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Parametric performance analysis of Renewable Energy Sources HVAC systems for buildings

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Abstract

The indoor climate control of buildings represents today the highest percentage of energy consumption in European Union. Hence the evaluation of the best performing HVAC system is a strategic target for both energy consumption and greenhouse gas emissions reduction.

This paper presents a deep analysis of the performance of Renewable Energy Sources HVAC systems for buildings. The technologies considered are biomass boiler, aerothermal, geothermal and absorption heat pumps.

The proposed method estimates all the parameters according to the theory of the "big is better". For each parameter a function has been defined to evaluate how much the performance of each technology depends from it. The analysis take in account also the environment in which each technology operates.

The result is a set of dimensionless parameters, through which it is possible to extrapolate the assessments of performance. It can include both cost-effectiveness and feasibility of a given technology and the contribution to the achievement of European objectives to 2020.

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Keywords: HVAC systems, Renewable Energy Sources, Parametric Analysis.

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Nomenclature

C_{tot}	overall cost per kWh of useful energy produced
C_0	cost of installation per kWh of useful energy produced
C_i	primary energy consumptions cost per kWh of useful energy produced
C_m	maintenance cost per kWh of useful energy produced
C_{CO2}	cost impact of CO_2 emissions per kWh of useful energy produced
$C_0^*(P)$	installation cost in function of installed power
P	installed power of HVAC plant
$c^*(P)$	consumption of HVAC plant per kWh of useful energy produced and in function of installed power
$hours_{U.L.}$	hours of useful life
$€_u$	cost of fuel or electricity per unit of consumption
$\Delta\eta$ (E.T.)	variation in performance in function of external temperature
kg_{CO2}	mass of CO_2 emitted
$€kg._{CO2}$	cost per kg of CO_2 emitted
$\%_{(CO2-f)}$	percentage of CO_2 in the exhaust flow of absorption heat pumps
$\dot{m}_f$	exhaust flow of absorption heat pumps

1. Introduction

A residential building has to be an healthy place where to find the best climate condition. This requirement often involves big energy consumption and high cost for the installations.

The graph in Figure 1 shows how civil applications have the greatest percentage of primary energy consumption in Europe [1]. The first column shows the percentage distribution of primary energy in individual sectors, where the highest percentage belongs to the civilian sector. This sector is mainly composed of buildings used for domestic purposes, where the end-use of energy is mainly dedicated to conditioning in both winter and summer.

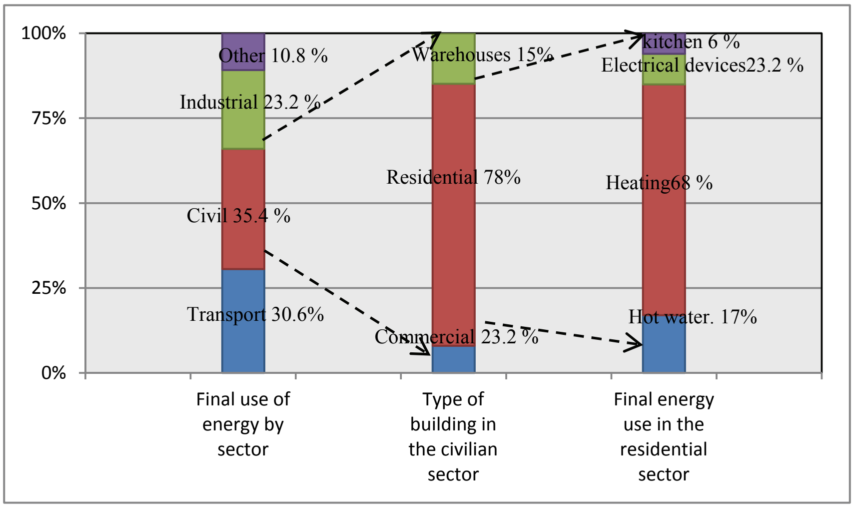

Fig. 1 Primary energy sharing in civil applications in Europe (2012) [1].

