Numerical investigation of the castle of Zena energy needs and a feasibility study for the implementation of electric and gas driven heat pump

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Nomenclature

COP	Electric heat pump Coefficient Of Performance [*adim.*]
EER	Electric heat pump Energy Efficiency Ratio [*adim.*]
GUE	Absorption heat pump Gas Utilization Efficiency [*adim.*]
NPV	Net Present Value [€]
PV	Present discounted Value [€]
Q	Thermal power [kW]
$T_{air,SP}$	Air temperature set-point [$^{\circ}C$]
T_c	Comfort temperature for an indoor environment [$^{\circ}C$]
T_{DM}	Daily mean of the external temperature [$^{\circ}C$]
T_{RM80}	Running mean of the external temperature [$^{\circ}C$]

Subscripts

f	Fuel
el	Electric energy
PE	Primary energy

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1. Introduction

Many Italian buildings have a historical value. In order to reduce the national building energy consumption, a refurbishment of this sort of buildings is needed, as well as an effective use of appropriate HVAC technologies today available. Nowadays, designers often choose the plant and equipment according to their previous experience and information from technical data sheet, without performing a prior detailed analyses to verify their performance in a whole annual cycle and under dynamic conditions. This article highlights the importance of numerical preliminary analysis to identify the best plant system, in terms of energy consumption, economic benefits and environmental impact.

The work presented in this paper has two main purposes: first of all, the identification of a simple design procedure to increase the overall energy performance in historical buildings; secondly, this procedure has been applied to a case study and results have been presented.

As far as the design process is concerned, it is based on the detailed numerical simulation of the building-plant system. Some technologies of heat and cold generation are compared in terms of primary energy consumption, economic and environmental benefits. In the recent past, this procedure has been used in the framework of the S.O.C.R.A.T.E.S. project [1]: its primary object of study is the Castle of Zena (Italy, Piacenza) and its surroundings, but it is also aimed at the definition of general purpose models and methodologies that lead to the functional recovery of buildings with high historical and architectural value.

The actual Castle building has been used as a case study in the work described in this paper, being analysed through numerical simulations using the TRNsys 16 calculus suite [2]. The modelling process is made of three main steps: we have divided the building into thermal zones, in which rooms with similar use destination are grouped; then internal and external boundary conditions have been defined. This has led to two main results: first, we have determined the thermal loads for both heating and cooling plants. Since the summer energy need obtained was low, we have used the adaptive comfort approach [3–6] to verify the need for a dedicated plant. The final step has been the simulation of four heat pump systems: two using an electric heat pumps (EHP) and two using an absorption heat pump (GAHP). For both the type of heat pump in one case the external air has been considered as energy source (AS) and the other a water source (WS).

We have calculated the primary energy consumption for the four technologies, then an economic and environmental assessments have been carried out.

2. Case study

Figure 1: Picture of the Zena Castle.

The Castle of Zena is a square building with an internal courtyard, a missing side, and is surrounded by a wall corresponding to the old moat. The original building seems to have been built in the XIII century, then has been modified and transformed during its life, until the last restoration works that took place in the Seventies (Figure 1).

The Castle consists of a basement floor (370 m^2), two main floors (700 m^2 each), and an attic (700 m^2, 225 of which are not fit for habitation). The overall net surface is around 2'470 m^2.

Among all the purposes of the S.O.C.R.A.T.E.S. project [1], one is the redefinition of the building functions. More in detail, it still has a residential function, together with hospitality and events (i.e. yoga and meditation classes): in the project there are four rooms, six meeting rooms, seven bedrooms with bathrooms, and a wine and food area.

In order to achieve a better thermal efficiency of the envelope, some improvements have been introduced: the old windows have been changed with more insulating double-glazing systems, and the floor between the first floor and the attic has been insulated too, only where the temperature of the room facing on its upper side is not controlled.

The next section deals with the investigation of the envelope energy performance through numerical simulations.

3. Building envelope numerical model

The first step of this work has been the evaluation of the Castle energy needs for heating and cooling, which has been performed through numerical simulations. For this purpose, the following data were required:

- drawings of the building under investigation (plans, sections and constructive details if any);
- hourly based climate data for the external environment (temperature, relative humidity, solar irradiation, etc.);
- energy requirements estimation related to the destination use of each room.

