Energy Efficient Building Design: the “Borgo Solare” Case Study

Niccolò Aste, Umberto Beneventano, Michela Buzzetti, Lavinia Tagliabue

Department of Building Environment Science & Technology, Politecnico di Milano, Milan, Italy

ABSTRACT: The purpose of the article is to describe the work carried out for an Italian project concerning the construction of a sustainable settlement named ‘Borgo Solare’. Borgo Solare is a residential complex situated in the outskirts of the town of Ferrara, constituted by buildings, squares, cycling tracks, green parks, water channels, fountains and a small lake. The main feature of Borgo Solare is that the whole project will be realized according to the criteria of sustainable architecture. This work consists in a specific analysis of the energetic aspects (loads and materials) of a small storey building. The purpose is an appraisal of the weight of the various factors related to environmental impact. The building is analysed in terms of energy performance, economic evaluation and environmental impact.

Keywords: residential building, energy performance, quality, sustainable architecture

1. INTRODUCTION

The project designing of Borgo Solare is carried out by a team of architects and researchers of Politecnico di Milano that have placed side by side the planning since the first steps and the real estate company Gambale that operates in the field of sustainable building components production.

The purposes of the project were the realisation of a settlement near Ferrara, in Northern Italy. The sustainability should be the central theme of this work, with a specific attention to energy performance of the buildings, the relationship with sun, green spaces and water, the connection to the urban context and compliance with local building traditions.

Preliminary studies have been focused to the distribution of the buildings in the site and to the consequent solar availability. The purpose was to realize the morphology and the configuration to optimise solar gains in winter and passive cooling in summer.

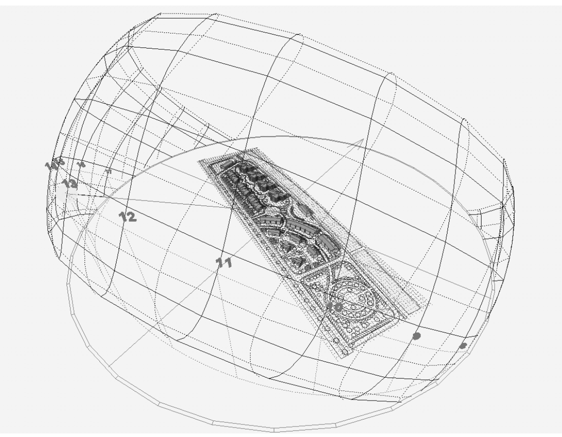

Figure 1: Solar evaluation of the settlement.

The relationship with water and green spaces has been studied to pursue a favourable external microclimate with benefits also on built environment.

In figure 1 it is shown a preliminary study about solar influence on the settlement.

The present study is focused on a specific building of the settlement, currently in phase of project and development.

The building is constituted by three plans and is subdivided in to 15 apartments. The specific morphology permits access to ventilation and irradiation for all apartments to achieve indoor air quality and use of environmental factors to minimize energy needs. The ratio of transparent and opaque envelope is nearly 20%. The balconies have been dimensioned to protect windows during summer and permit sun penetration in winter period.

Until 2005 the energy law in the Italian normative context was represented by the Law 10/91 which was an interesting and articulated energy law also with a first proposal of energy certification for built energy quality [1]. Since October 2005 the new Italian “energy efficiency in building” law, DL 192/05, is referred to the Directive 2001/91/CE and is mainly focused on heating loads that are restricted respect of the values indicated in the L10/91. The DL192/05 is related to increment in energy efficiency of buildings and introduces some control principles on summer load cooling [2].

The aim of Borgo Solare project is to realize higher performance energy buildings which respect both the old and actual limits by law, and in this work the planning choices are verified in an optic of economic feasibility and environmental sustainability, compared with the energy laws standards. The summer cooling load in building is not considered in the L10/91 and is marginally mentioned in DL192/05, therefore the present work is focused only on the theme of building heating load.

The majority of Italian built environment are characterized by elevated levels of consumption but, in an optic of energy reduction, some voluntary certification have been developed to establish energy limits, like KlimaHaus of province of Bolzano that resumes European energy quality standards (Denmark, Austria, Germany, France). It has been noted that in Italy this is the more relevant step to energy efficiency in building. For this reason the standards adopted in the Borgo Solare project are inspired to this virtuous model.

