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Technical and Cost-Optimal Evaluation of Thermal Plants for Energy Retrofitting of a Residential Building

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Abstract

With the adoption of the recast EPBD in 2010, EU Member States faced new tough challenges, moving towards new and retrofitted nearly-zero energy buildings by 2020 and the application of a cost-optimal methodology for setting minimum requirements for both the envelope and the technical systems. Attention often is focused on building envelope technologies however nowadays technical systems can be a powerful instrumental factor in achieving high levels of energy efficiency. Thermal systems producing heating and cooling have higher investment costs but it is possible to demonstrate that in a long term they are cost effective related with traditional high efficient technologies. Refurbishment and energy retrofitting in residential buildings is frequently approached with standard and traditional technologies preventing the penetration of different but already consolidated solutions. The paper shows the technical and economical comparison between three technical systems (gas boiler, ASHP and GSHP) as option to replace an oil boiler after a whole refurbishment of an apartment residential building in Milan, Italy. The retrofitting of the envelope was standard nevertheless the most innovative choice was on thermal system.

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Keywords:energy saving technologies, technical systems, technical and economical evaluation.

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1. Introduction

European Member States shall take the necessary measures to ensure that when buildings undergo major renovation, the energy performance of the whole building or the renovated part thereof is upgraded in order to meet minimum energy performance requirements so far as this is technically, functionally and economically feasible [1]. A technical and economical evaluation on energy saving strategies in building retrofitting it is thus crucial to evaluate cost effectiveness of such solutions [2]. The average annual energy consumption for heating in European countries varies from 150 to 230 kWh/m^2 [3] depending on climate zones, while in Italy the annual consumption for heating in the residential sector can be estimated at about 120-130 kWh/m^2 and in Northern Italy about 170-180 kWh/m^2. The average efficiency of thermal systems is between 75% and 80%.

The distribution of final energy consumption in the residential sector in Italy shows that heating is responsible about 70% due mainly to the characteristics of Italian households, but cooling demand is constantly increasing. In Italy, the new buildings represent less than 2% of the national total building stock and a percentage of 20% of the buildings were built before 1919. Today, more than 30% of the buildings have at least 50 years and a percentage of 64% is made up of houses built before the Law 373/1976 [4], the first Italian law to control heating energy consumption in buildings. It is easy to understand that the energy quality of the national building stock is far from the requirements introduced by national [5,6] and European regulations, however for this reason, the improvement can be relevant.

Nomenclature

OB	Oil Boiler
GB	Gas Boiler
ASHP	Air Source Heat Pump
COP	Coefficient of Performance
GSHP	Ground Source Heat Pump
ROI	Return of Investment
NPV	Net Present Value
TCI	Total Costs of Investment
OC	Operating Costs
TCO	Total Costs of Ownership

2. Case Study

The case study described in this paper is an apartment building (Fig.1) of the ‘70s in Milan, Italy, interested by a complete energy retrofitting by consolidated and replicable strategies [7]. Before the interventions the primary energy consumption supplied by the oil boiler (OB) was approximately 1,500 MWh/year. Power consumption reduction, evaluated as primary energy, after the refurbishment was higher than 80%, since the requirement is reduced from 225 kWh/m^2 year to 40 kWh/m^2 year by interventions on the envelope (i.e. insulation layer addition and enhanced windows) and thermal generation system. Primary energy value encloses other terms that are independent from the actual consumption of fuel as, for example, the electrical consumption due for pumping. Furthermore, using electricity, the specific consumption refers to a quantity of thermal energy equivalent in the national energy system, i.e. almost 2.5 times the electricity used [8]. The solutions adopted to retrofit the building envelope were fairly standard; a detailed evaluation of the thermal system technology was conducted, considering energetic, technical and economical factors [9,10,11]. For this purpose three thermal systems in replacement of existing oil fired boiler were compared. The systems, described in the following, are: gas condensing boiler, air source heat pump and ground source heat pump.

3. Plants features and specifications

The functionality of the systems had to be optimized with the existing structural constraints and the only options taken into account (as new heating system generator) were the ones whose return of the investment (ROI) is between 3 and 5 years. The described systems are alternatives, and possible compromises to limit the initial investment ensuring high efficiency [12,13].

The following assumptions are based on an energy requirement of the housing of about 3,362 GJ (equal to approximately 82,000 liters of diesel fuel per year). This value results by the new thermal insulation, ensuring a reduction by approximately 30% compared to consumption of the building before the retrofit on the envelope. The annual operating cost would therefore amount to approximately 82,500 €/year.