The assessment of the overall energy needs has been achieved simulating the behaviour of the building using a capacitive model defined in TRNsys 16 [2] software environment (TRaNsient SYstem Simulation). The latter consists of two main software: Simulation Studio (the calculation engine designed for the resolution of complex energy problems), and TRNbuild (the graphical user interface used for modelling building structures). The high level of complexity of these tools has allowed to perform an accurate analysis of the building under consideration, taking into account all those variables that would have been neglected using a simplified procedure [7].

In this section, all parameters and hypotheses assumed in the model definition are discussed, followed by the presentation of results.

3.1. Thermal zones and envelope definition

The first phase of the modelling process has been the subdivision of the building into thermal zones: rooms with the same usage have been grouped into the same zone of the model. Going more in detail, the whole building has been divided in eleven zones: five of them are equipped with heating and cooling plants, with fan-coil terminals; in all other zones internal temperature is not controlled. Even if this last group of zones does not have any energy need, they have been considered into the numerical model because they represent the boundary conditions for the rest of the enclosed environments.

As far as the first group of zones is concerned, it is composed by a part of the basement floor (CA_{20}), part of the levels above the ground (PA_{18}, PA_{20} and PA_{23}), and part of the attic (MA_{20}). The identification code of each zone is reported in Table 1, together with a brief description and the overall surface area.

Once those thermal zones of the Castle have been identified, we have defined every element of the envelope and of the internal partitions between adjacent zones, both in terms of geometry and thermophysical properties.

Table 1: List of the thermal zones contained in the numerical model of the building. For each zone are given the following information: identification code, a brief description, plant equipment (if any) and overall surface area.

Cod.	Description	$T_{air,SP}$ [°C]	Plant	S $[m^2]$
CA_{20}	Part of basement floor	20	fan-coil	138
PA_{18}	Building volume	18	fan-coil	40
PA_{20}	Building volume	20	fan-coil	732
PA_{23}	Building volume	23	fan-coil	41
MA_{20}	Part of mansard	20	fan-coil	23
CA_{NON}	Part of basement floor	-	none	213
CA_{ENO}	Wine and food	-	none	-
PA_{NON}	Building volume	-	none	-
PA_{P}	Portico	-	none	-
ST_{NON}	Attic	-	none	-
STAIRS	Stairwell	-	none	-

Dealing with walls, external and internal structures are made of solid bricks coated with plaster; the roof has a wooden structure, covered with tiles; the main stratigraphy of internal horizontal partitions consists of a brick vault, covered with a load distribution layer of concrete, followed by a binding layer of lime mortar and an internal tiles coating. As far as the transparent envelope elements are concerned, the original ones have been replaced during recent refurbishment, installing new windows with aluminium frame and double glazing systems. Moreover, on that occasion the floor between the first floor and the unheated part of the attic has been insulated. All the structures listed above have been considered in the numerical model, and have been simulated with the transfer functions method used by TRNbuild, which allows to take into account their behaviour under dynamic conditions.

3.2. Internal and external boundary conditions

The second step in the definition of the building numerical model is related to the assumption of consistent values for boundary conditions, for both external and internal environments.

Table 2: Comparison of the average monthly temperatures in Milan and Piacenza, as shown in [8].

Month	Milano	Piacenza — Month	Milano	Piacenza
Jan	1.7°C	0.1°C — Jul	25.1°C	23.2°C
Feb	4.2°C	2.4°C — Aug	24.1°C	22.3°C
Mar	9.2°C	7.7°C — Sep	20.4°C	18.9°C
Apr	14.0°C	12.2°C — Oct	14.0°C	12.8°C
May	17.9°C	16.3°C — Nov	7.9°C	6.9°C
Jun	22.5°C	20.7°C — Dec	3.1°C	2.0°C

Due to the lack of long-term information about the Piacenza climate conditions, we have used Milano-Linate Meteonorm climate station hourly values of temperature, relative humidity and solar irradiation. In this way it was possible to perform detailed calculations on an hourly time-step. Moreover, we can notice that the average temperature difference is lower than 2°C during the whole year [8], as shown in Table 2: for this reason we can reduce our adjustments to the level of qualitative considerations.

Considering now the internal boundary conditions, they can be divided into mechanical ventilation and infiltrations, heating and cooling plant, and finally internal gains.

Regarding the air change rate, we can notice that they can only be provided by opening windows and through infiltrations, because there is no dedicated facility: the historical value of the building does not allow the installation of an invasive system such as a ventilation plant. Moreover, taking into account the kind of events that takes place in these rooms, mechanical ventilation is not needed (small crowd, low metabolic rate during meditation activity). This has been reproduced in the model defining a variable value for air change rate during a representative day: going more in detail, we have assumed 1.0 h^{-1} for two hours a day, to simulate the windows opening, while in the rest of the day this value is reduced to 0.3 $^{-1}$ (which is typical for modern window frames).

