

Paper III

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WHOLE COST ANALYSIS OF BUILDING ENVELOPE TECHNOLOGIES ACCORDING TO THE EUROPEAN STANDARD EN 15459

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Abstract: *The thermal design of a building is a compromise between different needs: fulfilment of performance requirements, energy savings and cost savings. While the best energy system is usually chosen by means of an economic evaluation, the selection of façade technologies is frequently a compromise between intent of the architect, constraining energy requirements and budget. A specific method for the calculation of the economic performance of energy saving options in buildings has been introduced by the European Standard EN 15459 (in Italy UNI EN 15459:2008).*

In this work, the whole cost analysis method is applied, as outlined in the Standard, to assess the overall economic and energy feasibility of different types of building façade technologies. The aim is to apply this methodology in order to optimize the choice of building envelope that minimizes the hard costs due to construction and the operational costs due to energy consumption for heating and cooling.

This research shows the comparison of six different envelope technologies applied to a high rise office building. The energy performance is evaluated with a dynamic simulation

carried out by means of the ESP-r code. The cost of the energy source and the construction process is estimated using current Italian prices. Finally, the relationship between construction costs and energy costs is evaluated to define the economic effectiveness of each building envelope technology.

Keywords: Economic Evaluation, Energy Performance, Global Cost Calculation

1. INTRODUCTION

According to the new European Directive for energy performance in buildings, buildings account for 40% of total energy consumption in the Union. The sector is expanding, which is bound to increase its energy consumption. This trend raises some environmental issues such as the exhaustion of energy resources, global warming, the depletion of the ozone layer and climatic changes. In order to reduce the growing energy expenditure, the European Directive imposes the adoption of measures to improve the energy efficiency in buildings. These measures should take into account the local weather conditions as well as indoor climate environment and cost-effectiveness (2010/31/EU, 2010). The EPBD established that the European Union Member States should fix minimum requirements for the energy performance of buildings and building elements. Those requirements should be set with a view to achieving the cost-optimal balance between the investments involved and the energy costs saved throughout the lifecycle of the building. As a consequence, there is a growing interest on the overall sustainability of buildings, not only focusing on the consumption of non-renewable resources during their operating life, but also taking into account the global energy consumption and the overall economic performance during the whole lifespan of the building (Aste, Adhikari and Buzzetti, 2010). Therefore, the design of a building is a compromise between different needs: fulfilment of performance requirements, energy savings, cost savings. It is well known that the various criteria for the selection/optimization of an envelope technology or an energy system may show different results, depending on the criterion selected (Fabrizio, Filippi, Perino and Serra, 2006). While the best energy system is usually chosen by means of an economic evaluation (Fabrizio, Filippi and Virgone, 2009), the selection of façade technologies is frequently a compromise between the intent of the architect, the energy requirements and the budget (Vrijders, J. and Delem, L.) Particularly, frequently different building envelope typologies are compared by taking into account energy consumption and neglecting economic evaluation. The necessity of a method to calculate and compare economic performance of different energy saving options in buildings has arisen. This method has been introduced by the European Standard EN 15459 (Grignon-Massé, Rivière and Adnot, 2011). In this work, the global cost analysis method is applied, as outlined in the Standard, to assess the overall economic and energy feasibility of different types of building façade technologies. The aim of this research is to apply this methodology in order to optimize the choice of building envelope that minimizes the hard cost due to construction and the operational costs due to energy consumption for space heating and cooling.

2. RESEARCH PRACTICE

This paper shows the comparison of six different building envelope technologies (that have the same thermal transmittance) of a high rise office building case study in terms of

the whole cost analysis. The energy performance was evaluated following one of the three methods proposed by ISO CEN 13790:2008, which is the dynamic simulation carried out by means of the ESP-r code. The economic evaluation was carried out following the procedure described in the European Standard EN 15459. The costs of the energy source and the construction process (taking into account materials and on site work) were acquired from current Italian price lists. Finally, the relationship between construction costs and energy costs is evaluated to define the economic effectiveness of each building envelope technology.

2.1 Case study

A comparison between the trend of the last twenty years in energy consumption for residential and tertiary buildings in Italy shows a significant growth in the second category. From 1990 up to now, the total energy consumption in tertiary buildings has shown a growth of 42% (Enea, 2008). The analysis of the use of buildings could reveal an explanation for this trend. In fact, the relationship between enhanced comfort levels and productivity tends to increase the energy demand for heating and cooling space and artificial lighting. This is why this analysis focuses on a tertiary building.

The case study is a twenty-storey 36000 m² office building. The building is isolated and is characterized by a rectangular plan with main orientation on East and West. The geometrical data of the building are reported in Table 1.

Table 1. Building geometrical data

	Unit of measurement	Value
Building envelope area	m ²	12600
Opaque wall area	m ²	6300
Window area	m ²	6300
Ground floor area	m ²	1800
Roof area	m ²	1800
Gross area of typical floor	m ²	1800

The structure is built in reinforced concrete. The roof is plane, tiled and insulated. The ground floor is insulated and it is in contact with an unconditioned basement. The ratio of the transparent area to the opaque envelope is 50%.

Window components are constituted by a low-e triple glass filled with krypton and by a metal frame with thermal break. They are equipped with movable and adjustable external shading devices in order to control the excessive heat due to solar radiation during the summer and allow useful solar gains in winter. Table 2 lists the window features.

Table 2. Windows features

	Unit of measurement	Value
Type	-	triple glass (6-12-6-12-6 2lowE(2,5) krypton)
Thermal transmittance	W/m ² K	1,7
Solar Heat Gain Coefficient SHGC	-	0,65

In the present work, the opaque envelope is considered as it was built with six different types of façade technologies. All these different solutions have the same U-value, equal to 0,22 W/m²K, but present several values of superficial mass, M_s. The thermal and geometrical features of the six façade technologies are shown in Table 3.

Table 3. Thermal and geometrical features of the six different façade technologies

ID	Materials (from external to internal)	Thickness [cm]	U [W/m ² K]	M _s [kg/m ²]
1	Brick – Insulation – Lightweight Masonry – Plaster	56	0,22	654
2	Plaster – Insulation – Lightweight Masonry – Plaster	48	0,22	405
3	Concrete block – Insulation – Plaster	41	0,22	655
4	Brick – Insulation – Lightweight Masonry – Air Gap – Clay block	59	0,22	650
5	Aluminum Foil – Air gap – Insulation – Lightweight Masonry – Air Gap – Plasterboard	62	0,22	235
6	Stone – Air Gap – Insulation – Lightweight Masonry – Plaster	49	0,22	554

The building shape, the ground floor, the roof and the window components remain unchanged.

The energy system and the HVAC components are also the same for all the simulations. For heating and cooling, the considered primary system is a reversible heat pump; the terminals of heating and cooling system are four-pipe fan coil units.

3. CALCULATION METHODS AND TOOLS

In order to evaluate the performances of the different building envelope technologies, the adopted methodology is broken down into the following steps related to energy and economic aspects:

- energy performance evaluation;
- economic evaluation of hard cost due to construction;
- economic evaluation of operational cost due to energy consumption for heating and cooling.

3.1 Energy performance evaluation

The calculation of energy demand for the six versions of the case study was carried out by means of the ESP-r code which runs dynamic analysis on an hourly basis (ESRU 2002, Clarke 2001), with greater attention to detail and precision compared to the standard calculation procedures indicated by the European Standard EN ISO 13790:2008 (Corrado and Fabrizio, 2007). In particular, this standard proposes three different methods with several levels of detail to calculate the energy use for space heating and cooling of a building:

- a monthly quasi-steady state calculation method;
- a simple hourly calculation method;
- a detailed simulation method.

In this work, the energy performance was evaluated by the dynamic simulation method.

The building model was created in software Design Builder (DesignBuilder, 2008), which has a user friendly interface, and then imported in ESP-r. ESP is a general purpose, multi-domain (building thermal, inter-zone air flow, intra-zone air movement, HVAC systems and electrical power flow) simulation environment which has been under development for more than 25 years. It uses the pattern of `simulation follows description` where additional technical domain solvers are invoked as the building and system description evolves. Users have options to increase the geometric, environmental control and operational complexity of models to match the requirements of particular projects. It supports an explicit energy balance in each zone and at each surface and uses message passing between the solvers to support inter-domain interactions (Clarke 2001). ESP-r is distributed as a suite of tools. A *project manager* controls the development of models and requests computational services from other modules in the suite as well as 3rd party tools. Support modules include: climate display and analysis, an integrated (all domain) simulation engine, environmental impact assessment, 2D-3D conduction grid definitions, shading/insolation calculations, viewfactor calculations, short-timestep data definitions, mycotoxin analysis, model conversion (e.g. between CAD and ESP-r) and an interface with the visual simulation suite Radiance (Crawley, Hand, Kummert and Griffith, 2005).

ESP-r is distributed under a GPL license through a website which also includes an extensive publications list, example models, cross-referenced source code, tutorials and resources for developers. It runs on almost all computing platforms and under most operating systems. Although ESP-r has a strong research heritage (e.g. it supports simultaneous building fabric/network mass flow and CFD domains), it is used as a consulting tool by architects, engineers, and multidisciplinary practices and as an engine for other simulation environments.