This result depends on several factors (e.g. inadequate building envelope or obsolete installations) which in some cases can represent the major barrier to the attainment of optimal indoor climate comfort coupled with the environmental protection. At this purpose, Renewable Energy Sources (RES) HVAC systems pursue well these needs, but often their characteristics are not fully suitable. This consideration involves a careful study, that will try to understand which solutions would lead to an improvement of this situation, by analyzing factors that affect both the outdoor/indoor climate conditions and the economic impact for the users.

This study explores some of the most interesting RES HVAC systems, with a parametric analysis that evaluates quality and cost of the following technologies: biomass boilers and heat pumps. The technologies chosen consist of machines with a high energy efficiency, low environmental impact and low emission of greenhouse gases. The replacement of old systems with these technologies can help to achieve the energy efficiency and environmental European objectives for 2020.

The study considers three types of HVAC systems for the entire annual heat demand:

- combination of biomass boiler and air heat pump
- geothermal heat pump
- heat pump absorption,

In the first type, the air heat pump is used only in summer time, in order to avoid the defrost problem. In winter time the thermal energy demand is entirely covered by the biomass boiler.

2. Methodology description

The study evaluates the *Overall cost* C_{tot} of the proposed technologies, calculating an economic value for each phase of life cycle, from installation to disposal, depending on the amount of energy produced by the machine. The study is divided into several stages: initially all the necessary data for the description of the operation profile of the machine are obtained from the technical specifications; then the costs are calculated, as a function of the requested power and the external temperature in which they are installed. Finally, an assessment is made for three study cases, related to the operation of the machine in Northern, Center and Southern of Italy, calculating the total cost to be sustained in order to meet the needs of both winter and summer conditions.

As said before, the technologies considered are three: the first is the combination of biomass boilers and air heat pumps for use in winter and summer respectively; the other cases concern the use of geothermal heat pumps and absorption heat pumps, which can be used to meet the full demand annually. The *Overall cost* C_{tot} is calculated in function the unit of energy produced during the whole life cycle, as the sum of the costs involved with the achievement of the thermal comfort.

$$C_{tot} = C_0 + C_i + C_m + C_{CO_2} \quad (1)$$

The costs are detailed in Table 1. The formulas used to derive the considered values are displayed too.

Table 1. List of costs with equations.

Cost	Formulas	Unit	Description
$\boldsymbol{C_0}$	$\frac{C_0^*(P)}{P} \cdot \frac{1}{hours_{U.L.}}$	€/kWh	Initial cost distributed over the whole life of the machine in terms of energy produced.
$\boldsymbol{C_i}$	$\frac{c^*(P)}{P} \cdot \frac{1}{\Delta\eta(E.T.)} \cdot €_u$	€/kWh	Cost for the production of a unit of energy in function of the environmental conditions.
$\boldsymbol{C_m}$	value depending on each technology	€/kWh	Annual cost to keep the machine in a suitable condition for correct operation.
$\boldsymbol{C_{CO_2}}$	$\frac{kg_{CO2}}{kWh} \cdot €_{kg\ co2}$	€/kWh	Economic impact caused by emissions of greenhouse gases.

2.1. Initial cost - C_0

The *Initial cost* - C_0 is the cost for installing the machine and make it operating. It is a specific cost per unit of useful energy produced and it is calculated by considering the total years of operation, in order relate the initial cost to the entire period of operation. All the plant components are considered in the definition of the *Initial cost* - C_0.

This cost includes what is necessary for its installation, systems, thermal storage or fuel tanks, and, in the case of geothermal energy, the cost of drilling the ground for field probes. It comprises also the disposal cost at the end of life cycle.

2.2. Primary energy consumptions cost - C_i

It is the economic value for the production of a unit of thermal energy. This cost depends on the power developed by the machine and also on the temperature of the external environment, but only for machines that use air as an heat source. This dependence implies a variation of efficiency and therefore also the costs. The variation of performance data for heat pumps has been calculated by evaluating the ideal cycle on the Pressure-Enthalpy diagram for each external temperature. In the absorption machine considered in the study, the variation of performance is given directly by the constructor [2].

2.3. Maintenance cost - C_m

The cost of maintenance depends on the activities required for a proper operation of all the plant components during their life. This cost considers both scheduled maintenance and corrective maintenance and machine operation. For the scheduled maintenance it is needed the visit of a technician and the cost is a function of the power plant and size of the user. Normally one annual inspection it is needed. The economic evaluation for corrective maintenance is more difficult, because it depends on aleatory factors. In general it can be said that a proper scheduled maintenance can reduce the corrective maintenance for a non-significant impact. The values of these costs and of the machine operation have been assessed both by taking into account companies operating in the sector, but also manpower standard values derived from official tables [3].