2. METHODOLOGY

2.1 Analysis themes

The analysis methodology carried out in this work is articulated in evaluation steps related to energy and economical aspects of the building:

1. Energy performance of the building (heating);
2. Economical evaluation of construction materials and operating costs with high performance HVAC systems;
3. Evaluation of embodied energy in materials;
4. Environmental impact measured in CO_2 emissions.

The case study is a three storey residential building with a T shape floor plan, optimized in function of orientation, solar availability and surrounding natural and built environment.

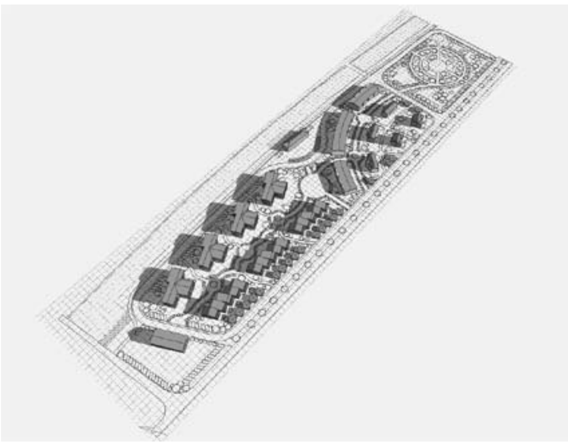

Figure 2: View of the settlement

2.2 Building specifications

The building analysis is conducted on three levels of energy quality, defined from the envelope thermal resistance, ecological properties of building materials, related to embodied energy, and plant efficiency. The analysis conducted consists in energy simulation and economic and environmental evaluation of the building compliance to the different energy standards by law described previously (L10/91, DM192/05, KlimaHaus). The three different standards have been applied in three different versions of the building, named respectively Case A, Case B, Case C. The analysis assumes as variables the envelope stratification and HVAC system typology. The building shape and characteristics and the other system components remain unchanged. Because the differences of the three case studies concerning variations in envelope stratification and efficiency of the plants, economic and energetic evaluation are referred to these items.

Considering the architectural ,a great part of building embodied energy is due to the envelope. For this reason in the analysis it is considered only this relevant quote. The reference values of grey energy are taken from Italian production standards [3].

Also the cost analysis estimates only the envelope materials. The labour and construction costs are considered equivalent for the three kind of envelope, that differ in stratification layers. Therefore the costs are calculated only for vertical walls, windows and insulation materials used in the different cases. No evaluation was made on the structure, paints and finishes. On the other side, the costs indicate for the HVAC systems are related to standard products availability in the market and are referred only to the central generators considering the same connected distribution systems in the building.

The elaborated data are as follows:

- total loss surface area	(m^2)	1964
- total windows surface area	(m^2)	168
- floor surface	(m^2)	1162
- volume of thermal zone	(m^2)	1155

The base case (A) respects the standard of the L10/91 that recently has been integrated with the DL192. The new energy law introduces limits of energy consumption (for site and morphology) and U-value (for opaque and transparent envelope) but for the energy calculation the reference is still the L10/91. The second type of envelope (B) is constituted to observe the heating limits ($\leq$80 kWh/m^2 year and Surface/Volume ratio = 0.5) and U-value (0.46 W/m^2K vertical opaque envelope, 0.45 W/m^2K horizontal opaque envelope, 2.8 W/m^2K transparent envelope) supplied in the tables of DL192 for the zone including Ferrara city (Climatic Zone: E). The third case C pursues the best practice for energy reduction in Italian context with envelope characteristic to obtain heating load lower than 30 kWh/m^2 year (Class A standard KlimaHaus) [4].

2.3 Plant specification

The energy performance analysis considers two different HVAC systems to evaluate primary energy needs. The heating plants assumed are characterized by high performance to provide the necessary energy, and presupposed solutions for the energetic reduction as sustainable systems. The two hypotheses assumed for HVAC plants are: a geothermal heat pump and a condensing boiler alimented by natural gas. The efficiency values are considered taking into account also the average efficiencies related to thermal regulation, building flats distribution and supply terminals (supposed radiant floors) are:

1. HP - COP = 3.8
2. CB - η = 0.85

The CB efficiency value includes the performance reduction due to the aging of the condensing boiler, higher with respect to the same process for the heat pump.