3.1.1 Dynamic simulation assumptions

The office building was partitioned into one unconditioned thermal zone (below ground floor) and zones representing each single open space offices. The proposed case study was modelled by four open space offices (North, South, East and West) for each floor. As a consequence, the layout of a typical floor was designed by four rectangular plant open space areas, modelled as single thermal zones. Two of these with a main orientation to the South and North respectively have three external walls. The other two, with main orientation to the East and West have only one external wall. The case study floor typical layout is shown in Figure 1.

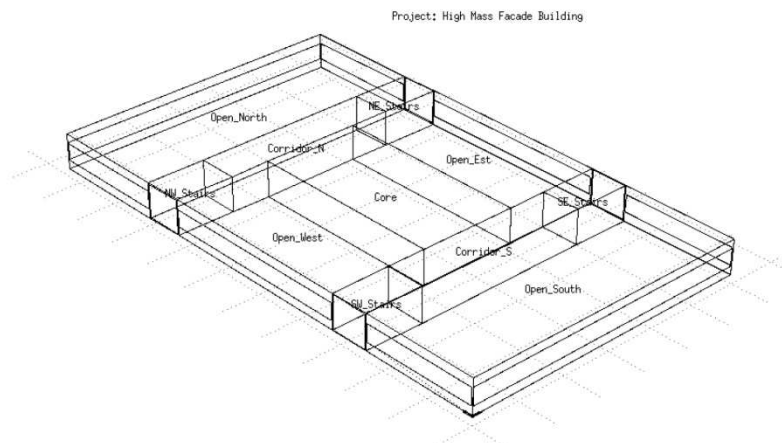


Figure 1 - ESP-r wireframe model of case study floor typical layout.

The input data used for the analysis consisted in the different thermo-physical building envelope features and system specifications.

In order to cancel out the effects of system intermittency on energy demand, a continuous operating schedule of the HVAC system was considered in all cases, assuming a dual setpoint with deadband control, with a heating set point of 20 °C and a cooling set point of 26 °C.

Internal gains were assumed to be equal to 6 W/m² with a constant schedule and a constant ventilation flow rate of 0,7 volumes/h.

To simulate the solar control, it was assumed that if the total solar radiation incident on the windows exceeded 300 W/m², the shading devices would be active.

The weather data used for simulations correspond to a typical meteorological year in Turin, which is located in the North West part of Italy at the foot of the Alps and has a continental climate with cold-dry winters and hot-humid summers. The hourly weather data of Turin were taken from the International Weather for Energy Calculation database (IWEC weather files) developed by ASHRAE in 2001.

3.1.2 Annual electricity consumption for space heating and cooling

The annual energy needs for space heating and cooling for the analyzed six different types of façade technologies are shown in Figures 2 and 3 respectively.

The same type of primary energy system, a reversible heat pump for heating and cooling, was adopted in all the various ID. The features of the heat pumps chosen for the six buildings characterized by different envelope technologies are reported in Table 4.

Table 5 reports the annual energy use for space heating and cooling for the six configurations.

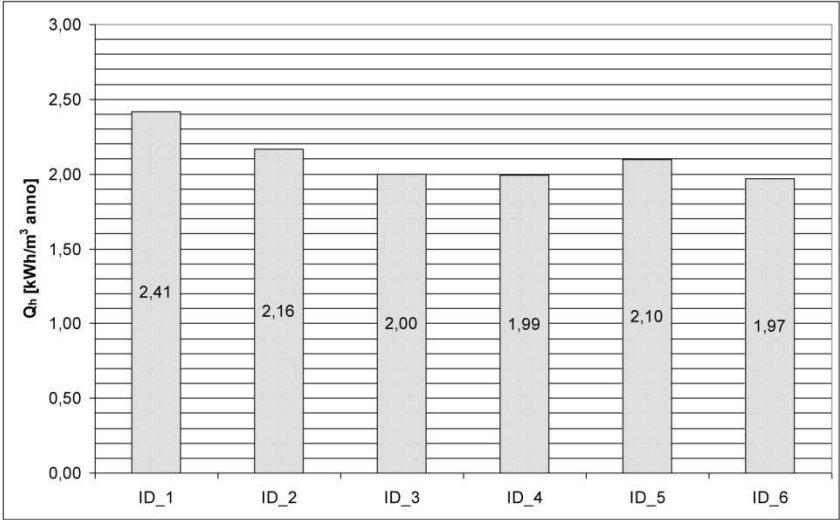


Figure 2 - Annual energy needs for space heating.

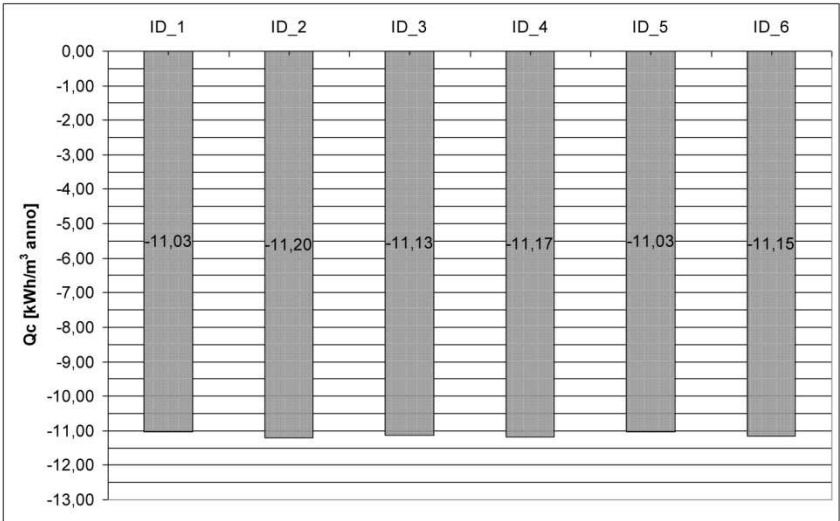


Figure 3 - Annual energy needs for space cooling.

Table 4. Heat pumps features

	ID_1	ID_2	ID_3	ID_4	ID_5	ID_6
P_c [kW]	150	150	110	165	165	150
EER [-]	2,92	2,92	2,12	2,13	2,13	2,92
ESEER [-]	4,15	4,15	3,83	3,85	3,85	4,15
P_h [kW]	171	171	129	201	201	171
COP [-]	3,28	3,28	2,99	3,08	3,08	3,28

Table 5. Energy consumptions for space heating and cooling

	ID_1	ID_2	ID_3	ID_4	ID_5	ID_6
E_H [kWh _e /m ³ year]	0,74	0,66	0,67	0,65	0,68	0,60
E_c [kWh _e /m ³ year]	2,66	2,70	2,91	2,90	2,86	2,69

3.2 Economic evaluation

The economic evaluation was carried out following the procedure described in the European Standard EN 15459. This standard provides a calculation method for the economic issues of heating systems and other systems that are involved in the energy demand and energy consumption of the building. It can be applied to all types of buildings. The described method can be used, fully or partly, for the following applications:

- to consider the economic feasibility of energy saving options in buildings;
- to compare different solutions of energy saving options in buildings (e.g. plant types, fuels);
- to evaluate economic performance of an overall design of the building (e.g. trade-off between energy demand and energy efficiency of heating systems);
- to assess the effect of possible energy conservation measures on an existing heating system, by the economic calculation of the cost of energy use with and without the energy conservation measure.

This standard is part of the method for calculation of economic performance of energy saving options in buildings: for example, insulation, better performing heat generators and distribution systems, efficient lighting, renewable sources, combined heat and power.

EN 15459 describes two different calculation methods: global cost and annuity cost method.

According to the first method, all the costs refer to the starting year by applying an appropriate *present value factor*. The whole cost is determined by summing up the global costs of initial investment costs, periodic and replacement costs, annual costs and energy costs and subtracting the global cost of the final value.

For the annuity cost calculation, the calculation period is fixed and corresponds to the intended payback period of the building. The total annualized cost is determined by summing up the annualized costs of systems and components (investment and replacements), the annual costs (operational costs, maintenance costs, added costs) and

the energy costs. The different types of investment and replacement costs are converted to annualized costs by applying the appropriate *annuity factor*.

In this research, the EN 15459 was used to compare different envelope solutions evaluating their global costs. According to the Standard, costs were separated into investment costs (including periodic replacement of components and systems) and running costs. Organisation of the different types of costs is given in Figure 4; the boxes with costs that were taken into account in this evaluation are coloured in grey.

Calculation of global cost considers the initial investment C_1 and for every component or system j the annual costs for every year i (referring to the starting year) and the final value. Global cost is directly linked to the duration of the calculation period τ and it can be written as:

$$C_G(\tau) = C_1 + \sum_j \left[\sum_{i=1}^{\tau} (C_{a,i}(j) \cdot R_d(i)) - V_{f,\tau}(j) \right] \quad (1)$$

where $C_G(\tau)$ represents the global cost referred to starting year τ_0 , C_1 is the initial investment cost, $C_{a,i}(j)$ is the annual cost for component j at the year i (including running costs and periodic or replacement costs), $R_d(i)$ is the discount rate for year i , $V_{f,\tau}(j)$ is the final value of component j at the end of the calculation period (referred to the starting year τ_0).

In order to refer the costs to the starting year, the present value factor f_{pv} or the discount rate R_d are used. In particular, for the replacement costs and the final value the discount rate coefficient R_d is utilized, while for running costs the present value factor f_{pv} is used.

