. The author concluded that combination provides a notable increase over 10% in exergy efficiency since the electrical power generated by the PVT reduces the needs of electrical power input. It was also concluded that the exergy efficiency is inversely proportional to the ambient temperature.

Byrne and Ghoubali (2019), conducted an exergy analysis of ASHP for simultaneous heating and cooling operations. The authors also considered systems with two different refrigerants, R407C and R290, the later presented a higher exergy efficiency due to the refrigerant selection and the equipment components. In all cases, the compressors presented the highest exergy destruction values.

3. Methods

To perform an exergy analysis of an ASHP and a GSHP, simulation models for both devices for heating and cooling modes were developed in Python using the TESPy library, designed by Witte and Tuschy (2020). For a better understanding, the cooling and heating provided by both equipments in the simulation is 1 kW. In this manner, the results of the exergy analyses will be proportional to this amount of thermal power. The data for all the simulations is presented in Table 1. For the ASHP simulation, the air temperatures considered were the average values for winter and summer in Covilhã, periods which require the highest heating and cooling rates, respectively.

The GSHP model comprised a closed loop. The ground temperature values were measured at several depths in the region and, since they do not present a high variance along the year, their total average was considered. For the model, a borehole of 5 m with an average ground temperature of 22 ºC was considered. Furthermore, even though the bioterium HVAC system also includes other components, such as air treatment units and fan coils, in the present work, only the HPs systems will be analysed.

Other aspect that was contemplated for both ASHP and GSHP models was the refrigerant employed as working fluid. In this manner, six refrigerants were examined, R134a, R410A, R32, R1234yf, R1234ze, and R290 (propane). The first two, R134a and R410A are refrigerants predominantly used for this type of application. Nevertheless, in virtue of their elevated global warming potential (GWP) index, they have entered a phase out process after the Kyoto Protocol. In the medium term, R32 is a possible choice as it presents a GWP notably lower. Three other possibilities, in the long term, are the HFO refrigerants R1234yf, R1234ze, and the organic refrigerant R290, which are alternatives with a low GWP index, as depicted in Table 2.

Table 1. Temperature Data Values

	Summer (°C)	Winter (°C)
Outside Air	35	0
Ground 5m	22	
Ground 15m	26	
Ground 20m	28	
Ground 30m	33	

Table 2. Refrigerants analysed (Linde, 2019).

Refrigerant	GWP
R134a	1430
R410A	2088
R32	675
R1234yf	4
R1234ze	6
R290	3

4. Results and Discussion

In all the simulations, the results for each system and refrigerant presented certain variations. In cooling mode, as illustrated in Figure 3, the ASHP component that presented the highest exergy destruction was the compressor for all the refrigerants, except for R32 which presented an exergy destruction in the condenser slightly higher. Nevertheless, the average exergy destruction in compressor taking all systems into account was around 33%. Meanwhile, during heating, the component with the highest exergy destruction was the expansion valve, as presented in Figure 4, with an average of 38%. Additionally, the total exergy destruction of the ASHP in heating mode was approximately 20% lower when compared to the same equipment in cooling mode, correspondingly to the fact that the COP for heating is higher than for cooling.

Following to the compressor, for the ASHP during the cooling mode, the components that presented the highest exergy destructions in all systems were the condenser, the expansion valve, the evaporator, and the condenser fan. The only exceptions were the system with R32, where the exergy destruction in the condenser was slightly higher than that in the compressor and the system with R1234yf, where the expansion valve presented an exergy destruction slightly greater than in the condenser.

Concurrently, for the ASHP operating in heating mode, following to the expansion valve, the components with the highest exergy destructions were evaporator, compressor, condenser, and evaporator fan in most cases. The only exceptions were the system with R410A, where the exergy destruction in the condenser was higher than that in the compressor, and the system with R32, where the exergy destruction in the condenser was the second largest, not being overcome only by the expansion valve. The large exergy destructions that occur in condenser and evaporator for cooling and heating modes, respectively, are a consequence of the larger temperature lift.