As introduced before, no evaluation have been made about heating elements, distribution systems and accessory devices, their cost is considered approximately equivalent in both (CB and HP) the cases. Even the maintenance costs are considered equivalent and therefore not taken in account in the evaluation. This hypothesis is highly conservative for the heat pump, because it can be easily proven that HP yearly maintenance is cheaper than the one required for the CB system, according to the Italian law and standards.

The analysis evaluates the envelope capability on thermal regulation and the values of thermal energy consumption. The run costs of the building and the pay back time are estimated in relation with both HVAC system typologies. In the base case the hypothesis on HVAC plant make provision for only the more conventional system because it seemed that it is not suitable to install a high performance plant in a building characterized by a low performance envelope.

The thermal power of the plants foreseen in the three cases results from the energy simulations explained below. The adopted values are shown in the following table.

Table 1: Type and thermal power of the HVAC palnts

Case	Type of HVAC plant	Thermal power (kW)
A	CB	61
B	CB, HB	31
C	CB, HB	21

2.4 Simulation tool

The energy and environmental performances of the cases study has been carried out by using the software EnergyPlus 1.2.3.031, which runs exhaustive analysis on hourly base, with a greater detail with respect to the standard calculation procedures indicated by law.

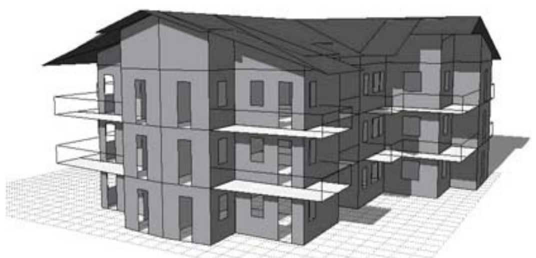

Figure 3: Building simulation model.

3. BUILDING ANALYSIS

The analysis assumes common Italian standard parameters related to the functional destination of the building. The value considered for internal gains in the thermal zones is 5 W/m^2; the air changes estimated, due to ventilation and infiltration, are 0.5 V/h (reference value suggested by UNI EN 832) [5].

3.1 Case A (base case L10/91)

The envelope is constituted from vertical and horizontal massive part to exploit the thermal mass, without other insulation layers, and transparent window surfaces capable to gain a percentage of 84.5% (SHGC – Solar Heat Gain Coefficient) of thermal energy from solar radiation. The envelope is made to respect heat loads limits. The stratification consists in an external brick, an air gap (9 cm) and an internal hollow brick with plaster. The total wall thickness is 30 cm.

Table 2: Case A - Envelope materials and U-Values.

Envelope surface	Element	Materials	U-value [W/m^{2}K]
Opaque	wall	plaster/brick/ air gap/hollow brick/plaster	1.50
	floor	concrete slab on ground/tiled floor	1.50
	roof	tiled pitched wood/concrete slab	0.81
Transparent	window	single glazed timber frame	6

The materials used in this technological solution involve a value of embodied energy that is part of the energy balance and environmental impact of the building.

The insulation layer is not used in the base case but is added in other two cases (in vertical walls and in the slabs). The embodied energy calculated for the base case A, therefore, includes only materials related to vertical skin of the building (opaque and transparent).

Table 3: Case A - Embodied energy of materials.

Material	m^3	kWh/m^3	kWh
Brick	105.84	1250	132’300
Hollow brick	70.56	815	57’506
Windows	6.72	15000	100’800

The total amount of embodied energy for this case is 290 MWh (2.5 kWh/m^2 year referred to floor area).

For the case A the cost related to the materials considered is 56’784 €. The CB plant assumed cost is 7’000 €.

3.2 Case B (DM192/05)

The second case, that introduces the new law thermal limits for U-values and heat load, adds to the case A stratification an insulation layer in polystyrene (in vertical layer 5 cm, in horizontal layer 6.5 cm) partitions. In the vertical wall the insulation material is inserted in the air gap that is reduced to 4 cm. In order to reach the standard U-value the transparent surfaces are improved with double glazed timber frame windows. The double glazed window with gas argon in the gap offers high performance in heat loss reductions but permits a minor heat gain due to solar radiation (SHGC = 75%). The total wall thickness remains equal to case A.