Defining heating and cooling plant, at this stage of the work under discussion, means defining set-point temperatures and time schedules. This has led to the evaluation of the thermal loads related to the building envelope. Going more in detail about winter set-point temperature, we have to emphasize that we have assumed two different values: the first is the comfort value (around 20°C) [9], which is reached when the plant is set to ON; then, for the rest of the day, we have set a guaranteed minimum temperature value (15-16°C).

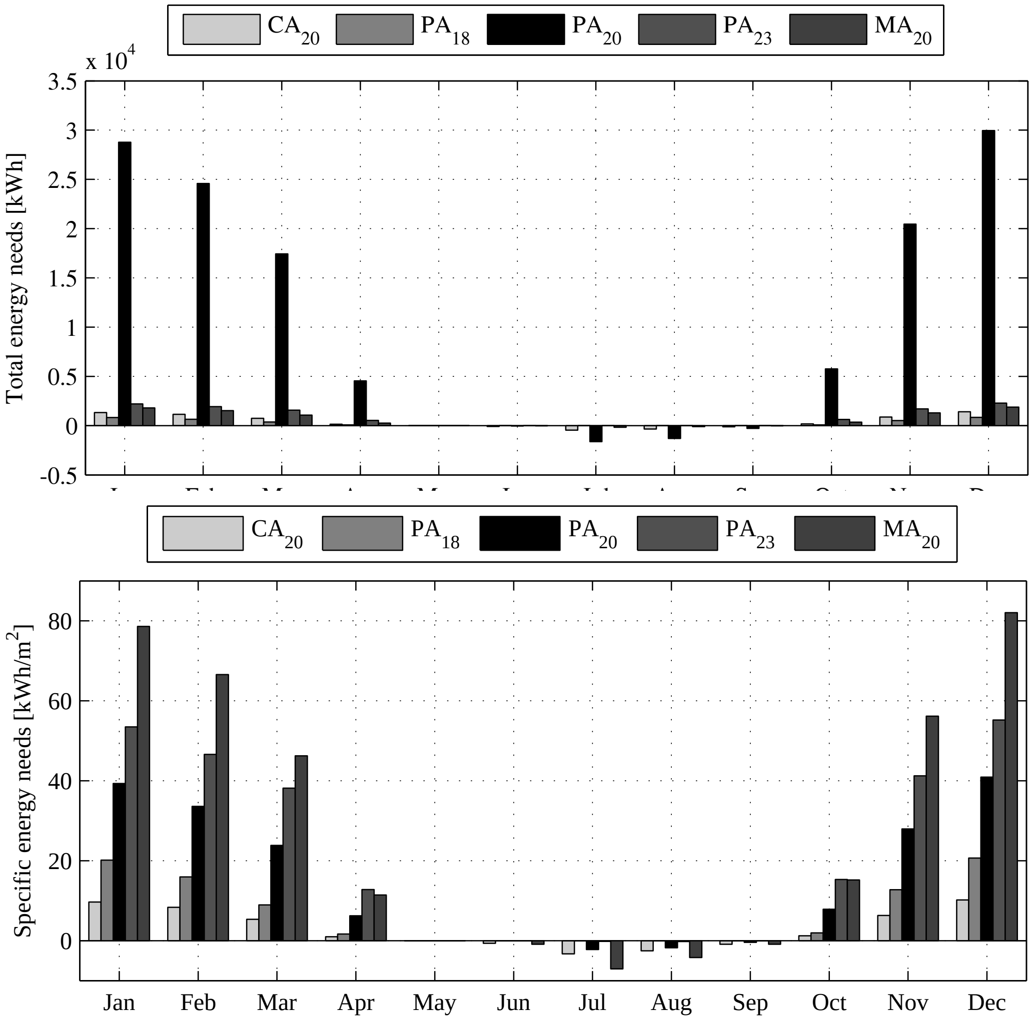
Dealing with internal gains, we have evaluated the number of occupants of each zone, together with the kind of lighting and electrical equipment. For each one of the mentioned heat sources, it has been determined the daily and/or weekly time schedule. Moreover, in order to achieve a better representation of the average year, within the S.O.C.R.A.T.E.S. project has been evaluated a monthly average rate of usage of the zones of the castles, obtaining a sort of annual schedule.