As for the *Initial cost* - C_0, also the *Maintenance cost* - C_m is a specific cost per unit of useful energy produced and it is calculated by considering the total years of operation, in order relate the initial cost to the entire period of operation.

2.4. Cost of CO2 emissions - C_{CO_2}

The cost of CO_2 emitted is calculated as the cost of the environmental impact resulting from the operation the considered HVAC technologies. The amount of CO_2 is calculated only in the case where this is produced from fossil fuels, as occurs for electricity production or use of a natural gas boiler. In the first case it is considered the value given by public institution [4], for which the emission of carbon dioxide for the production of electricity was $510 g_{CO2}/kWh$ in 2009. For absorption heat pumps the following relation it is used:

$$\frac{kg_{co2}}{kWh} = \frac{\%_{(CO_2-f)} \cdot \dot{m}_f}{P} \tag{2}$$

The parameters in the formula can be obtained from the technical sheets of the machines studied [2]. After having obtained the amount of CO_2 produced, it is possible to estimate the cost given to each kg of CO_2 produced an economic value. The evaluation of this parameter is not easy because it depends on many factors, but in general it is set around an average value of 0.03 €/kg_{CO2} [5].

Once all the costs of Table 1 have been calculated for each technology it is possible evaluate the *Overall cost* $C_{tot}$to by using expression (1) just adding all the costs. Then it is possible to develop the parametric analysis of the *Overall cost* C_{tot} in function of the installed power and of the environmental condition.

For the evaluation of the cost in the different climatic zones, the daily average temperatures trend it has been considered. Then the frequency of a given temperature is evaluated. Finally it is possible to calculate the total annual cost as the sum of the total costs for a given temperature multiplied by the frequency of days with that temperature. The operation daily hours of each HVAC plant it is also considered for the zones concerned.

3. Results

The graph in Figure 2 shows the trends of *Initial cost* - C_0 for the different power of the HVAC technologies studied, calculated in eurocents. The value was calculated in function of the total amount of energy that the machine would produce every during its life.

The value is considered on the entire annual requirement, for this reason type of system that includes the biomass boiler and heat pumps was evaluated together. As shown, the trend of absorption heat pumps is constant, this is due to the fact that this technologies is characterized by modular machines as concern power, so the specific cost for installed power remains unchanged.

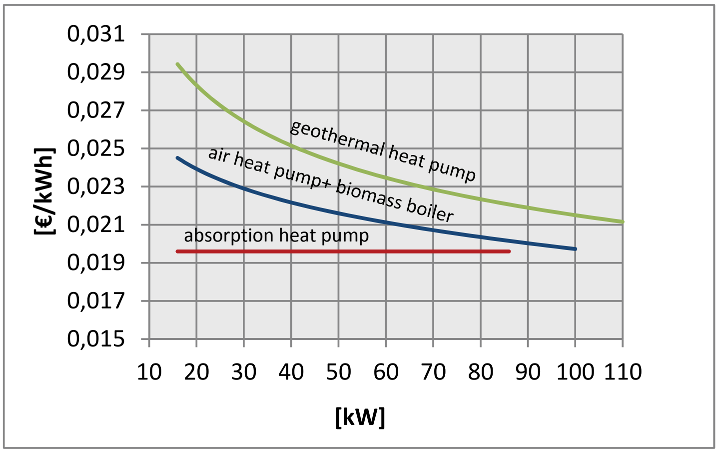

Fig. 2. Initial cost - C_0 of the different HVAC technologies analyzed.

The *Primary energy consumptions cost* - C_i are evaluated individually for each technology and separated between summer and winter. In Figure 3 are reported C_i in summer, while in Figure 4. C_i is evaluated for winter consumption. The values are reported in eurocents and in function of installed power and external temperature.