Table 4: Case B - Envelope materials and U-Values.

Envelope surface	Element	Materials	U-value [W/m^{2}K]
Opaque	wall	plaster/brick/ insulation/air gap/ hollow brick/plaster	0.44
	floor	concrete slab on ground/insulation/tiled floor	0.40
	roof	tiled pitched wood/insulation/ concrete slab	0.34
Transparent	window	double glazed timber frame	2.7

The embodied energy increase is consequential mainly to the interposition of polystyrene board that requires a chemical and complex production process with use of propellant gases. This process has a high environmental impact related to atmospheric pollution and during the operating time of the building, risks are connected to toxic emissions in case of fire.

The increment of embodied energy is related to double glazed windows too. The total amount of the embodied energy in this case is about 452 MWh (3.8 kWh/m^2 year referred to floor area).

Table 5: Case B - Embodied energy of materials.

Material	m^3	kWh/m^3	kWh
Polystyrene extruded	86.45	700	60’515
Brick	105.84	1250	132’300
Hollow brick	70.56	815	57’506
Windows	13.44	15000	201’600

The estimated cost related to the variations in building materials grows up to 85’206 € with an extra cost about 28’422 €. The economic increment with respect to the base case is due to the insulation material and the better windows. The HVAC plants costs are: for the HP system 25’000 € and for the CB system 5’000 € (+18’000 € and -2000 € with respect to the base case). It must be noted that the economic saving for the CB system is related to the best performance of the building and the energy reduction achieved).

3.3 Case C

The envelope stratification adopted in Borgo Solare resumes the local traditional constructive practices adding materials characterized by elevated energy performance. In stead of the simple brick, the massive part of the wall is made of a high performance thermal-brick (Poroton), lightened with additional materials to improve thermal properties.

An external additional insulation layer is realized with natural panes of wood fiberboard, more ecological in terms of component, production process, possibility of sustainable cast off and occupant safety and security.

However the wood fiberboard is 20% more expensive with respect to synthetic insulation material.

The KlimaHaus standard adopted defines U-values for all opaque and transparent building elements with high performance. In the case C, thermal characteristics respect the limits indicated for the best energy performance (Class A).

To obtain high energy performance levels for windows the glass stratification include a double glass with low-e coating and gas argon in the inner gap with the consequent cost increment. The SHGC factor is 60% but the heat loss reduction with respect to a single glazed window amount to 62%.

Table 6: Case C - Envelope materials and U-Values.

Envelope surface	Element	Materials	U-value [W/m^{2}K]
Opaque	wall	plaster/poroton/ insulation/air gap/ hollow brick/plaster	0.22
	floor	concrete slab on ground/insulation/ tiled floor	0.36
	roof	tiled pitched wood/insulation/ concrete slab	0.22
Transparent	window	double glazed low-e timber frame	1.3

The embodied energy related to the integration of high performance materials in the constructive solutions in the case study C amount to 487 MWh (4.2 kWh/m^2 year, referred to floor area), very close to the value estimated for the case study B. This result is due to the higher thickness of insulation layer to reach the standard U-value although the embodied energy of the natural wood fiberboard is lower than polystyrene.

Table 7: Case C - Embodied energy of materials.

Material	m^3	kWh/m^3	kWh
Wood fiberboard	167.08	590	98’577
Proton	264.60	490	129’654
Hollow brick	70.56	815	57’506
Windows	13.44	15000	201’600

The envelope extra cost with respect to the base case to reach the energy reduction of heat load is about 60’437 €, due to the costs of the transparent surfaces and the insulation layer. The total cost amount to 117’221 €. It has to be noted that the cost of thermo brick with respect to the simple brick doesn’t result relevant. In this case the HVAC plants costs are respectively: for the HP system 18’000 € and for the CB system 4’000 € (+11’000 € and -3000 € with respect to the base case).

4. RESULTS

4.1 Energy performance comparison

The case A heat load is about 96 kWh/m^2 year, the consumption obtained with the restricted standard in order to pursue European Directive represented by case B amount to 42 kWh/m^2 year (-47% with respect to the upper limit indicated). The best case C results 25 kWh/m^2 year. The load reduction obtainable with the DM192/05 standard is about 56% and with the characteristics of Borgo Solare project reaches the quote of 74%.