The following equation expresses the discount rate coefficient R_d , which depends on the interest rate R_R :

$$R_d = \frac{1}{(1 + R_R)^p} \quad (2)$$

However for annual costs it is necessary to consider the present value factor, which depends on the real interest rate R_R and on the number of years n , and can be determined as the following expression:

$$f_{pv}(n) = \frac{(1 + R_R) - 1}{R_R (1 + R_R)^n} \quad (3)$$

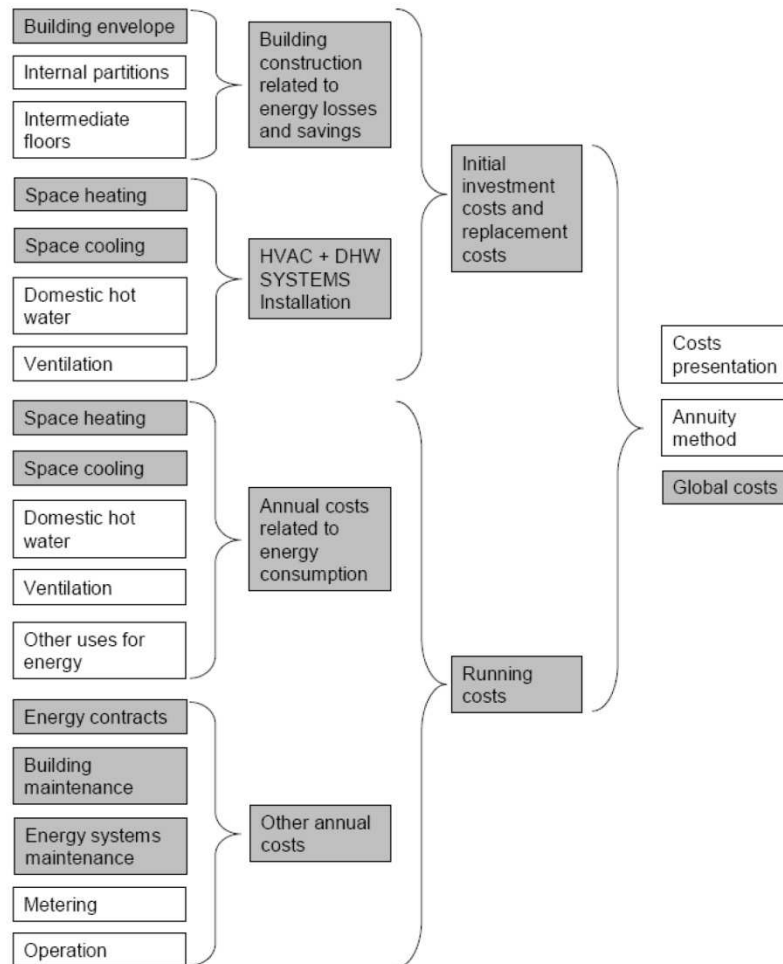


Figure 4 – Organization of costs.

3.2.1 Global cost calculation method

Figure 5 illustrates the various stages of the calculation method that is described hereinafter and that was used to evaluate the case study characterized by the six different envelope solutions. First of all it was necessary to gather some financial and project data. Then cost regarding components, systems and energy were valued. Finally, the global cost of the six different envelope solutions was calculated.

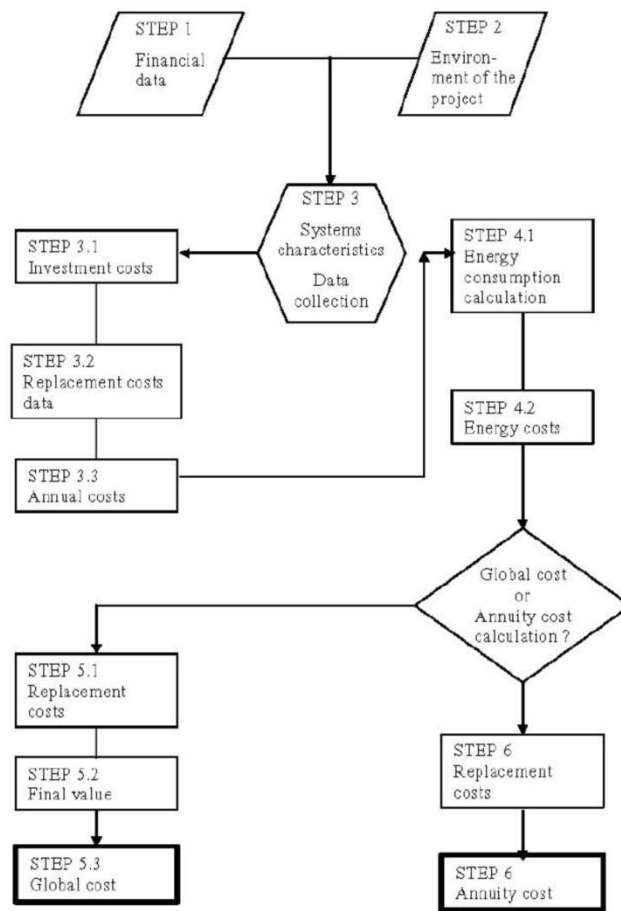


Figure 5 – Flowchart of the different stages of the method.

3.2.1.1 Step 1: financial data gathering

The financial data, which are tabulated in Table 6, consist in:

- duration of calculation;
- discount rate;

The duration of the calculation, that represents the number of years that are taken into account for the global cost calculation method, was fixed. According to the analyzed object it was set as equal to the lifetime of the building, 50 years.

Table 6. Financial data

	Value
Duration of the calculation	50 years
Interest rate	2,5 %

3.2.1.2 Step 2: project data gathering

The project data are:

- information about the environment of the project;
- meteorological data;
- constraints/opportunity related to energy.

Information was obtained from the design project and was taken into account in the previous phase of energy performance evaluation.

3.2.1.3 Step 3: evaluation of costs regarding components and systems (investment, replacement)

Data concerning components and systems were collected; information about their lifespan, maintenance and operation was found in the Annex A of EN 15459:2007.

The investment cost (taking into account materials and manpower) was calculated for window components, ground floor, roof and for the six different configurations of external walls. Also the investment cost of the space heating and cooling system was evaluated. In this case the unit prices of a reversible heat pump and of a four-pipe fan coil unit were appraised. Unit prices were established from the current Italian pricelist. In particular, two different pricelists were consulted: that of Piedmont Region and Milan's one (Regione Piemonte, 2010, Comune di Milano, 2010). For each building component the construction cost used was the average value of the two costs resulting from these pricelists. Table 7 reports the investment cost for components and energy systems of the six different façade technologies.

Table 7. Investment costs for building components and energy systems

Investment cost	Total cost year 0 [€]	Present value factor	Global cost [€]
Energy system ID 1	244.664	1	244.664
Energy system ID 2	244.664	1	244.664
Energy system ID 3	205.606	1	205.606
Energy system ID 4	248.209	1	248.209
Energy system ID 5	244.664	1	244.664
Energy system ID 6	244.664	1	244.664
Building ID 1	4.241.600	1	4.241.600
Building ID 2	4.041.323	1	4.041.323
Building ID 3	3.872.136	1	3.872.136
Building ID 4	4.336.415	1	4.336.415
Building ID 5	3.924.143	1	3.924.143
Building ID 6	4.864.544	1	4.864.544

The timing of and the costs for replacement of systems were considered; these data, listed in Table 8 and 9, were acquired from the Annex A of EN 15459. The costs for replacement of fan coil units were calculated 15, 30 and 45 years after the starting year; while the costs for replacement of heat pump were estimated for 20 and 40 years later than the starting year. Costs for replacement of building components were ignored.

Table 8. Data for lifespan and maintenance costs of components of the energy system

Component	Lifespan [years]	Annual preventive maintenance including operation, repair and servicing costs in % of the initial investment
Fan coil unit	15	4%
Heat pump	20	3%

Table 9. Example of calculation of costs for replacement of energy system components

Replacement cost	Total VAT incl. year 0 [€]	Discount rate coefficient R_d	Global cost [€]
Replacement program for lifespan 15 years:			
Fan coil units ID 1	107.374	0,69047	74.138
Fan coil units ID 2	107.374	0,69047	74.138
Fan coil units ID 3	100.466	0,69047	69.368
Fan coil units ID 4	110.919	0,69047	76.585
Fan coil units ID 5	107.374	0,69047	74.138
Fan coil units ID 6	107.374	0,69047	74.138
Replacement program for lifespan 20 years:			
Heat pumps ID 1	137.290	0,61027	83.784
Heat pumps ID 2	137.290	0,61027	83.784
Heat pumps ID 3	105.139	0,61027	64.163
Heat pumps ID 4	137.290	0,61027	83.784
Heat pumps ID 5	137.290	0,61027	83.784
Heat pumps ID 6	137.290	0,61027	83.784

With regards to running costs, operational costs (excluding energy) and repairs of systems, insurance and taxes were not taken into account in this evaluation. Only the maintenance costs of energy systems were considered, while those of building components were ignored.