Once the building model and the boundary conditions have been defined as described above, numerical simulations have been performed. Their results are presented and discussed in the following section.

3.3. Results and discussion

The main result obtained with the simulation described in the previous section is the thermal energy need for heating and cooling the Castle. More in detail, we have achieved an hourly load profile for each zone considered. Figure 2(a) reports monthly integrals values of the calculated energy requirements. The monthly profile is also represented in Figure 2(b). We can observe that the thermal zone with the greatest impact on the overall energy requirement is PA_{20}. For this reason, further analyses are focused only on this part of the Castle.

Considering now the cooling energy need of the mentioned area, we can state that it is lower than the winter energy demand. Therefore, a second simulation has been performed without the activation of the cooling plant in summer. In this way, we have been able to evaluate free floating indoor thermal conditions, used to perform an adaptive comfort analysis [3–6].



(b)

Figure 2: Monthly values of energy needs integrals ((a) total and (b) specific values). Positive values are referred to the heating plant, while negative values are related to the cooling season.

This approach is based on the theory that building occupants could tolerate indoor thermal conditions in a range wider than that provided by a cooling plant, if they are allowed to adapt their environment (change clothes, control openings, etc.). Therefore, a comfort temperature is calculated as a function of a reference external temperature, according to the following equations [6]:

$$T_c = 0.302 \cdot T_{RM80} + 19.39 \quad (1)$$

where T_c is the comfort temperature, and T_{RM80} is the running mean of the external temperature (°C) in the *n-th* day for an index 0.08, calculated as follows:

$$T_{RM80} = 0.80 \cdot T_{RM,n-1} + 0.20 \cdot T_{DM,n-1} \quad (2)$$

where $T_{RM,n-1}$ and $T_{DM,n-1}$ are the running and the daily mean temperature of the day n-1 (°C). Once the comfort temperature has been calculated for each hourly time-step of the simulation, a comfort range (°C) has been calculated considering a half amplitude related to the actual comfort temperature:

$$\Delta T_c = -0.189 \cdot T_c + 6.35 \quad (3)$$

The described procedure is called Adaptive Comfort Algorithm (ACA) [4, 6]. In Figure 3 is represented the number of hourly time-step below, in and over the comfort range (vertical axis) for each degree of reference temperature (horizontal axis).

The histogram represented in Figure 3 suggests that, in free-floating conditions, a significant part (almost the 50%) of the cooling season is characterized by an internal temperature value above the upper limit of the corresponding comfort range. Therefore, we can assume that the adaptive comfort approach does not fit the case under discussion, and that a cooling plant has to be included into the project.

4. Heating and cooling plants

In this section the analyses related to heating and cooling plants are described.

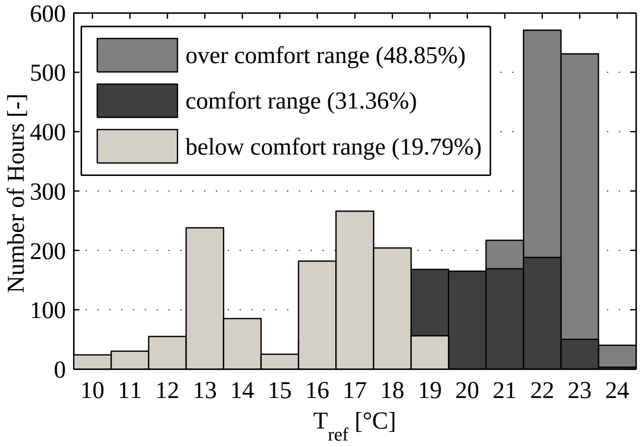


Figure 3: Number of hours below, in and over the comfort range, calculated as a function of the external ref-erence temperature T_{RM80}. For each group, its weight on the overall amount of hours is reported.

4.1. Description

Due to the historical constraints and the installation effort needed it has been decided to exclude the HVAC technologies belonging to the category of all-air systems [10]: water systems have been selected instead. In particular, among them a two pipe fan-coil units have been chosen as emissions systems, characterized by easy integration despite the good emission efficiency. The water inlet temperature is set to 50°C for heating mode and 7°C for cooling mode.