The whole energy performance of the building is defined by the losses and gains balance consequent to envelope thermal quality and capability to use the amount of heat gain for energy indoor control.

The window distribution in the building design pursues the aim to reduce heat losses in the Northern orientation and to exploit the solar gains in the other orientations. The ratio between transparent and opaque surfaces is about 20%. The heat losses due to transmission through windows amount to 40% with respect to the losses connected to opaque surfaces in the case A, 62% in the case B and 58% in the case C. The window energy balance in winter period is heavily determined by the heat loss value in comparison of the solar gains, so the reduction of solar gains connected to the case C kind of window doesn't affect significantly the energy performance result, due to the best U-value.

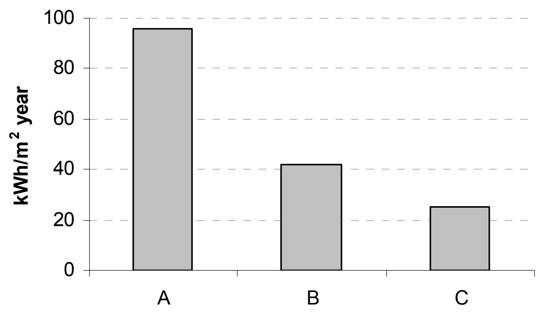

Figure 4: Heating loads of the building.

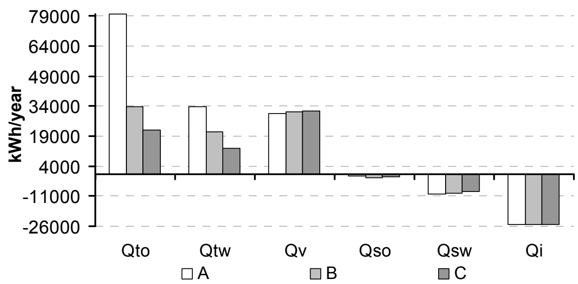

Figure 5: Thermal losses and gains (Qt=transmission losses through opaque and transparent surfaces, Qv=ventilation losses, Qs=solar heat gains due to opaque and transparent surfaces, Qi=internal heat gains.

The worse opaque envelope (case A) implies a relevant weight of thermal losses due to transmission with respect to the ventilation quote. This item become more and more significant in the thermal balance when the envelope thermal resistance grows. In the case A the incidence of ventilation heat loss with respect to the whole heat losses amounts to 21%, in the case B is 36% and in case C is 46%. For an average thermal resistance (opaque and transparent surfaces) of about 0.75 W/m^2K, ventilation becomes the more relevant factor with respect to the losses.

In figure 6 monthly thermal loads of the three cases are shown.

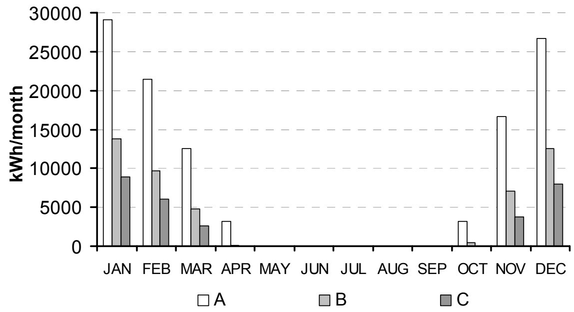

Figure 6: Monthly heating loads of the building.

4.2 Costs comparison

Considerations about materials costs evidence that the extra cost to improve the case A to case B amount 50%. For the best practice case (C) the materials cost results more than doubled with respect to the base case.

In figure 7, the materials costs are summed to HVAC systems costs for different hypotheses to visualize the initial building costs; it has to be noted that the increase of envelope materials cost involves a significant reduction for HVAC costs. In figure 8 operating costs data are shown.

Best results are achieved by the installation of the HP system in the best performance building (C) although the cost of electricity is three times more than natural gas (the costs are referred to Italian average energy context, i.e. electricity 0.15 €/kWh, thermal energy by natural gas 0.05 €/kWh).