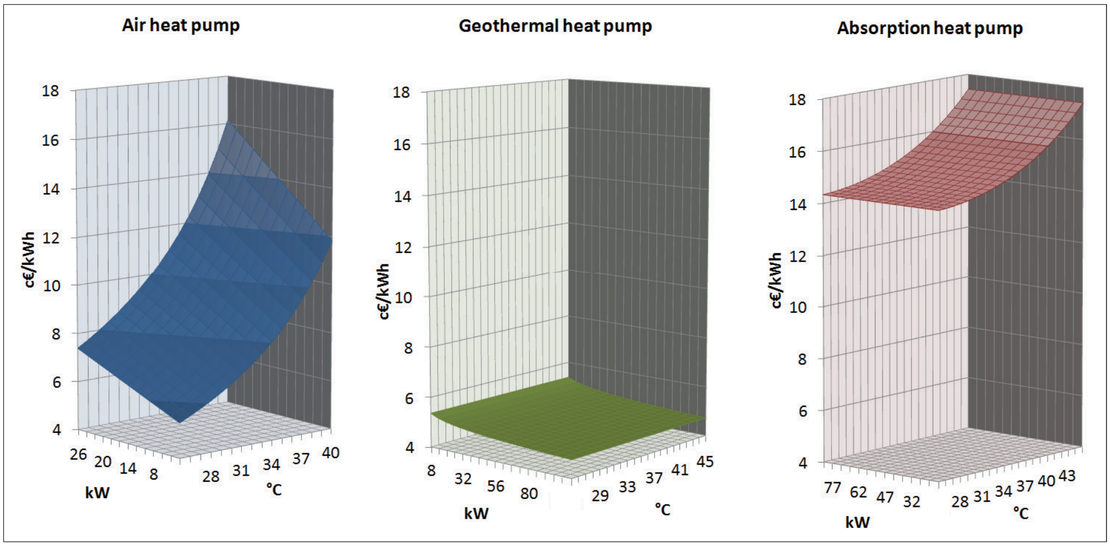

Fig. 3. Primary energy consumptions cost - C_i in summer of the different HVAC technologies analyzed

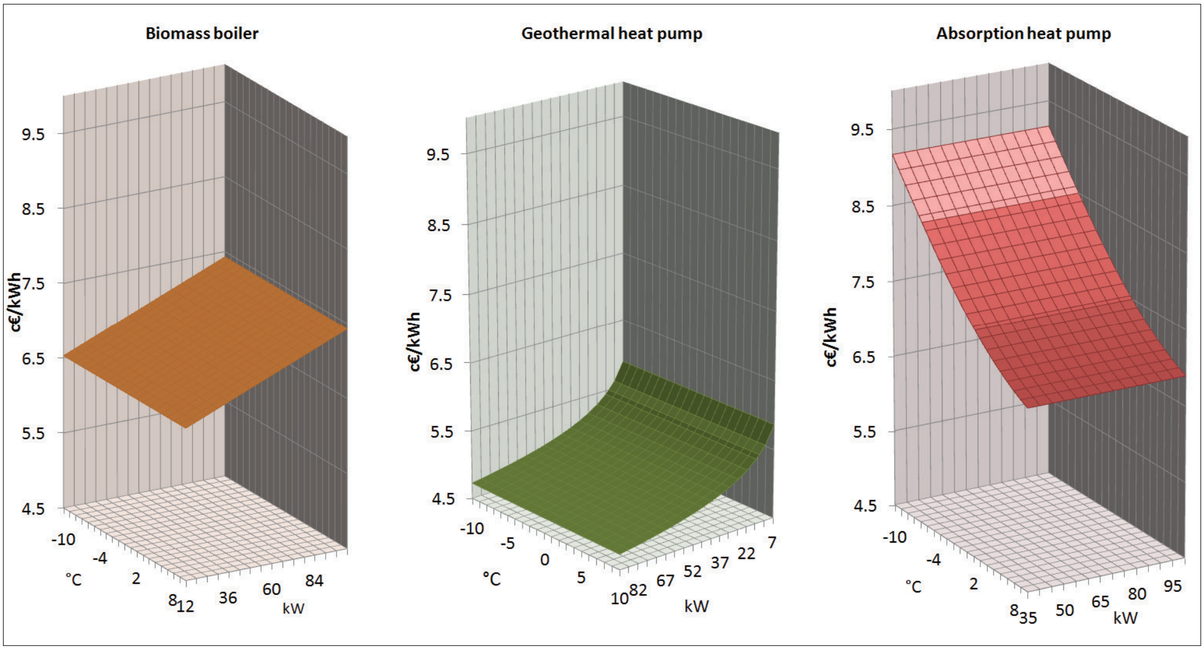

Fig. 4. Primary energy consumptions cost - C_i in winter of the different HVAC technologies analyzed