Given the environmental and landscape constraints, wind, photovoltaic and solar thermal technologies have been excluded. Therefore, the heat pump system was chosen as generation system using renewable energy. In the present study two different type of heat pump system (HP) [11] are analysed. The first one is the widely used electric heat pump (EHP) based on a compression cycle electrically powered. The second one is the less spread gas driven absorption heat pump (GAHP) [12]. Moreover two types of both heat pump technologies have been analysed. The first one is an air source heat pump (AS), while the second one is a water source heat pump (WS) connected to the existing well.

4.2. Plant mathematical modelling

All space heating/cooling system can be seen as the sum of the following sub-systems: emission and control, distribution, storage, generation. In this paper only the generation subsystem will be changed in the four proposed plant, so the modelling of the others does not influence the comparison among the proposed plant.

The four proposed generation sub-systems have been modelled as "black-box" mathematical model. The "black-box" inputs are the forward and return temperature of the working fluid to the fan-coils loop and the temperature of the external air or of the aquifer. Its main output is the consumption of the generation sub-system. The inputs and the output are linked through a system of equations [13]. The main equations have a polynomial form, like Eq. 4, and are able to fit well the performance data at full load of a selected heat pump manufacturer [14].

$$Q = p_{00}+p_{10}\cdot x+p_{01}\cdot y+p_{20}\cdot x^2+p_{11}\cdot x\cdot y+p_{02}\cdot y^2+p_{30}\cdot x^3+ \\ +p_{21}\cdot x^2\cdot y+p_{12}\cdot x\cdot y^2+p_{03}\cdot y^3+p_{40}\cdot x^4+p_{31}\cdot x^3\cdot y+p_{22}\cdot x^2\cdot y^2+ \\ +p_{13}\cdot x\cdot y^3+p_{04}\cdot y^4+p_{50}\cdot x^5+p_{41}\cdot x^4\cdot y+p_{32}\cdot x^3\cdot y^2+ \\ +p_{23}\cdot x^2\cdot y^3+p_{14}\cdot x\cdot y^4+p_{05}\cdot y^5 \quad (4)$$

The consumption of the EHP-AS is calculated using the COP (Figure 4(a)) during the hot season and the EER during the cold season (Figure 4(a)).

Also for the consumption of the EHP-WW the COP (Figure 4(b)) and the EER (Figure 4(b)) have been used, moreover the consumption of the water pump used to deliver the aquifer water to the HP via well has been considered. The water pump has been designed on the basis of a geological report on the castle well.

Lastly, for the GAHP-AS and the GAHP-WS the methane gas consumption are respectively derived from the GUE in Figure 4(c) and Figure 4(d), in addition to the electric power consumption due to the fan and the internal pump.

The four generation sub-systems have been considered able to work at partial load without performance decrease, thus neglecting the seasonal performance optimization [15], since they are modulating and linked to a thermal storage. The latter has been introduced in order to keep the capacity ratio (CR - thermal power demand to the heat pump in the specific operating conditions divided by the thermal power declared, referring to the same operating temperatures) higher than 0.6. According to [16], in this range of CR no correction to the full load performance coefficient is needed for electrical heat pumps. This is also true for the absorption heat pumps, according to [17].

4.3. Results

Neglecting, the control, emission, storage and distribution sub-system energy needs, there are two systems with the lowest primary energy consumption (Figure 5): the EHP-WS and the GAHP-WS (around 130 kWh/m^2/year), followed by the GAHP-AS (147 kWh/m^2/year) and the EHP-AS (around 180 kWh/m^2/year). The conversion factor in primary energy used are 1 kWh$_{PE}$/kWh$_f$ for the thermal energy and 2.18 kWh$_{PE}$/kWh $_{el}$ for the electric energy.

The best performance of the two water source heat pump comes from the constant positive difference between the temperature of the aquifer (13°C) and the external air temperature (Table 2). Indeed, the difference, in terms of primary energy consumption, among the analysed system is linked to the so-called thermal lift of the heat pump: this is the difference between the heat source (external air or aquifer) and the output hot temperature of the heat pump.

As we can see in Figure 6, during spring and autumn there is a performance improvement for every system, except the water source heat pump, due to a progressive reduction of the thermal lift.