When comparing all the exergy analyses, in terms of refrigerants, the R134a presented the lowest exergy destructions for the ASHP in cooling mode, followed by R1234ze, R290, R32, R1234yf, and R410A. However, the results are slightly different during heating mode, where R134a maintains the best outcome, but now followed by R32, R290, R1234ze, R410A, and R1234yf. More details are provided in Table 3.

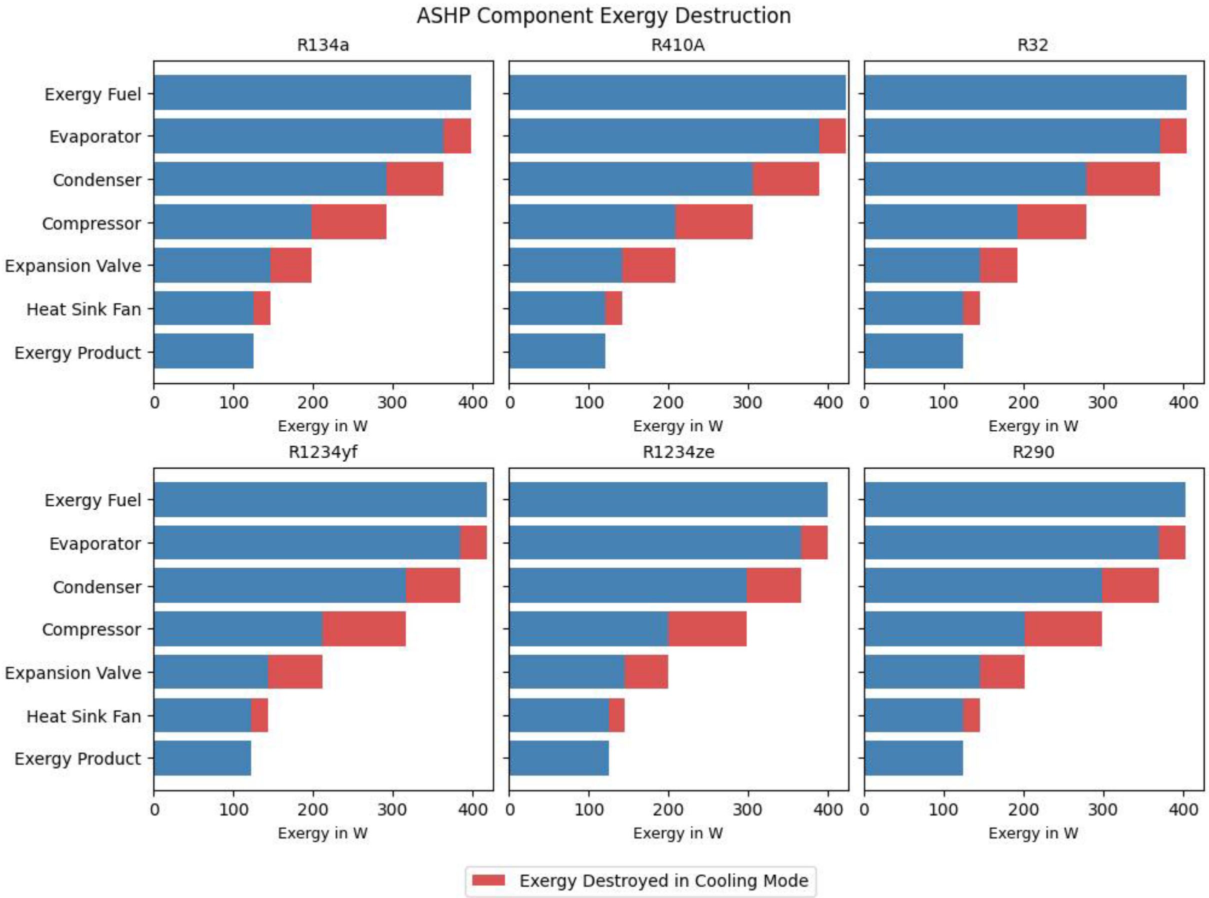

Figure 3. ASHP Cooling

The GSHP during the cooling mode contains about 74% of the exergy of the ASHP in the same mode. However, the ratio of exergy destruction to the total exergy is considerably smaller in the GSHP, around 49%, whereas it is about 70% in the ASHP. One of the main reasons for that is the fact that, due to a smaller temperature lift, less work is required by the compressor. As regards to heating mode, the GSHP holds about 65% of the exergy available in the ASHP. The ratio of exergy destruction to the total exergy for heating is quite similar for both equipment types, with an average of 52%. The total average exergy destruction in GSHP in both cooling and heating modes are also reasonably similar; that is due to the more constant ground temperature.

For all the refrigerants, during cooling mode, the condenser and evaporator were the components with largest exergy destructions as the values presented by them were practically equal, as presented in Figure 5, and represent around 59% of the total system exergy destruction. The only case where the difference between them was more noticeable was for the system with R32, where the average exergy destruction was 5% higher in the condenser. Following to both heat exchangers, the components that resulted in the largest exergy destruction were the expansion valve and the compressor.

In heating mode, the component with the largest exergy destruction is, for most cases, the expansion valve with an average value of about 42% of the total destroyed exergy; however, this also depends on the refrigerant employed, as it is presented in Figure 6. There was only one exception, since the component with the largest exergy destruction in the system with R32 was the condenser. Following to the expansion valve, the components with largest exergy destruction were the heat exchangers with very similar values, and, lastly, the compressor. Besides the system with R32, the only case that presented a more remarkable difference between the condenser and the evaporator was the system with R410A, where the condenser's exergy destruction surpassed the evaporator's values in 3.3%.