3.2.1.4 Step 4: evaluation of energy costs

According with Standard 15459, energy costs were separated into two parts:

- the first part is directly related to energy consumption according to meters or fuel oil consumption of the building; the method for determination of energy consumption can be coupled to the energy content of the fuel according to data from the provider;
- the second part is fixed according to the quantity of energy subscribed with energy utilities or rental for energy systems (e.g. gas tank, electricity transformation); this cost was established as equal to 100 €/kW anno.

The tariff for electricity was coupled with energy consumption that had been estimated by dynamic simulation. A mean energy cost was assumed as equal to 0,20 €/kWh.

In this paper, environmental costs related to energy and energy sales were ignored.

Considered energy costs are tabulated in Table 10.

Table 10. Energy costs

	Value
Electricity price for kWh (consumption)	0,20 €/kWh
Electricity price for kW (tariff)	100 €/kW

3.2.1.5 Step 5: global cost calculation

Replacement costs throughout the calculation period were calculated based on timing of and costs for replacement of systems and components. Present value factor or discount rate is used to refer costs to the starting year.

The final value at the end of the calculation period was determined by summing up the final value of all systems and envelope components.

The final value of a specific system or component is calculated from the remaining lifetime (by the end of the calculation period) of the last replacement of the system or component, assuming linear depreciation over its lifespan. The final value is determined as remaining lifetime divided by lifespan and multiplied by the last replacement cost and refers to the starting year with an appropriate discount rate. Figure 6 represents the illustration of the concept of the final value given by the EN 15459, while Table 11 reports the final values of energy system components converted into global costs.

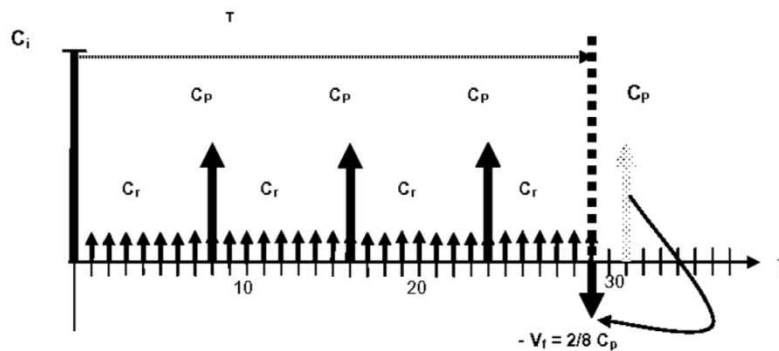


Figure 6 – Illustration of the final value concept.

Table 11. Final values of energy system components converted in global costs

Final value at the end of the period of calculation	Total VAT incl. year 0 [€]	Discount rate coefficient R_d	Global cost [€]
Fan coil units ID 1	18.790	0,29094	-5.466
Fan coil units ID 2	18.790	0,29094	-5.466
Fan coil units ID 3	17.581	0,29094	-5.115
Fan coil units ID 4	19.410	0,29094	-5.647
Fan coil units ID 5	18.790	0,29094	-5.466
Fan coil units ID 6	18.790	0,29094	-5.466
Heat pumps ID 1	43.148	0,29094	-12.553
Heat pumps ID 2	43.148	0,29094	-12.553
Heat pumps ID 3	33.043	0,29094	-9.613
Heat pumps ID 4	43.148	0,29094	-12.553
Heat pumps ID 5	43.148	0,29094	-12.553
Heat pumps ID 6	43.148	0,29094	-12.553

The different types of cost (initial investment costs, periodic and replacement costs, running costs) as well as the final value were converted to global cost referring to the starting year by applying the appropriate present value factor. The present value factor was different for different types of cost, due to different rates of price development for energy, manpower, products, maintenance and added costs.

The total global cost is determined by summing up the global costs of initial investment costs, periodic and replacement costs, annual costs and energy costs and subtracting the global cost of the final value. It is reported in Figure 7.

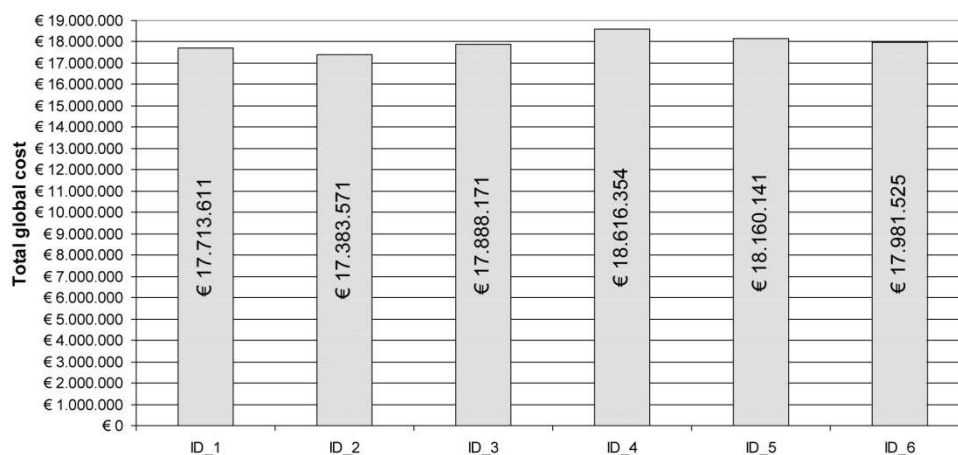


Figure 7 – Total global cost.

4. DISCUSSION OF THE RESULTS AND CONCLUSIONS

From the values of the total global costs reported in Figure 7, it can be deduced that the most profitable scenario is ID_2 (global cost of 17,384 M€ over 50 years), which is a “light” envelope technology (Plaster – Insulation – Lightweight Masonry – Plaster), characterized by lower superficial mass. Technologies that are more complex, e.g. ventilated facades of ID_5 and ID_6 have a larger investment cost that is not compensated by the energy savings.

It is interesting to point out that in the various cost categories, ID_2 is never the one that has the lowest value. For example, the lowest investment cost of building envelope is ID_3 (3,8 M€), while ID_2 is the lowest but two; the lowest investment cost of systems is ID_3 again.

On the energy costs side, there is a small variation due to the different annual energy need for heating and cooling (Figures 2 and 3) and ID_6 has the lowest energy cost.

The total global cost methodology (and the equivalent annuity cost methodology) is a powerful tool with which analyze the trade-off between different choices that have an impact on building energy performance in various contexts, not only in the HVAC systems context. In the case study presented, the variation of the building envelope technology in a small range of variability (the various building envelope alternatives were quite similar in terms of energy performance, since they were based on the same thermal transmittance) proved to have an appreciable impact on the total energy cost of an office building. This is due to the combination of energy cost, investment cost, maintenance cost, renovation cost and the final value, whose calculation is no trivial task, as it is demonstrated by the example described.

Some of the drawbacks encountered in the application of the standard concern the retrieval of prices. For completeness of the assessment, it is necessary to refer to more than one pricelist, and frequently they do not consider the manpower costs for a specific material or process. Maintenance costs are also difficult to assess, especially as regards the building features (maintenance costs of the systems are suggested by the Standard). As regards the application of the methodology, it should be noted that the EN 15459 Standard can be more easily implemented for the evaluation of various primary and secondary systems performance, than for the entire building. However, the standard clearly states that one of its applications is the assessment of the economic performance of an overall design of the building.

Following this work, the Authors believe that the EN 15459 Standard is a useful tool for the economic assessment of sustainable building, and intend to apply it to relate the energy certification labelling to the material properties of the envelope, and to evaluate the trade-off between energy demand reduction and systems efficiency increase in near-zero energy buildings.

NOMENCLATURE

C_G [€]	global cost (corresponding to calculation period τ)
C_i [€]	initial investment costs (at the time τ_0)
$C_{a,i(j)}$ [€]	annual cost of the year i (nominal value)
COP [-]	Coefficient of Performance
E_c [kWh/m ³ year]	energy consumption for space cooling
E_h [kWh/m ³ year]	energy consumption for space heating
EER [-]	Energy Efficiency Ratio
ESEER [-]	European Seasonal Energy Efficiency Ratio
$f_{pv}(n)$ [-]	present value factor (for year n)

$n_r [j]$	number of replacement of component or system j within the calculation period
$M_s [kg/m^2]$	superficial mass
$P_c [kW]$	cooling capacity
$P_h [kW]$	heating capacity
$R_d (i) [%]$	discount rate coefficient (for year i)
$R_R (i) [%]$	interest rate (for year i)
τ [year]	calculation period
τ_0 [year]	starting year for the calculation
$U [W/m^2K]$	thermal transmittance
$V_{f,\tau} (j) [€]$	final value of component or system j (corresponding to calculation period τ)

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Paper IV

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LIVELLI DI PRESTAZIONE ENERGETICA OTTIMALI PER EDIFICI A ENERGIA QUASI ZERO: IL CASO DI UN EDIFICIO MULTIFAMILIARE

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SOMMARIO

Il livello di prestazione energetica ottimale in funzione dei costi (*cost optimal level of energy performance*) è la quantità di energia necessaria per il soddisfacimento del fabbisogno energetico dell'edificio, che richiede il costo più basso durante il ciclo di vita economico stimato dell'edificio stesso. Il concetto è stato definito dalla Direttiva Europea 2010/31/UE del 19 maggio 2010 (*EPBD recast*) che richiede agli Stati Membri l'applicazione di un quadro comparativo metodologico per il calcolo del livello ottimale di prestazione energetica su edifici di riferimento. Tale quadro metodologico prevede lo sviluppo, da parte di ciascuno Stato Membro, di una serie di edifici di riferimento a livello nazionale o regionale (*Reference Building*), da utilizzare come edifici tipo rappresentativi del patrimonio edilizio, ed ai quali applicare ipotesi di misure per il miglioramento dell'efficienza energetica per determinare i target prestazionali degli edifici ad energia quasi zero.