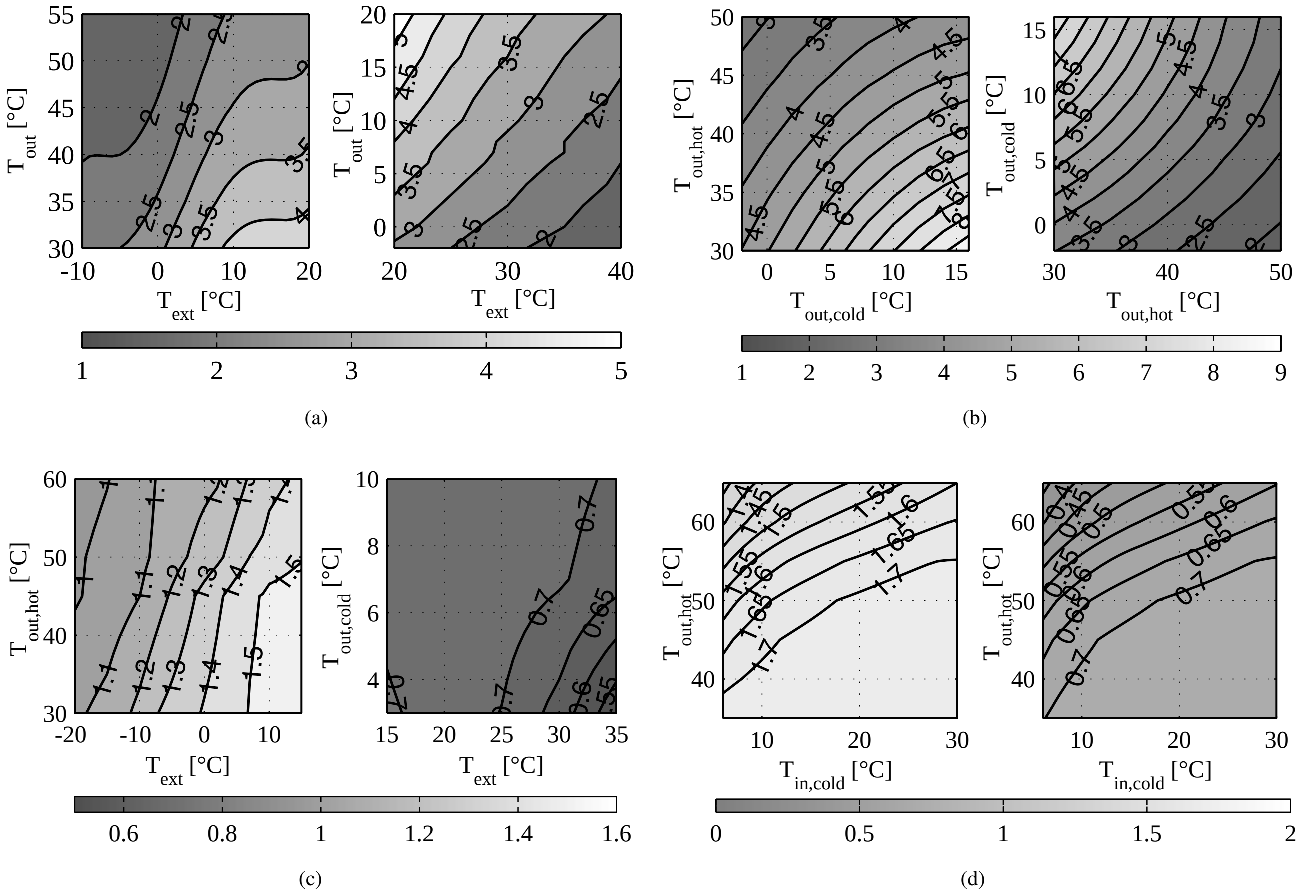


Figure 4: (a) EHP-AS contour plot of COP (left) and EER (right). (b) EHP-WS contour plot of COP (left) and EER (right). (c) GAHP-AS contour plot of GUE in heating mode (left) and GUE in cooling mode (right). (d) GAHP-WS contour plot of GUE in heating mode (left) and GUE in cooling mode (right).

5. Economic and environmental assessment

From the economic point of view, the four proposed system lead to different results. First of all, the initial system's cost is different. The analysis considers only the generation sub-system. The reference for the systems cost is the Italian public works construction prices [18]. The initial purchase and installation cost of the EHP-WS are less then the EHP-AS (21'000 €and 42'000 €respectively). The higher initial cost of the EHP-AS is due to the need of a higher nominal heating capacity, in order to meet the heating power requirements when the external air temperature is lower then the rating conditions (lower COP). On the other hand, the GAHP-AS and the GAHP-WS are respectively about 30% and 80% more expensive than the EHP-WS, due to the higher cost of the absorption technology.