3.1. Modular condensing boilers

The gas boiler (GB) is the most immediate solution but the less efficient system. Substantially the intervention would consist in the replacement of the existing boiler with gas condensing boilers. To avoid the problems associated with fire prevention regulations, it would be advisable to use open spaces. The idea is to replace the existing central heating plant with a single, modular gas boiler. This solution implies a reduction of the length of the pipes and a simpler management, in accordance with mandatory fire regulations. The inherent problems are the identification of the designated spaces on the rooftop of the building and gas pipeline network to connect the highest floors. The consumption in terms of methane would be about 101.000 Nm3/year, which means, with a supply price of 0.75 €/Nm3, an annual cost of about 76,000 €. The economical savings can be therefore estimated in approximately 10 to 15% compared with existing system.

3.2. Air source heat pump

The air source heat pump (ASHP), equipped with fans, has a not negligible visual impact, that has to be carefully assessed, and a noise impact that may be mitigated with additional costs. The energy consumption, considering an average coefficient of performance (COP) in winter of 3.5 (optimistic), can be estimated in 267,000 kWh/year and the operating costs, assuming a price of electricity equal to 0.22 €/kWh would amount to 59,000 €/year. In comparison with oil, savings of 30% could be achieved.

3.3. Ground source heat pump

The construction features of the building allow the adoption of a heat pump with ground exchange, using geothermal probes (GSHP) below the first underground floor (i.e. car parking), or a system using as exchange fluid outside air. A heat pump system would achieve the complete thermal needs of the building in winter and partially in summer (in this second case only sensible heat needs can be fulfilled due to limitation in the distribution system). The primary energy to feed these heat pumps may be electricity or natural gas but in this analysis were considered only the electrical type, due to constraint related to fire regulations [14].

Using a geothermal heat pump with low enthalpy (GSHP) there are not visual and noise impacts and efficiency is higher. With this system it is possible to cool the building during the summer simply by circulating the water between the geothermal heat exchanger (Fig.1) and the terminals, without using the heat pump, therefore called “free cooling”, reducing costs. Average winter COP may exceed 4.8 resulting in an annual consumption of 200,000 kWh of electricity. Operating costs, assuming a price electricity of 0.22 €/kWh would be around 44,000 €/year. Savings of about 50% could be achieved.

Fig. 1. (a) Façade of the residential building; (b) garage plant with the excavation to install the probes; (c) probes used in the project.

4. Methodology

Considering the cost of electricity as 0.22 €/kWh subjected to an annual medium increase of 2% was calculated the net present value (NPV) of the thermal plants. By this economic parameter it is possible to understand if the investment is profitable, when the NPV is positive. The NPV value is calculated as:

$$NPV = -TCI + \sum_{t=1}^{n} \frac{F_t}{(1+r)^t} \tag{1}$$

Where TCI is the total costs of investment, expressed in €; F_t is the cash flow, i.e. the annual saving, expressed in €; r is the national interest rate (4%); t represents the progressive number of the year [15].

5. Result and discussion

In table 1 for the existing system and for each option proposed are resumed the total cost of investment (TCI), operating costs (OC) and total costs of ownership (TCO) including the total cost of acquisition and operating costs. It must be added that maintaining the oil boiler (OB) or using the gas boiler (GB) additional adjustment costs related to fire regulations have to be considered. Using ASHP costs to achieve noise mitigation have to be added.

Table 1 Investment cost and operating cost for the different thermal systems in two temporal scenarios.

	Total costs in 10 years			Total costs in 20 years		
Plant	TCI [€]	OC [€]	TCO [€]	TCI [€]	OC [€]	TCO [€]
Oil boiler		1.250.000	1.250.000		2.500.000	2.500.000
Gas boiler	130.000	760.000	890.000	130.000	1.520.000	1.650.000
ASHP	220.000	590.000	810.000	220.000	590.000	1.400.000
GSHP	450.000	300.000	750.000	450.000	600.000	1.050.000

The amounts of energy expressed are shown for each system considering the existing building (EB) and the refurbished building (RB) equipped with the different thermal systems (Fig. 2). For each thermal system the running cost in 10 and 20 years are plotted (Fig. 2).