Figures 5 and 6 show respectively the values of *Maintenance cost* - C_m and *Cost of CO₂ emissions* -C_{CO2}. Note that the trend of C_m is the same for all the heat pump considered. It varies only in function of installed power and not external temperature.

The C_{CO2_2} value is constant also in function of installed power.

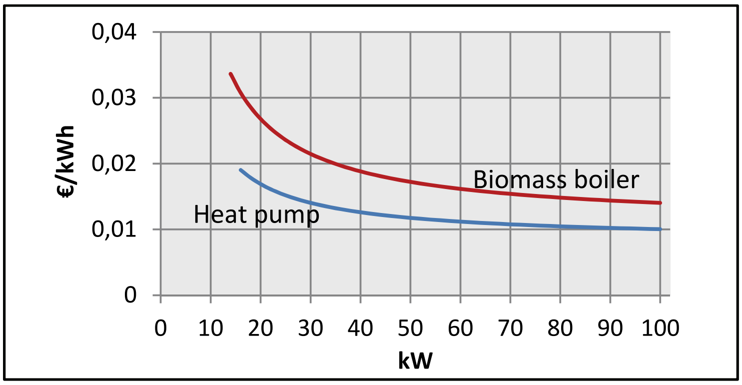

Fig. 5. Maintenance cost - C_m of the different HVAC technologies analyzed.

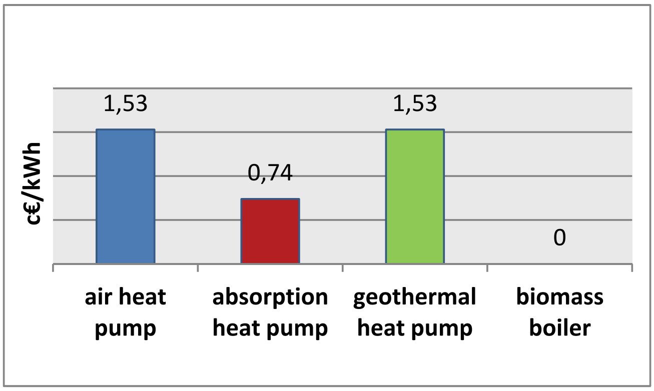

Fig. 6. Cost of CO2 emissions - C_{CO2} of the different HVAC technologies analyzed.

After having obtained all the specific costs it is possible to evaluate the add them together to obtain the *Overall cost* C_{tot} that identifies the economic value for the production of a kWh of useful energy during the life of each HVAC technology considered. This evaluation is reported in a 3D graph for each technology studied in Figures 7 and 8. Each graphs are related respectively to summer and winter operation and the values are shown in function of installed power and external temperature.

These graphs put in relation the *Overall cost* C_{tot} of the considered technologies with two of the most important external parameters to consider in designing an HVAC plants: the *required power* and the *operative external temperature*. Therefore it is possible to make a first assessment of which technology is the most convenient in function of power and external conditions.