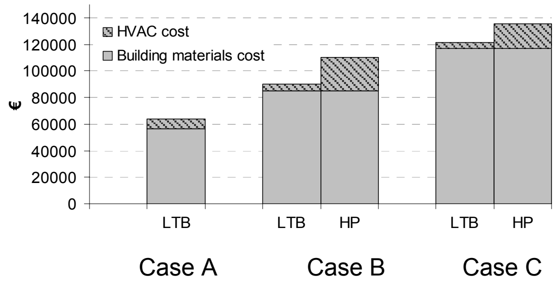

Figure 7: Initial costs for the buildings.

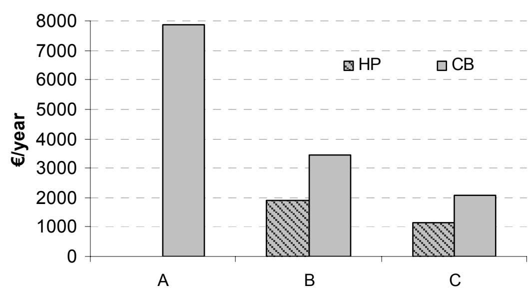

Figure 8: Operating costs of the buildings

The extra cost of the heat pump compared to the condensing boiler is five time greater but the operating costs are reduced by about 36%.

The cost analysis proceeds with the evaluation of the whole costs of the three case studies (due to materials improvement, HVAC investment cost and operating costs), considering a period of thirty years in which HVAC systems costs are considered amortizable.

The pay back time calculation is conservative and assumes the cost of energy (thermal and electric) fixed during the whole period although the growth trend of energy cost makes to preview a relevant reduction of the pay back time results.

Installing a CB system to supply energy to the three case studies, it is possible in case B and case C to amortize the initial extra cost through the operating cost reduction respectively in 7 and 11 years with respect to the case A. This pay back time is highly compatible with the user needs. In case of HP plants, the pay back time with respect to base case is slightly longer, although economically feasible.

The economical analysis is developed on thirty years basis. In this period, case B and case C result identical, but it has to be noticed that the real life cycle of the building is usually longer (over fifty years). Considering a long term period, the case C, with the best energy performance, represents the best choice, in terms of economics.

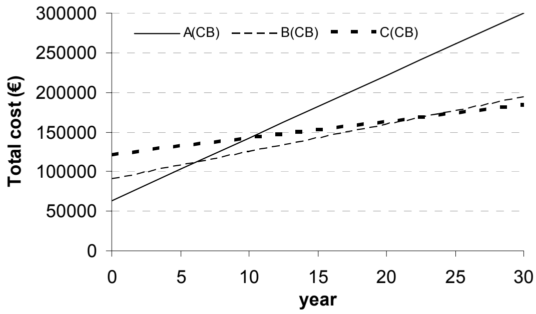

Figure 9: Costs of the buildings with CB system in 30 years.

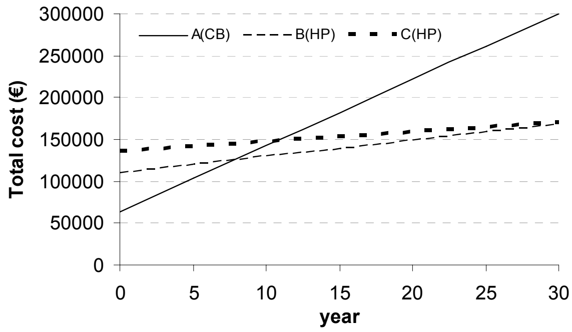

Figure 10: Cost of the buildings with HP system in 30 years.

4.3 Embodied energy comparison

The environmental benefits are highly relevant and imply advantages for whole society and environment. The following analysis is extended to fifty years to include a period adequate to the consequences on safety and environmental impact.

The increment of embodied energy due to high performance materials involves amount to 55% for case B case and 67% for case C, in respect to the base case. As shown in figure 11, considering the whole primary energy related to materials and energy operating needs in 50 years, there is a relevant reduction with respect to the base case, for case B (52% with CB and 70% with HP), still more relevant for case C (68% with CB and 79% with HP).

The advantage with HP installation to energy supply permits to assert that a best choice for human and natural environment is achieved by energy efficient envelope coupled with a HVAC high performance plant.