The result of the analysis, considering only the heating needs and a domestic boiler (seasonal efficiency on the higher heating value 85%) as reference, shows that the EHP-AS is not favourable, because it does not lead to cost savings in the yearly bill. Differently from the EHP-AS, the GAHP-AS, the EHP-WS and the GAHP-WS lead to an initial cost savings in the yearly bill of respectively around 2'600 €, 3'200 € and 3'600 € compared to a domestic boiler. Therefore, in the present case study the EHP-WS have the shortest pay-back time, 7 years, (Figure 7), thanks to the use of the existing well and the lower initial cost, against the 14 years of the GAHP.

This analysis is carried out considering a specific cost of 0.65 €/Sm^3 for the methane gas, a specific cost of 0.2 €/kWh for the electric energy, a discount rate of 4% and a null rate of grow of specific energy cost.

Beside the economic analysis, an environmental assessment of the four systems has been performed through the calculation of the greenhouse gas (only carbon dioxide has been considered) and pollutants emissions (carbon monoxide and sulfur and nitrogen oxides). Specific emissions for each substance are reported in Table 3, grouped by energy source [19]. They have been multiplied by the primary energy requirements calculated for the three configurations, obtaining the overall yearly emissions (Figure 8).

As we can observe in Figure 8, we could obtain a significant reduction of green-house gas emission (CO_2) replacing the EHP-AS with the GAHP-AS (-26%), the EHP-WS (-28%) or the GAHP-WS (-34%). EHP-WS gives also benefits in terms of pollutants emissions, while both GAHP technologies lead to worse performances (NOx emissions +15% and +1% respec-

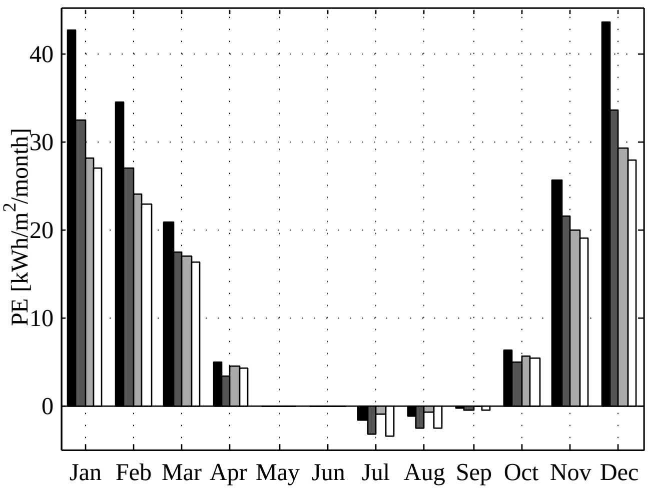


Figure 5: Monthly primary energy consumption. Positive values are referred to the heating consumption, while negative values are related to the cooling consumption.

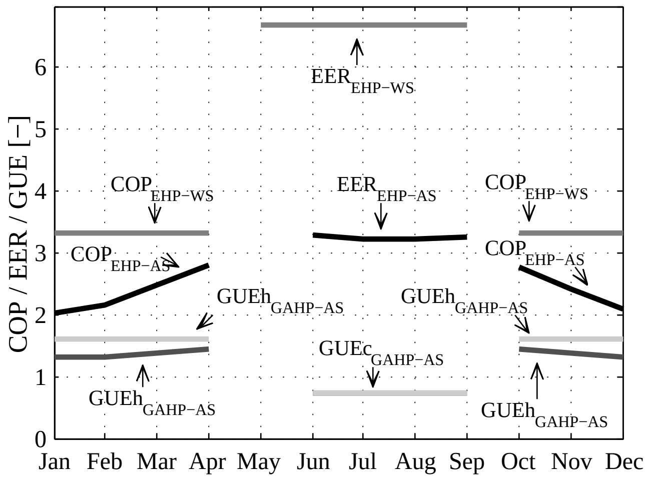


Figure 6: COP and EER monthly values of EHP-AS and EHP-WS (left axis); and on the right axis the GUE monthly values of GAHP-AS in heating and cooling mode (GUE_{hot}, GUE_{cool}).