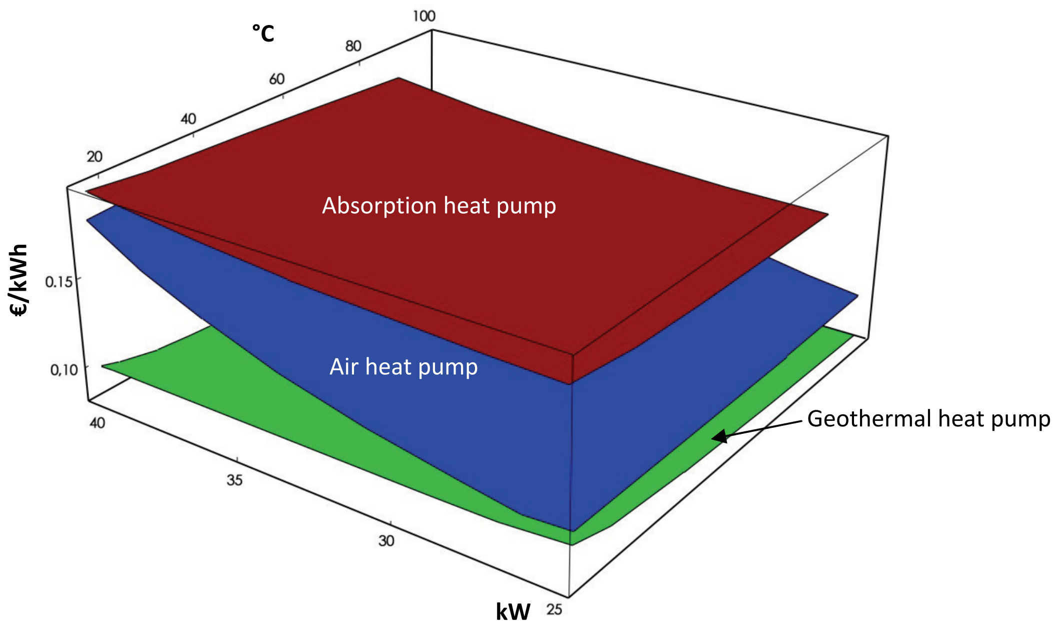

Fig. 7. Overall cost C_{tot} in summer of the different HVAC technologies analyzed.

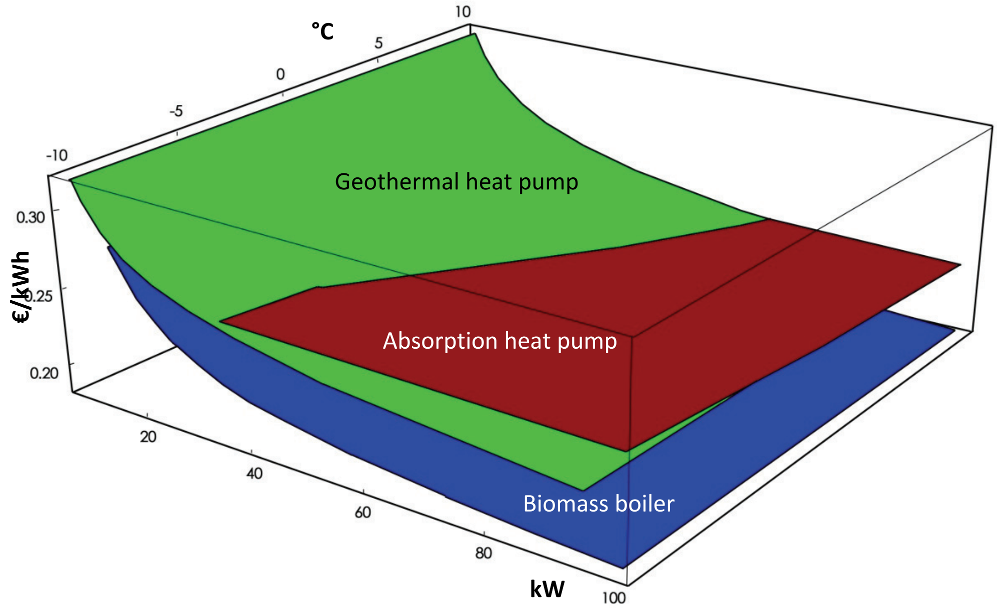

Fig. 8. Overall cost C_{tot} in winter of the different HVAC technologies analyzed.

However, by using the 3D graphs it is quite difficult a specific assessment of the cost for a particular climate condition. To do this some specific cases of three different climatic zones have been studied: Northern, Center and Southern of Italy. For them it is given the *Overall cost* C_{tot} in relation to the thermal power installed (Figure 9).