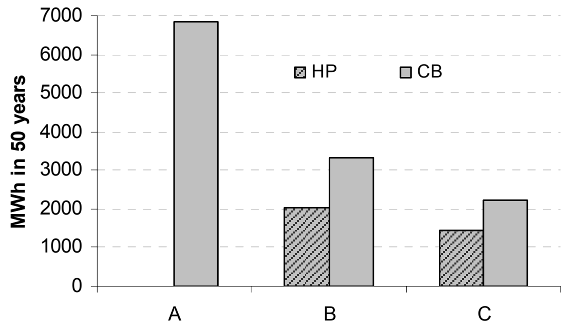

Figure 11: Amount of primary energy of the buildings.

The analysis doesn't include primary energy for supply systems, and this has been considered the same for the different cases.

4.4 Carbon dioxide (CO_2) emissions evaluation

The environmental analysis is concluded with the CO_2 emissions analysis related to the different HVAC system energy supply.

As foreseen respect to the base case A, the case B results an atmospheric pollution reduction of about 56% with the use of CB system and 70% with HP plant. The best practice case C reaches to about 74% with CB system and 81% with HP plants. This shows that the better energy performance corresponds to less environmental impact.

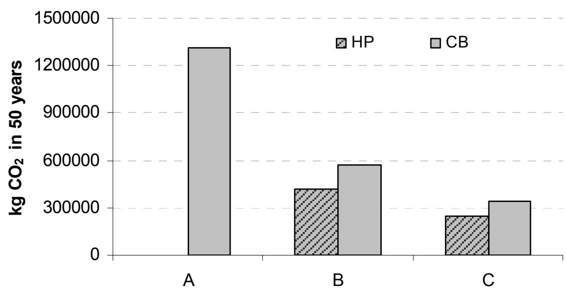

Figure 12: Carbon dioxide emissions related to heating loads.

5. CONCLUSIONS

The analyses presented in this study demonstrate the validity of the application of the sustainable architectural criteria. From economic point of view, it is shown that the improvements in the envelope thermal properties and in the HVAC plants in respect to the old Italian normative standards are convenient and are repaid in few years. In the long term, moreover, the cost of application of advanced standard, as those used in Borgo Solare, appears more convenient to that prescribed by the new normative.

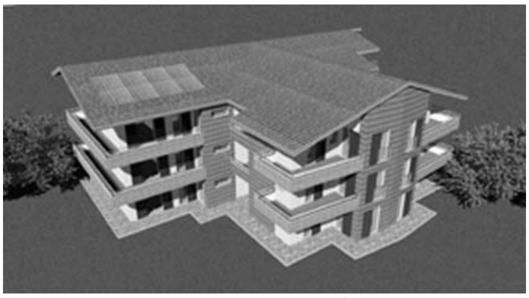

Figure 13: Building render (case C).

The building solution characterized by best energy performance allows economical feasibility and a significant reduction on environmental impact on ecosystem. The conservative estimation, due to the simple pay back time calculations, permits to evaluate benefit of major relevance at the real conditions.

The evaluation on system costs comparing condensing boiler and heat pump doesn't consider the advantage and cost reduction with the possible summer use of the heat pump for cooling. Since in the Italian context the request for summer air-conditioning is following a growth trend resulting a heavy increase in the electric consumption, it is possible to foresee an additional requirement of cooling supply systems. With traditional solution this fact involves ulterior pollution, additional cost for the plant and an adaptation work on the building avoid with heat pump use.

REFERENCES

[1] Legge 9 gennaio 1991,n.10 - Norme per l'attuazione del piano energetico nazionale in materia di uso razionale dell'energia, di risparmio energetico e di sviluppo delle fonti rinnovabili di energia.

[2] Decreto Legislativo 19 Agosto 2005, n.192 - Attuazione della direttiva 2002/91/CE relativa al rendimento energetico nell'edilizia.

[3] ITACA, Gruppo Interregionale in materia di Bioedilizia, Protocollo ITACA per la valutazione della qualità energetica ed ambientale di un edificio, Roma, 2003

[4] Klima Haus, Autonome Provinz Bolzen – Südtirol, Amt fur Luft und Larm, 2006

[5] UNI EN 832:2001 – Thermal Performance of buildings – Calculation of energy use for heating – Residential buildings, CTI – Comitato Termotecnico Italiano UNI.