L'obiettivo di questa ricerca è l'individuazione per un edificio residenziale esistente del livello di prestazione energetica ottimale in funzione dei costi, attraverso l'applicazione del quadro metodologico comparativo della Direttiva europea *EPBD recast*. L'edificio di riferimento è un edificio multifamiliare per appartamenti realmente esistente (*Real Building*), costruito negli anni '60 e selezionato dal database di archetipi del progetto europeo IEE TABULA. All'edificio sono state applicate differenti misure di efficientamento energetico, valutate a livello energetico attraverso l'uso di un software di simulazione dinamica (EnergyPlus) ed a livello economico attraverso l'applicazione del metodo del costo globale secondo la norma UNI EN 15459.

1. INTRODUZIONE

La Direttiva europea 2010/31/EU del 19 maggio 2010 sulla prestazione energetica degli edifici, nota come *EPBD recast* [1], prescrive l'elaborazione da parte di tutti gli Stati Membri di un piano per lo sviluppo di edifici ad energia quasi zero, vale a dire di edifici ad altissima prestazione energetica, con un fabbisogno netto di energia primaria molto basso, coperto in forte misura da fonti rinnovabili. A tale riguardo, nelle linee guida della *EPBD recast* [2] è illustrato un quadro metodologico comparativo per la definizione di livelli ottimali di prestazione energetica degli edifici e dei componenti edilizi, in funzione dei costi. Tali livelli corrispondono alla quantità di energia necessaria per il soddisfacimento del fabbisogno energetico dell'edificio che richiede il costo più basso durante un ciclo di vita economico stimato. Tale quadro richiede pertanto la definizione, a livello nazionale o regionale, di requisiti minimi di prestazione energetica e la predisposizione di misure per il miglioramento della stessa per gli edifici esistenti e per quelli di nuova costruzione, che siano efficaci anche sotto il profilo dei costi.

A ciascuno Stato Membro è inoltre demandata la creazione di una serie di edifici di riferimento, denominati *Reference Buildings*, ovvero edifici rappresentativi di determinate categorie edilizie a livello nazionale o regionale, ai quali verranno applicate le misure di efficientamento e per i quali sarà calcolato il livello ottimale della prestazione energetica in funzione dei costi. Per ulteriori dettagli in merito al quadro

metodologico si veda l'articolo "Livelli di prestazione energetica ottimali per edifici a energia quasi zero: Creazione degli edifici di riferimento" riguardante la definizione di *Reference Building* in conformità con la *EPBD recast*.

La presente memoria descrive l'applicazione del quadro metodologico comparativo dell'*EPBD* ad un edificio di riferimento residenziale. La ricerca analizza differenti ipotesi di efficientamento energetico sull'edificio di riferimento, sia a livello di involucro edilizio che di sistema impiantistico, e calcola il costo globale corrispondente a ciascuna ipotesi applicata attraverso la metodologia del costo globale della norma UNI EN 15459 [3]. Sono così individuati per il *Reference Building* i livelli ottimali di prestazione energetica in funzione dei costi.

2. IL REFERENCE BUILDING

Il modello di *Reference Building* è un *Real Building*, ossia un edificio realmente esistente, selezionato mediante analisi statistica come edificio tipo, con caratteristiche medie rispetto al campione di edifici analizzati.

Il *Reference Building* utilizzato per il presente studio è stato selezionato all'interno della struttura armonizzata di tipologie edilizie a destinazione residenziale del progetto TABULA (*Typology Approach for BUILDing stock Energy Assessment*) [4], al quale hanno partecipato 13 Stati europei, tra cui l'Italia. Il *Reference Building*, un edificio per appartamenti

appartenente all'epoca di costruzione 1946-1960, è stato scelto in quanto rappresentativo della tipologia di edifici residenziali multifamiliari, molto diffusa sul territorio nazionale per l'epoca di costruzione considerata. Inoltre, a margine di elevati consumi energetici, l'edificio consente per caratteristiche architettonico-costruttive, legate principalmente all'epoca di costruzione, di individuare una tipologia più differenziata di interventi di riqualificazione volti a migliorare l'efficienza a livello energetico dell'edificio (Fig. 1).

Il *Reference Building*, sito nell'area urbana di Torino, a Moncalieri, presenta una pianta rettangolare esposta lungo l'asse longitudinale disposto secondo la direzione N-O e S-E.

Lo stabile, con una superficie lorda di pavimento complessiva di 1890 m² e un'altezza di 4 p.f.t., è costituito in totale da 24 alloggi; sono presenti un piano interrato e un sottotetto non riscaldati. Di seguito, nella Tabella 1 si riportano le caratteristiche geometriche principali del *Reference Building*.

Tabella 1. Caratteristiche dimensionali *Reference Building*

Dimensioni in pianta		12.60 x 37.50 m
SLP piano tipo		472.50 m ²
SLP appartamento tipo		73.45 m ²
Altezza interpiano		3.10 m
Facciata N-E	Muratura esterna	170.10 m ²
	Muratura esterna	383.70 m ²
Facciata S-E	Superficie trasparente	122.58 m ²
	Muratura esterna	170.10 m ²
Facciata S-O	Muratura esterna	326.30 m ²
	Superficie trasparente	94.06 m ²

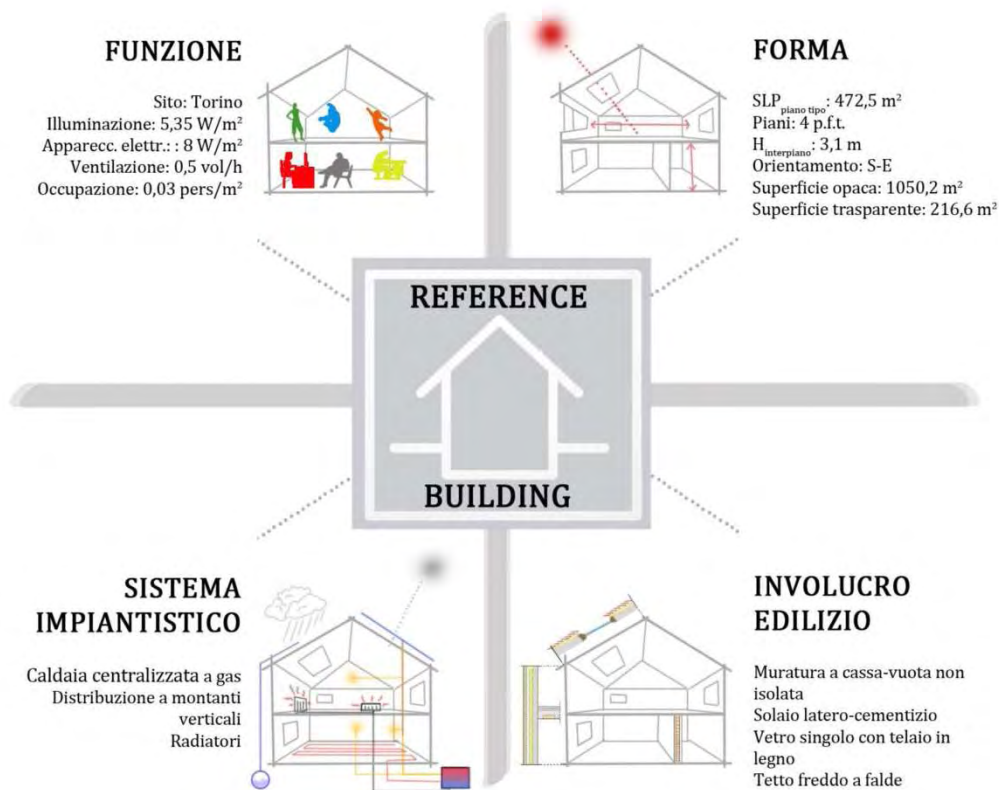


Figura 1. Caratteristiche del *Reference Building*

Coerentemente con la descrizione dell'archivio di TABULA, l'edificio presenta tecnologie costruttive tradizionali, caratteristiche del patrimonio edilizio italiano per l'epoca di costruzione considerata, ovvero costruzioni di tipo massivo realizzate con laterizi e senza materiale isolante termico all'interno delle strutture. In particolare, l'edificio è costituito da una muratura a cassa-vuota con mattoni forati di 30 cm e da una muratura in calcestruzzo di 18 cm, rispettivamente come componenti di involucro verticale opaco verso l'esterno e verso ambienti non riscaldati. La copertura è del tipo a falde con una struttura in tavolato di legno ed il solaio, sia inferiore che superiore, è latero-cementizio. I serramenti sono a vetro singolo con telaio in legno.

Per quanto concerne il sistema impiantistico a servizio dell'edificio, il sistema di generazione è costituito da una caldaia a gas con un sistema di distribuzione a colonne montanti verticali e con radiatori come terminali di impianto. La produzione dell'acqua calda sanitaria è invece garantita attraverso un boiler elettrico ad accumulo, con distribuzione separata per appartamento, senza ricircolo.