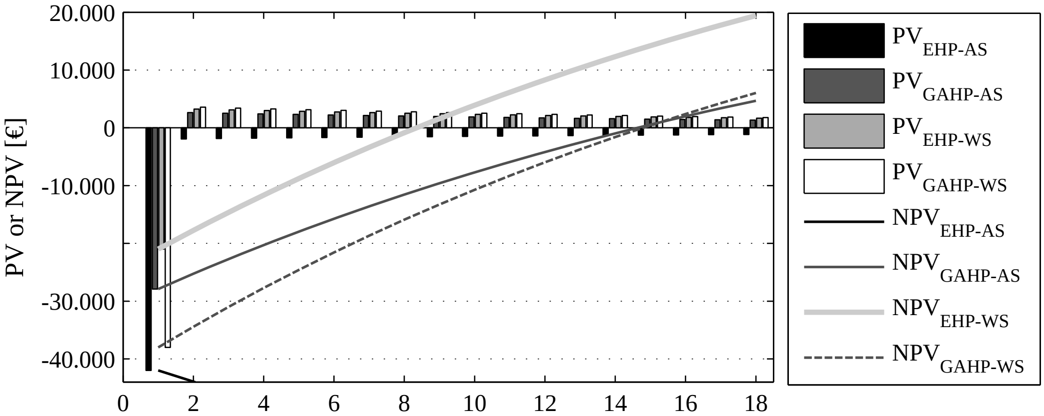


Figure 7: Present discounted Value (bar) and Net Present Value (curve).

Table 3: specific emissions relative to nitrogen oxides and sulfur oxides (NO_x and SO_x), carbon monoxide (CO) and carbon dioxide (CO_2).

	Electricity	**Gas**
CO_2 [g/kWh]	600	250
NO_x [g/kWh]	0.6	0.4
CO [g/kWh]	0.1	0.08
SO_x [g/kWh]	1	0.05

tively, CO emissions +37% and +20% respectively) if compared to EHP-AS. SO_x are reduced in all three cases from the reference point given by EHP-AS, showing a greater effectiveness of the gas absorption technology (≈86% for both AS and WS).

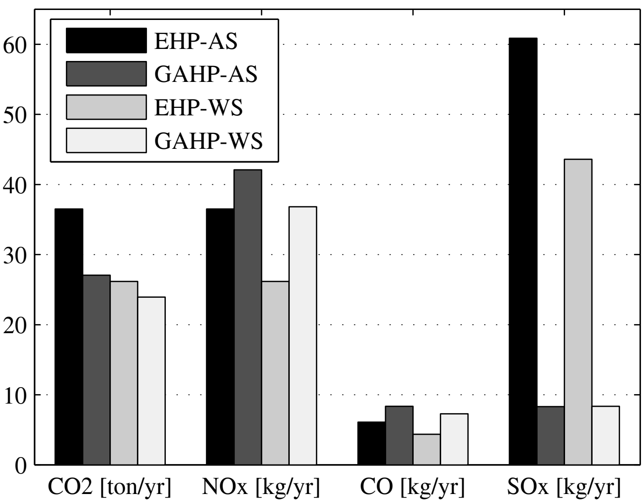


Figure 8: Annual emissions of greenhouse gas and pollutants, for EHP-AS, GAHP-AS, GAHP-WS and EHP-WS.

6. Conclusion

In the previous sections of this work, a feasibility study of the Castle of Zena has been performed, through numerical simulations for both the building envelope and the heating and cooling plants.

First of all, we have obtained the annual thermal energy need for every zone of the building: considering an overall value of around 160'000 kWh in winter and 4'600 kWh in summer, we have observed that it mainly comes from the zone PA_{20} (80% and 71% in heating and cooling season respectively). Therefore, all other analyses are focused on this part of the building.

Then, considering the almost negligible summer energy need (around 4.5 kWh/m^2/year), we have applied the adaptive comfort algorithm, in order to verify the need for a cooling plant. The analysis carried out shows that internal air temperature during half of the considered hours is above the comfort range. For this reason, a cooling system has been considered.

The systems with the lowest primary energy consumptions are the EHP-WS and the GAHP-WS (around 130 kWh/m^2/year), followed by the GAHP-AS (147 kWh/m^2/year) and the EHP-AS (180 kWh/m^2/year).

Lastly, the best investment would be on the EHP-WS with a pay-back time of 7 years, partly due to the fact that a well already exists and does not weight on the initial outlay.

In terms of environmental effects, some benefits are achieved replacing the EHP-AS with the other three technologies. Considering the emission of greenhouse gases, a significant reduction is achieved in all three cases. Dealing with the pollutant emissions the most effective is the EHP-WS, while the GAHP (either AS or WS) leads to the maximum SOx emission reduction compared to the EHP-AS.

According to all the presented results, the EHP-WS technology seems to be the better choice for the analysed building, on the other hand, excluding the water source, the gas absorption heat pump is the better.

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