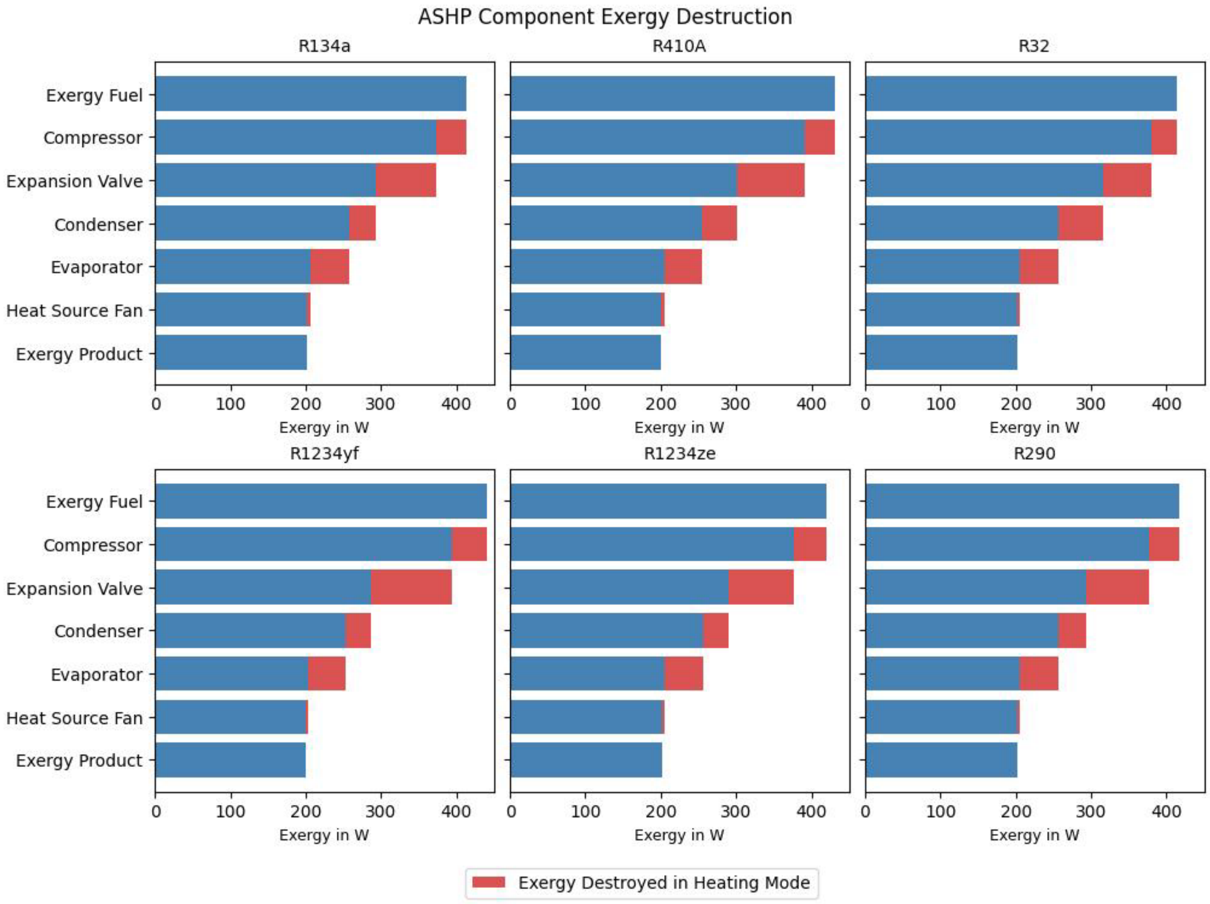

Figure 4. ASHP Heating

Table 3. Exergy Destruction per kW of Refrigerants for ASHP in Cooling and Heating Modes

Refrigerant	Exergy Destruction in Cooling Mode (W)	Exergy Destruction in Heating Mode (W)
R134a	272.23	211.80
R410A	300.14	230.58
R32	280.62	212.86
R1234yf	295.00	239.90
R1234ze	275.09	218.15
R290	278.38	216.29