3. GLI INTERVENTI DI RIQUALIFICAZIONE

L'*EPBD recast* richiede a tutti gli Stati Membri lo sviluppo di una serie di interventi finalizzati al miglioramento della prestazione energetica dell'edificio. Gli interventi dovranno essere unificati tra di loro al fine di definire almeno dieci differenti ipotesi di intervento.

L'edificio selezionato è un *Reference Building* per edifici esistenti, pertanto le ipotesi di efficientamento sono costituite da interventi di riqualificazione energetica. L'edificio è sito a Torino, in zona climatica E, pertanto come riferimento normativo è stata considerata la legge regionale del Piemonte n.13 del Maggio 2007 "Disposizioni in materia di rendimento energetico dell'edilizia". La definizione ed applicazione di interventi di riqualificazione energetica, *Energy Efficiency Measures* (EEM), è stata svolta in due fasi: la prima caratterizzata da interventi di riqualificazione a livello di involucro edilizio e la seconda a livello impiantistico.

Le ipotesi di interventi di riqualificazione dell'involucro edilizio sono state definite in funzione di tre livelli di miglioramento della trasmittanza termica dei componenti edilizi. I primi due livelli, EEM1 e EEM2 sono stati rispettivamente fissati in conformità col livello "vigente" e "convenzionato" dell'allegato 3 della Delibera n.46-11968 del 4 Agosto 2009 della Regione Piemonte. Il terzo livello EEM3, definito "avanzato", è caratterizzato da trasmittanze termiche molto basse (inferiori rispetto al livello "convenzionato") al fine di ridurre fortemente il fabbisogno per riscaldamento ambientale dell'edificio.

Le ipotesi sono state inoltre distinte in interventi di tipo omogeneo e di tipo disomogeneo, in relazione all'applicazione dei suddetti interventi a tutti i componenti esterni dell'involucro edilizio o a singoli/combinati componenti di involucro. In questa fase, complessivamente sono state applicate al *Reference Building* 10 ipotesi di intervento, come indicato nella Tabella 2.

Tabella 2. Ipotesi di intervento a livello dell'involucro edilizio

EEM (Energy Efficiency Measure)		U [W/m ² K]	
RB	Pareti	1.15	
	Finestre	4.9	
	Solaio Superiore	1.65	
	Solaio inferiore	1.30	
INTERVENTI OMOGENEI	EEM1	Pareti	0.33
		Finestre	2.00
		Solaio Superiore	0.30
		Solaio inferiore	0.30
	EEM2	Pareti	0.25
		Finestre	1.70
		Solaio Superiore	0.23
		Solaio inferiore	0.23
	EEM3	Pareti	0.18
		Finestre	1.70
		Solaio Superiore	0.16
		Solaio inferiore	0.16
INTERVENTI DISOMOGENEI	EEM4	Pareti	0.33
		Finestre	2.00
		Solaio Superiore	1.65
		Solaio inferiore	1.30
	EEM5	Pareti	0.33
		Finestre	4.90
		Solaio Superiore	0.30
		Solaio inferiore	0.30
	EEM6	Pareti	1.15
		Finestre	2.00
		Solaio Superiore	1.65
		Solaio inferiore	1.30
	EEM7	Pareti	0.25
		Finestre	4.9
		Solaio Superiore	1.65
		Solaio inferiore	1.30
	EEM8	Pareti	0.25
		Finestre	4.9
		Solaio Superiore	0.23
		Solaio inferiore	0.23
EEM9	Pareti	0.18	
	Finestre	1.70	
	Solaio Superiore	1.65	
	Solaio inferiore	1.30	
EEM10	Pareti	0.18	
	Finestre	4.90	
	Solaio Superiore	1.65	
	Solaio inferiore	1.30	

Una volta analizzati i costi globali dei 10 interventi di riqualificazione energetica descritti sopra, sono stati scelti per la fase di analisi successiva, oltre al *Reference Building*, l'EEM1 e l'EEM3. Questi due casi sono stati scelti in quanto rappresentano la miglior combinazione tra il minor consumo energetico e il minor costo globale.

La seconda fase di analisi ha visto l'applicazione ai casi sopra selezionati di misure di riqualificazione impiantistica; tali misure sono state combinate tra loro a formare diversi pacchetti di interventi.

Le singole misure di riqualificazione hanno previsto:

- la sostituzione della caldaia esistente con una caldaia a condensazione maggiormente efficiente ($\eta_g = 0.99$);
- l'aumento dell'efficienza del sistema di distribuzione, andando ad isolare le tubazioni presenti nello scantinato;
- l'installazione delle valvole termostatiche sui radiatori esistenti;
- la sostituzione dei radiatori con dei pannelli radianti a pavimento;
- l'inserimento di un impianto di ventilazione meccanica controllata con recuperatore di calore ($\eta = 0.70$);
- la realizzazione di un impianto fotovoltaico sulla falda orientata a sud-est del tetto dell'edificio; questo è caratterizzato da una superficie effettiva installata di circa 240 m² con una potenza installata pari a 25 kW_p.

Il primo pacchetto di interventi (da EEM11 a EEM13) ha previsto la sostituzione della caldaia, l'inserimento delle valvole termostatiche e l'isolamento delle tubazioni.

Il secondo pacchetto di interventi (da EEM14 a EEM16) ha previsto la sostituzione della caldaia, l'isolamento delle tubazioni e l'inserimento dei pannelli radianti.

Il terzo pacchetto di interventi (da EEM17 a EEM19) ha previsto l'installazione dell'impianto fotovoltaico.

Il quarto pacchetto di interventi (da EEM20 a EEM22) ha previsto l'applicazione delle stesse misure del primo pacchetto combinate con l'installazione dell'impianto fotovoltaico.

Il quinto pacchetto di interventi (da EEM23 a EEM25) ha previsto l'applicazione delle stesse misure del secondo pacchetto combinate con l'installazione dell'impianto fotovoltaico.

Il sesto pacchetto di interventi (da EEM26 a EEM28) ha previsto l'applicazione delle stesse misure del primo pacchetto combinate con l'inserimento dell'impianto di ventilazione meccanica controllata.

Il settimo pacchetto di interventi (da EEM29 a EEM31) ha previsto l'applicazione delle stesse misure del secondo pacchetto combinate con l'inserimento dell'impianto di ventilazione meccanica controllata.

L'ottavo pacchetto di interventi (da EEM32 a EEM34) ha previsto l'applicazione delle stesse misure del sesto pacchetto combinate con l'installazione dell'impianto fotovoltaico sul tetto.

Il nono pacchetto di interventi (da EEM35 a EEM37) ha previsto l'applicazione delle stesse misure del settimo pacchetto combinate con l'installazione dell'impianto fotovoltaico sul tetto.

Di seguito in Tabella 3 vengono riassunti i diversi pacchetti di efficientamento energetico apportati al *Reference Building*, all'EEM1 e all'EEM3. Nella colonna denominata "EEM di applicazione" viene riportato il caso a cui vengono applicate le misure di efficientamento, mentre nella colonna denominata "ID" viene indicato l'identificativo con cui ci si riferirà all'intervento.

Tabella 3. Misure impiantistiche di efficientamento energetico

Descrizione di efficientamento	misura di	EEM di applicazione	ID
Pacchetto 1	caldaia condensazione + valvole termostatiche + isolamento tubi distribuzione	RB	EEM11
		EEM1	EEM12
		EEM3	EEM13
Pacchetto 2	caldaia condensazione + isolamento tubi distribuzione + pannelli radianti	RB	EEM14
		EEM1	EEM15
		EEM3	EEM16
Pacchetto 3	PV	RB	EEM17
		EEM1	EEM18
		EEM3	EEM19
Pacchetto 4	caldaia condensazione + valvole termostatiche + isolamento tubi distribuzione + PV	RB	EEM20
		EEM1	EEM21
		EEM3	EEM22
Pacchetto 5	caldaia condensazione + isolamento tubi distribuzione + pannelli radianti + PV	RB	EEM23
		EEM1	EEM24
		EEM3	EEM25
Pacchetto 6	caldaia condensazione + valvole termostatiche + isolamento tubi distribuzione + VM	RB	EEM26
		EEM1	EEM27
		EEM3	EEM28
Pacchetto 7	caldaia condensazione + isolamento tubi distribuzione + pannelli radianti + VM	RB	EEM29
		EEM1	EEM30
		EEM3	EEM31
Pacchetto 8	caldaia condensazione + valvole termostatiche + isolamento tubi distribuzione + PV + VM	RB	EEM32
		EEM1	EEM33
		EEM3	EEM34
Pacchetto 9	caldaia condensazione + isolamento tubi distribuzione + pannelli radianti + PV + VM	RB	EEM35
		EEM1	EEM36
		EEM3	EEM37

Si è deciso di non apportare modifiche all'impianto di produzione di acqua calda sanitaria. Pertanto nelle successive analisi economiche non è stato preso in considerazione, né dal

punto di vista del costo dell'energia derivante dai relativi consumi né per ciò che riguarda costi di sostituzione e di manutenzione.