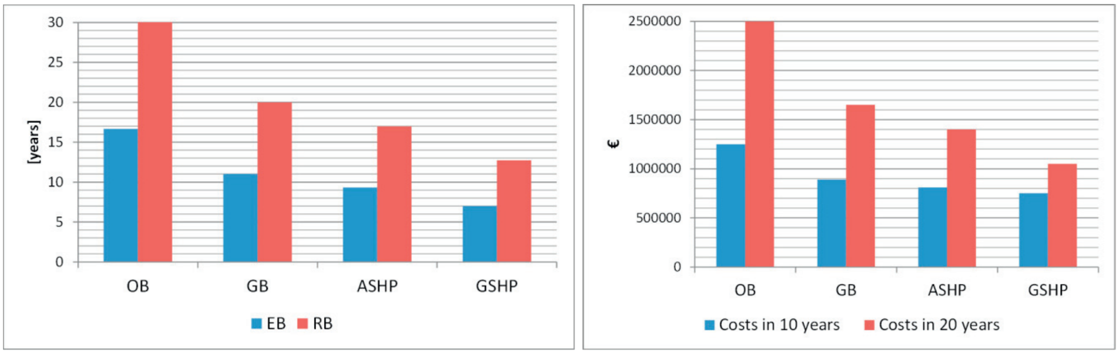

Fig. 2 Thermal and electric energy and costs (investment + running costs) for the different cases.

The NPV curves calculated for the three compared plants (i.e. gas boiler, ASHP, GSHP) are plotted in Fig. 3. It is possible to appreciate that the air source heat pump shows better results in term of cost-optimal performance in the short term however the GSHP, which is the system installed after the evaluation process in the case study, is cost-effective in a period that is compatible with the operating life of the building and present an higher NPV compared to ASHP after 15 years.

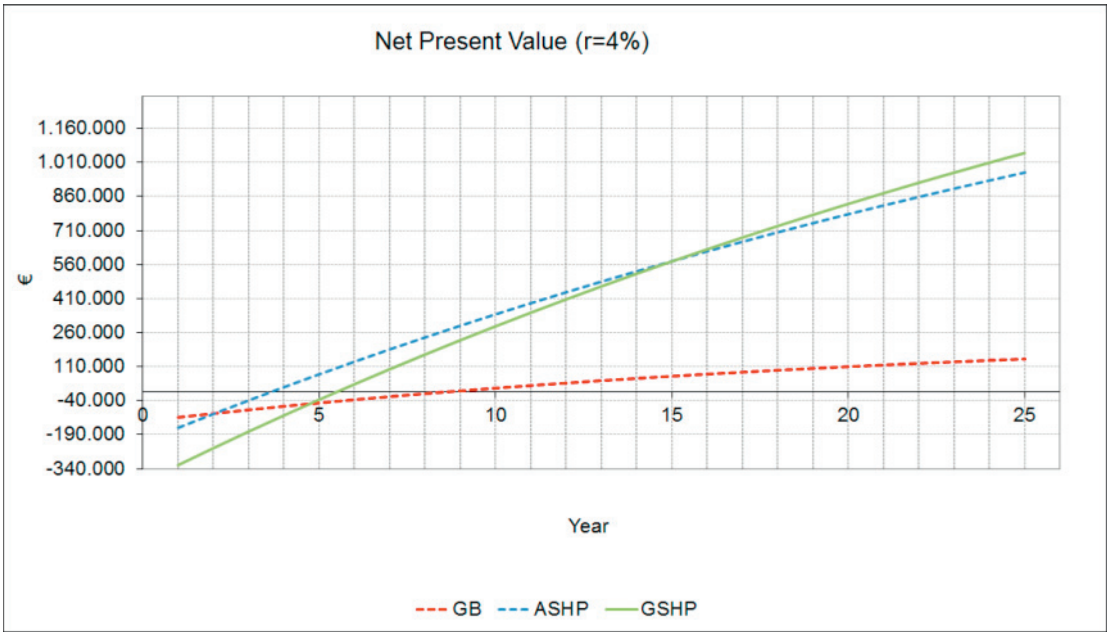

Fig. 3 Curve NPV for the three thermal systems compared.

6. Conclusions

Energy retrofit on existing buildings has high potential in reducing consumption on the building stock. Strategies and systems with high efficiency and economical feasibility have to be assessed and calculated in order to supply methodologies for intervening in the hugest scope of energy decrease in the built environment. Reduction of primary energy consumption for heating and air conditioning of about 80% is achievable with simple interventions of increasing thermal resistance of the building envelope and establishing a synergy with the thermal plants. Existing building structural constrains and more severe regulations for energy, healthy and safety can be complied with cost effectiveness solutions installing ground source heat pumps in the lower spaces of the buildings. The more expensive and invasive technological solution as first glance results to be more efficient and cost-optimal by a technical and economical analysis.

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