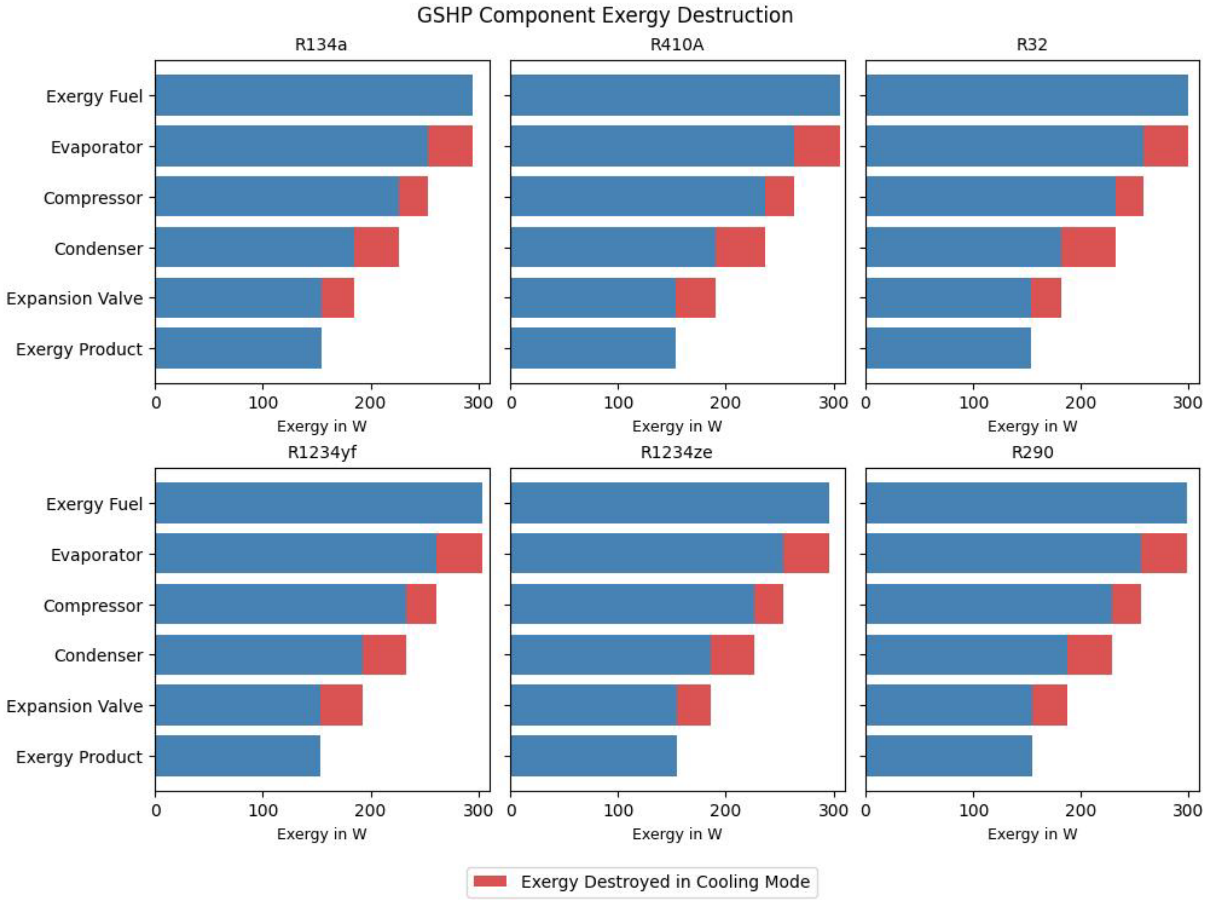

Figure 5. GSHP Cooling

Like the ASHP in cooling mode, when comparing all the exergy analyses, in terms of refrigerants, the R134a presented the lowest exergy destructions for the GSHP in both modes, followed by R1234ze, R290, R32, R1234yf, and R410A. More details are provided in Table 4.

Table 4. Exergy Destruction per kW of Refrigerants for GSHP in Cooling and Heating Modes

Refrigerant	Exergy Destruction in Cooling Mode (W)	Exergy Destruction in Heating Mode (W)
R134a	140.60	136.29
R410A	152.51	152.76
R32	145.89	142.25
R1234yf	150.48	149.72
R1234ze	141.81	137.90
R290	144.15	140.59