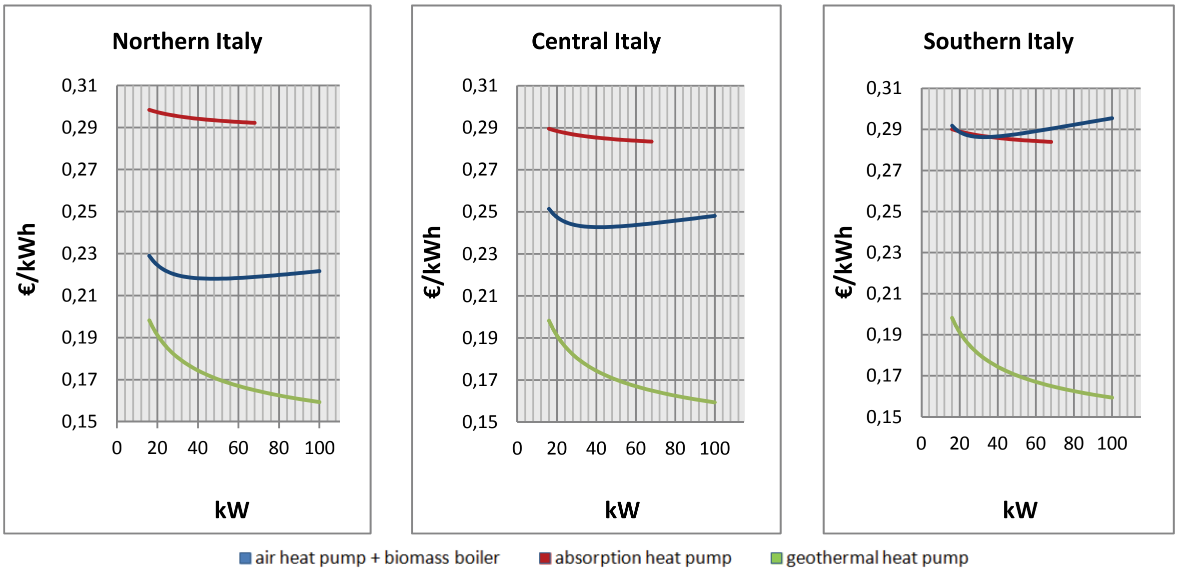

Fig 9. Overall cost C_{tot} of the different HVAC technologies analyzed for different climatic zones

4. Discussion

In graphs shown in Figure 9 there is not a substantial variation in different climatic zones, since the increasing in cost in a season is in general balanced by a decreasing in another season.

The combination of biomass boiler with the air heat pumps represents the most evident variation among the different climatic zones, in fact it is more expensive in hot climate zones, due to a reduced efficiency of the air heat pump for the increasing of the external temperature, during the summer time. As for the other climatic zones, the combination of heat pumps with a biomass boiler is cheaper, especially for cold climates.

This involves a detriment for the absorption heat pumps. It is a relatively young technology for the household sector and it is emerging in the energy market, but it cannot compete yet with the more mature electric heat pumps and their well established reliability.

A very important result regards the geothermal heat pumps that have always been considered a technology too expensive. The detailed economic analysis proposed has evaluated all the parameters that give the overall operation cost and it has highlighted some strategic aspects, such as their long life and low consumptions, that makes it to be taken into consideration as an emerging technology among other ones that are cheaper but with a shorter life and with higher operation costs.

5. Conclusion

The study conducted has a general validity and is very interesting as it concerns, but on the other hand it doesn't consider the particular aspects in a real project. In fact the installation of a plant may depend on many external factors that most of the time are subjective decisions of the user or that are addicted to limitations imposed by the external factors (such as availability of space). For example the geothermal heat pumps need a significant quantity of soil to install the ground loop and that is quite impossible to implement in an urban zone.

A very important consideration must be made on the absorption heat pumps which although not competitive, they offer excellent prospective for the near future. In addition, this technology has good chances to be implemented in trigeneration plants or in solar cooling plants. These solutions could decrease substantially the high energy consumption for air conditioning in summer. This technology can also use a geothermal source, increasing the efficiency with a direct lowering of the costs of operation and becoming independent from the external temperature which, as seen, is a decisive factor for it. The possibility to use any type of fuel opens scenarios very interesting especially with the use of the pellets which brings low consumption cost and a reduced environmental impact.

These considerations is a starting point for further developments such as the study a geothermal heat pump absorption with direct combustion of pellets or with the use of hot water generated by solar thermal panels. These solutions represent the fusion among the positive characteristics of all the technologies analyzed.

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