Non si sono apportate misure di efficientamento neanche all'impianto di illuminazione ed a quello relativo agli usi elettrici obbligati; i consumi, e i relativi costi, di queste due utenze sono stati considerati diminuiti della quota di autoconsumo coperta dall'energia elettrica prodotta dall'impianto fotovoltaico.

4. LA SIMULAZIONE ENERGETICA

4.1 Il modello termoenergetico

Il *Reference Building* è stato modellato attraverso la versione 6 di EnergyPlus, un programma per la simulazione termodinamica del sistema edificio-impianto, sviluppato dal *Department of Energy* degli Stati Uniti (US DOE).

La modellizzazione dell'edificio all'interno del codice di calcolo ha richiesto una serie di semplificazioni, in particolare a livello geometrico, sul *Reference Building*. L'edificio è stato suddiviso in 12 zone termiche riscaldate e 4 zone non riscaldate, costituite dai due vani scala, dal sottotetto e dal piano interrato. Nello specifico, in considerazione delle medesime condizioni al contorno, i due piani intermedi, il 2° e 3°, sono stati unificati al fine di semplificare il modello termoenergetico.

In merito alla definizione dei profili di utilizzo dell'edificio ed agli apporti interni gratuiti ad essi connessi, lo studio di TABULA non fornisce informazioni a riguardo essendo l'analisi condotta basata sul metodo di calcolo quasi stazionario. La presente ricerca ha condotto invece un'analisi della prestazione energetica dell'edificio basata su simulazioni energetiche in regime dinamico tramite l'ausilio del codice di calcolo EnergyPlus, richiedendo pertanto un maggior grado di dettaglio nella definizione del modello del *Reference Building*. A tale proposito è stato utilizzato un indice di affollamento di 0.04 pers/m², in conformità con la norma UNI 10339 [5]. I carichi interni relativi all'illuminazione ed all'utilizzo di apparecchiature elettriche sono rispettivamente pari a 5.35 W/m² e 8 W/m². Tali valori sono associati ad appositi profili di utilizzo ed occupazione estratti dal modello di *Reference Building* del *Department of Energy* (DOE) degli Stati Uniti per edifici multi-familiari, noto come *Mid-rise apartment* [6], adeguatamente contestualizzato alle abitudini del nostro paese.

L'impianto è stato considerato in funzione durante il periodo di riscaldamento dal 15 Ottobre al 15 Aprile in conformità con l'UNI/TS 11300-1. La temperatura di progetto dell'ambiente interno è fissata a 21°C dalle ore 07:00 alle ore 22:00, ed a 18°C nelle restanti ore. La ventilazione è assunta come naturale con un tasso di ricambio pari a 0.5 vol/ora.

I dati climatici utilizzati per la simulazione del *Reference Building* corrispondono all'anno tipo disponibile per la località climatica di Torino e scaricato dall'archivio di file climatici dell'*International Weather for Energy Calculation* (IWEC) sviluppo dall'ASHRAE.

4.2 I consumi energetici

Di seguito si riportano i consumi di energia primaria relativi alle ipotesi di riqualificazione riguardanti l'involucro edilizio, vale a dire le prime 10 EEM. Il fabbisogno di energia per riscaldamento prende in considerazione il rendimento dell'impianto e l'impiego del metano come combustibile. I

consumi di energia elettrica sono costituiti dall'energia relativa all'illuminazione ed agli usi elettrici obbligati. Il fattore di conversione in energia primaria per il gas metano è stato fissato pari a 1, mentre quello per l'energia elettrica è pari a 2.18, secondo la Delibera dell'Autorità per l'Energia Elettrica e Gas 3/08.

Come si evince dalla Figura 2, i consumi di energia elettrica sono invariati in tutte le ipotesi di intervento in quando i carichi interni sono costanti e non sono stati presi in considerazione interventi di controllo dell'illuminazione né di efficientamento delle apparecchiature elettriche impiegate nel *Reference Building*.

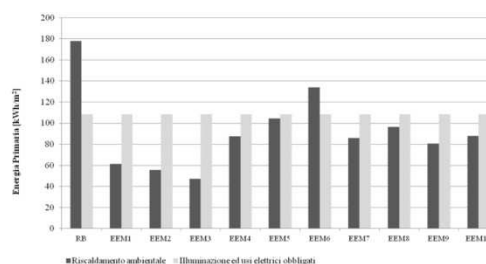


Figura 2. Consumi energetici annuali

Dalle prime tre ipotesi omogenee di intervento, EEM1, EEM2 e EEM3 si può constatare come all'aumentare dell'isolamento termico dei componenti di involucro corrisponda una riduzione dei fabbisogni di energia primaria, rispettivamente pari al 65%, 69% e 73% rispetto al *Reference Building*. In particolare l'EEM3, caratterizzata da trasmittanze termiche molto basse, richiede il minor consumo di energia primaria tra tutte le 10 ipotesi di riqualificazione dell'involucro edilizio.

Tra gli interventi non omogenei, l'ipotesi con il consumo maggiore è la EEM6, che prevede la sola sostituzione dei serramenti a livello "vigente" ed un risparmio a livello energetico del 24%. Le ipotesi EEM4, EEM7 e EEM9 si caratterizzano per valori affini di consumi energetici, con un risparmio energetico conseguibile pari rispettivamente al 51%, 52% e 54%. Tutte e tre le ipotesi prevedono, infatti, la riqualificazione dei componenti verticali opachi e trasparenti dell'involucro ai tre livelli di trasmittanza termica in precedenza citati.

Per quanto riguarda la produzione di energia elettrica da fonti rinnovabili, il 14% dell'energia prodotta in situ dall'impianto viene immessa in rete; mentre la percentuale di autoconsumo è pari all'86%. Per calcolare tale percentuale è stato simulato con EnergyPlus il fabbisogno orario di energia elettrica dell'edificio e la produzione oraria dell'impianto fotovoltaico: in tal modo è stato poi possibile determinare la percentuale di copertura del fabbisogno fornita dall'impianto.

Nella Tabella 4 vengono riportati i dati di produzione relativi all'impianto fotovoltaico.

Tabella 4. Dati relativi all'impianto fotovoltaico

Energia elettrica richiesta (illuminazione, usi elettrici obbligati, ausiliari impianto di riscaldamento)	69.013	kWh/anno
Energia elettrica prodotta da PV	26.118	kWh/anno
Energia elettrica immessa in rete	3.595	kWh/anno
Energia elettrica prelevata dalla rete	46.475	kWh/anno
Energia elettrica autoconsumata	22.522	kWh/anno

5. IL CALCOLO DEL COSTO GLOBALE

5.1 Il quadro metodologico

La valutazione economica dei diversi interventi di riqualificazione energetica è stata effettuata seguendo la metodologia descritta dalla norma EN 15459:2007 [3]. La norma specifica un metodo, applicabile a tutte le tipologie di edifici, per il calcolo economico dei sistemi edilizi ed impiantistici connessi al consumo di energia all'interno dell'edificio. Tale metodo può essere usato per:

- valutare la fattibilità economica di opzioni di riqualificazione energetica;
- confrontare differenti possibili opzioni di riqualificazione energetica (ad es. tipologie impiantistiche, combustibili, ecc.);
- valutare la prestazione economica globale di un progetto edilizio (es. compromesso tra fabbisogno energetico ed efficienza energetica degli impianti di riscaldamento);
- stimare l'effetto dell'utilizzo di misure di risparmio energetico su impianti esistenti, attraverso il calcolo economico dei costi dell'energia utilizzata con e senza applicazione di misure di risparmio energetico.

Lo Standard EN 15459 descrive due differenti metodologie di calcolo: il metodo del costo globale e quello delle annualità. In conformità a quanto indicato nell'*EPBD recast*, in questo lavoro, per valutare economicamente i diversi interventi di riqualificazione, è stato utilizzato il primo metodo. Esso prevede di attualizzare tutti i costi, attraverso l'applicazione di opportuni tassi di sconto, riferendoli all'anno cosiddetto "zero" in cui si è effettuato l'investimento iniziale.

Il costo globale di un intervento è costituito dalla somma del costo di investimento, dei costi periodici di sostituzione attualizzati, di quelli annuali attualizzati e di quelli relativi ai consumi energetici attualizzati; a tale sommatoria deve essere sottratto il valore finale attualizzato (Fig. 3). In particolare, il valore del costo globale $C_G(\tau)$ riferito all'anno iniziale τ_0 di ciascuna misura di efficientamento energetico è strettamente dipendente dalla durata del periodo di valutazione ed è esplicitato dalla seguente equazione:

$$C_G(\tau) = C_1 + \sum_j \left[\sum_{i=1}^{\tau} (C_{a,i}(j) \cdot R_d(i)) - V_{f,\tau}(j) \right] \quad (1)$$

dove C_1 rappresenta il costo di investimento iniziale; $C_{a,i}(j)$ il costo annuale di ogni elemento j all'anno i ed include costi di esercizio, costi periodici e costi di sostituzione; $R_d(i)$ il tasso di

attualizzazione per l'anno i ; $V_{f,\tau}(j)$ il valore finale dell'elemento j alla fine del periodo di calcolo considerato (facendo sempre riferimento all'anno iniziale τ_0).