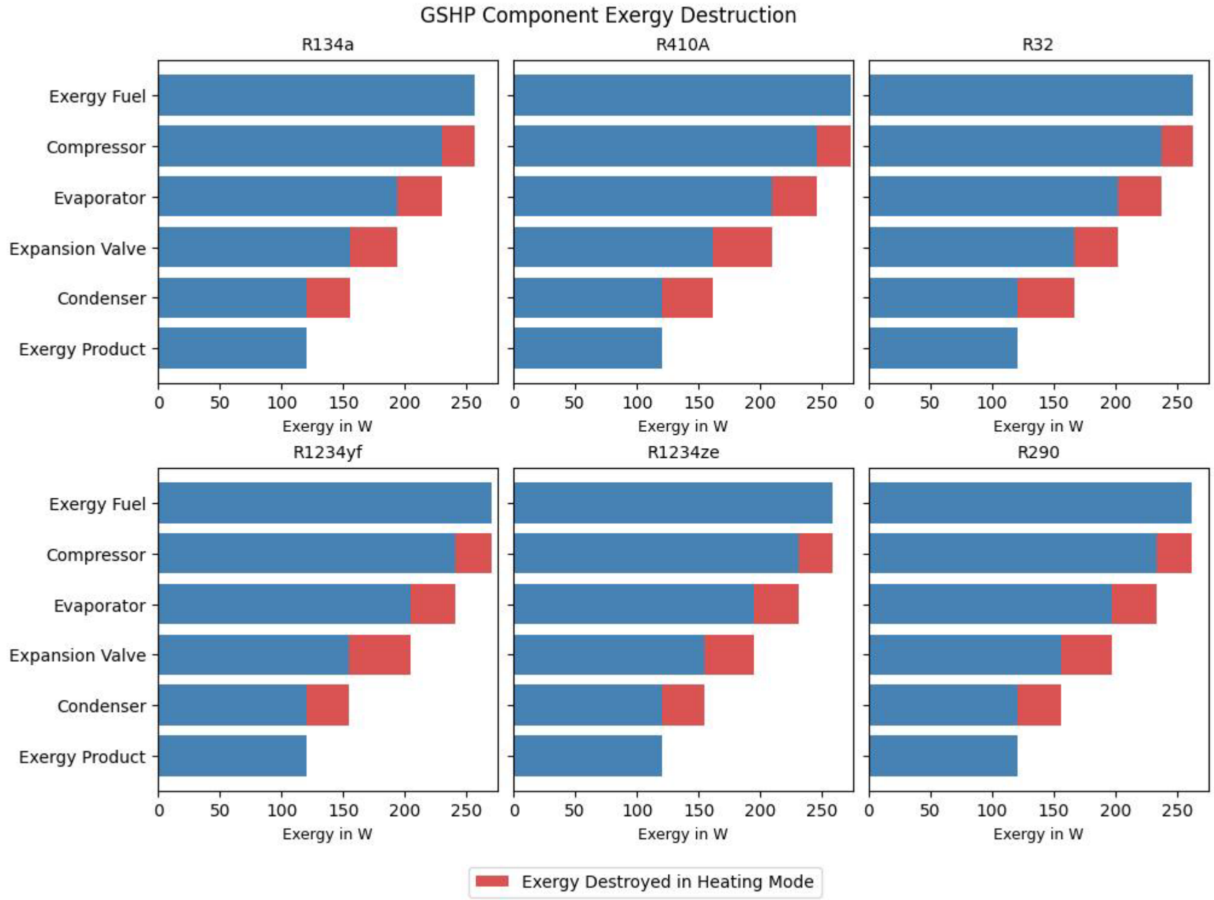

Figure 6. GSHP Heating

Table 5. COP of ASHP and GSHP in Cooling and Heating Modes

Refrigerant	Cooling		Heating	
	ASHP	GSHP	ASHP	GSHP
R134a	2.01	4.44	2.85	4.60
R1234ze	1.98	4.41	2.80	4.56
R290	1.96	4.35	2.82	4.50
R32	1.94	4.30	2.84	4.47
R1234yf	1.83	4.18	2.64	4.31
R410A	1.80	4.13	2.71	4.26

In terms of COP, for all the refrigerants, the GSHP outperforms the ASHP in both heating and cooling operations as it is presented in Figure 7. All the refrigerants present a similar trend for both equipment types with only slight differences. During cooling operation in both ASHP and GSHP, the refrigerant with highest COP was the R134a, followed by R1234ze, R290, R32, R1234yf, and, lastly, R410A. Similarly, during the heating operation, the R134a also present the highest COP for both equipment, but followed by R32, R290, R1234ze, R410A, and R1234yf in the ASHP, and by R1234ze, R290, R32, R1234yf, and, finally, R410A in the GSHP, as presented in Table 5.

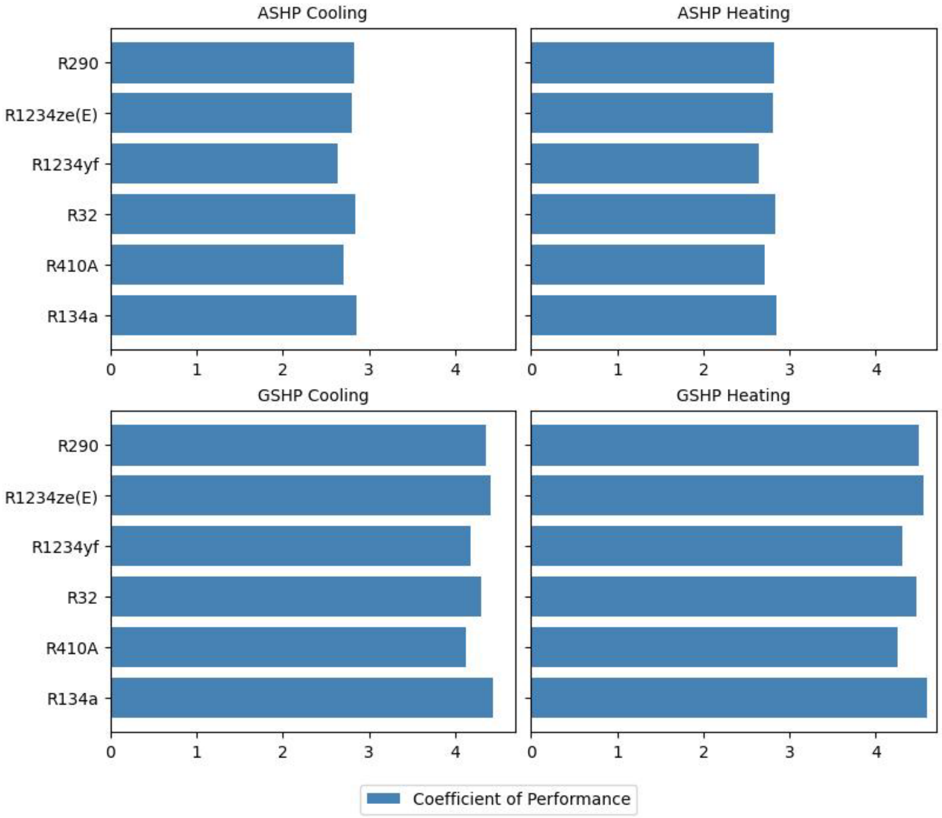

Figure 7. Refrigerants COP for ASHP and GSHP During Heating and Cooling Operations

5. Conclusion

The present work aimed to perform an exergy analysis for an air-source and for a ground-source heat pump considering six different refrigerants. The application under consideration is a bioterium, an environment that requires a continuous utilization of the HVAC equipment, either for cooling or heating, according to the thermal needs. Thus, both equipment were compared in terms of exergy efficiency for both functions. For the exergy analysis itself, an algorithm in Python was developed and employed.

In terms of equipment, the GSHP detains less available exergy than the ASHP. Nevertheless, the exergy destruction rates were significantly smaller with the former, which led to higher exergetic efficiencies and COPs for both cooling and heating modes. The main reason for that is the greater thermal stability of the ground when compared to the air, which presents a substantial variability along the year. In addition, and as a consequence, to these temperature parameters, the work provided by the compressor is reduced, which also reduces the energy input and, therefore, the exergy available alongside its destruction.

Since the exergy destruction is directly related to the entropy variation, the components with the highest exergy destructions were the compressor and expansion valve, except for R32 systems that must be further analysed. Nevertheless, the exergy destruction is also dependent on several thermodynamic and chemical properties of the refrigerant employed.

Among the analysed fluids, the one with best results was the R134a, which is currently in phase out process due to its elevated global warming potential. In this manner, a promising alternative in the long term are the refrigerants R1234ze and R290, which despite presenting a mild flammability level, present a low global warming potential. The refrigerant with worst results was the R410A, which is also in phase out process due to its high global warming potential. The results are quite similar when it comes to the COP concerning each refrigerant, where R134a and R410A presented the highest and the lowest COPs, respectively. Nevertheless, the differences among all the refrigerants analysed were minimum. Moreover, in terms of COP, R290 also appears to be a promising alternative in the near future.

In the future, more work will be developed, considering other refrigerants, applications, and systems with other components that may increase their COP, such as accumulators and liquid receivers.

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