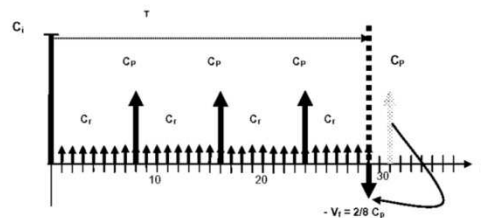


Figura 3. Schema del metodo del costo globale (tratto da EN 15459:2007)

Per attualizzare all'anno iniziale τ_0 i vari costi è necessario moltiplicarli per il tasso di sconto R_d oppure per il fattore di attualizzazione f_{pv} . Nello specifico, il primo è utilizzato nel caso dei costi periodici, come quelli di sostituzione o come il valore finale di un componente edilizio o impiantistico, mentre il secondo è utilizzato nel caso di costi che si ripetono annualmente, come quelli relativi al consumo energetico.

La seguente Eq. (2) esprime la dipendenza del tasso di sconto R_d dal tasso di interesse reale R_R , che a sua volta dipende dal tasso di inflazione e da quello di interesse del mercato Eq. (3):

$$R_d = \frac{1}{(1 + R_R)^p} \quad (2)$$

$$R_R = \frac{R - R_i}{1 + R_i} \quad (3)$$

L'Equazione (4) riporta invece il valore del fattore di attualizzazione f_{pv} , in funzione del tasso di interesse reale R_R e del numero di anni n :

$$f_{pv}(n) = \frac{(1 + R_R) - 1}{R_R (1 + R_R)^n} \quad (4)$$

5.2 Le assunzioni di calcolo

Dati finanziari. Il primo step della valutazione economica è consistito nella raccolta dei dati finanziari. Sono state fatte le seguenti assunzioni:

- durata del periodo di calcolo: trattandosi di un edificio esistente, è stato fissato pari a 30 anni [2];
- tasso di inflazione: il dato è stato assunto pari al 2.17%, valore che deriva dalla media dei tassi di inflazione degli ultimi 10 anni registrati dalla CIA (*Central Intelligence Agency*) [7] e dal Fondo Monetario Internazionale [8];
- tasso di interesse del mercato: è stato preso pari a 4.5%, conforme al tasso Euribor relativo al 2011;
- tasso di interesse reale: dipendendo dal tasso di inflazione e da quello di interesse del mercato

secondo Eq. (3), è risultato essere pari al 2.28%;

- tasso di inflazione dei costi dell'energia: è stato fissato pari al tasso di inflazione, ovvero 2.17%.

Costi di investimento. Per ciò che riguarda i costi di investimento, essi sono stati valutati per ciascun intervento di efficientamento energetico facendo riferimento al prezzario della Regione Piemonte del 2010 [9]; per attualizzare al 2011 i prezzi unitari, questi sono stati moltiplicati per un indice armonizzato dei prezzi al consumo pari a 2.9% [10].

Nel caso dei primi 10 interventi di riqualificazione sono stati stimati i costi di investimento per misure interessanti unicamente l'involucro (prendendo in considerazione sia i costi dei materiali sia quelli della manodopera), quali la cappottatura esterna delle facciate comprese tutte le opere accessorie per la realizzazione della stessa, l'isolamento del solaio inferiore, l'isolamento del solaio superiore, la sostituzione degli infissi. Nel caso degli interventi successivi sono stati stimati i costi di investimento per la sostituzione della caldaia esistente con una a condensazione, per l'inserimento delle valvole termostatiche, per l'isolamento delle tubazioni dell'impianto di distribuzione nel piano scantinato, per la sostituzione dei radiatori con i pannelli radianti a pavimento, per la realizzazione di un impianto di ventilazione meccanica con recuperatore di calore e per la realizzazione di un impianto fotovoltaico sul tetto.

Costi di periodici di sostituzione. Per quanto riguarda le parti costituenti l'involucro edilizio, si è ipotizzato di sostituire solo i serramenti, per i quali è stata considerata una vita media di 25 anni. Nel caso del *Reference Building* tuttavia, trattandosi di un edificio esistente, si è ipotizzato di sostituirli dopo 13 anni.

Per ciò che concerne i dati relativi alla durata dei componenti impiantistici invece si è fatto riferimento all'Appendice A della EN 15459:2007.

Costi annuali di manutenzione. Nelle analisi è stato considerato il costo di manutenzione solo degli componenti impiantistici, mentre sono stati ignorati i costi relativi agli elementi di involucro. Per i primi si è fatto riferimento all'Appendice A della EN 15459:2007, che ne riporta il valore espresso in termini percentuali rispetto al costo del componente stesso.

Costi legati al consumo energetico. Per ciascun intervento analizzato sono stati considerati i costi relativi ai consumi energetici per il riscaldamento ambientale (gas naturale), per gli ausiliari dell'impianto di riscaldamento (energia elettrica) e per l'illuminazione e gli usi elettrici obbligati (energia elettrica).

Per i costi energetici sono stati assunti i seguenti valori:

- costo del gas naturale pari a 0.72 €/m³;
- costo dell'energia elettrica pari a 0.17 €/kWh; inoltre, è stato assunto un valore pari a 100 €/kW per ciò che riguarda i costi fissi annuali.

Negli interventi in cui è stato inserito l'impianto fotovoltaico, sono state fatte le seguenti ipotesi:

- il prezzo di vendita dell'energia immessa in rete pari a 0.03 €/kWh;
- valore dell'incentivo del GSE (Gestore Servizi Energetici) assunto per 20 anni pari a 0.233 €/ kWh secondo quanto indicato dal Quarto Conto Energia per il primo semestre del 2012 [11].

6. I LIVELLI OTTIMALI DI PRESTAZIONE ENERGETICA IN FUNZIONE DEI COSTI

Nel grafico di Figura 4 vengono riportati i valori di costo globale, espressi in €/m², delle diverse misure di efficientamento energetico in funzione dell'energia primaria, espressa in kWh/m²anno. Nella quota di energia primaria sono compresi i consumi per il riscaldamento ambientale, per gli ausiliari elettrici dell'impianto di riscaldamento, per l'illuminazione e per gli usi elettrici obbligati.

Sul grafico i diversi punti rappresentano le differenti misure di efficientamento (EEM). In base alla disposizione dei punti estremi nel grafico è stato possibile tracciare una curva, che rappresenta la cosiddetta *cost curve* [2], il cui minimo rappresenta il *cost optimal level*. Si è inoltre evidenziato in grigio un intervallo di valori minimi della curva (*cost optimal range*).

Nel grafico, in corrispondenza del *Reference Building* è stata tracciata una linea verticale che rappresenta il massimo consumo possibile. Infatti, i consumi delle diverse misure di efficientamento energetico applicate al *Reference Building* non possono ricadere a destra di tale linea verticale.

Le misure di efficientamento consentono di risparmiare in termini assoluti da 37 kWh/m²anno a 193 kWh/m²anno (energia primaria); in termini percentuali il risparmio è compreso tra il 13 e il 78%.

In valore assoluto, il minimo valore di consumo si raggiunge con la misura di efficientamento EEM37. Questa prevede un efficientamento a livello di involucro molto elevato (con trasmittanze inferiori al livello "convenzionato") e l'applicazione di tutte le misure impiantistiche ipotizzate.

Per quanto riguarda i costi globali si evidenzia dal grafico che le diverse misure di efficientamento presentano valori sia inferiori sia superiori rispetto al *Reference Building*. I valori di costo globale maggiore sono determinati dal fatto che le spese di investimento per i diversi tipi di intervento non riescono ad essere ripagate dai risparmi economici legati ai risparmi energetici ottenuti. Ad esempio, nel caso dell'EEM31, che presenta il costo globale maggiore, i costi di investimento sono superiori al risparmio economico (rispetto al *Reference Building*) associato all'energia risparmiata, come mostrato dalla Tabella 5.

Tabella 5. Costi di investimento e risparmi economici legati al consumo di energia dell'EEM31

Costi di investimento	Involucro	€ 300 326.8
	Caldaia a condensazione	€ 8 496.35
	Isolamento tubazioni	€ 919.15
	Pannelli radianti	€ 118 842.76
	Impianto di ventilazione meccanica controllata	€ 93 892.34
	TOTALE	€ 522 477.37
Risparmio economico totale attualizzato (rispetto a RF)		€ 382 457.24

Come si può osservare gli interventi EEM18, EEM19, EEM21 e EEM22, risultano molto vicini alla curva di *cost optimal level*: tutti e quattro prevedono una riqualificazione a livello di involucro edilizio, ipotizzando un isolamento di tipo "convenzionato" (nel caso dell'EEM18 e 21) e di tipo "avanzato" (nel caso dell'EEM19 e 22). Nel caso dell'EEM18 e dell'EEM19 è stato inserito anche l'impianto fotovoltaico; l'EEM21 e l'EEM22 hanno previsto oltre all'installazione di quest'ultimo anche la sostituzione della caldaia, l'inserimento delle valvole termostatiche e l'isolamento delle tubazioni dell'impianto di distribuzione.

Gli interventi di efficientamento che presentano il minor costo globale sono l'EEM20 e l'EEM32 che non prevedono nessun efficientamento a livello di involucro edilizio, ma solo misure a livello impiantistico. In particolare, l'EEM20 ha ipotizzato la sostituzione della caldaia esistente con quella a condensazione, l'inserimento delle valvole termostatiche, l'isolamento delle tubazioni dell'impianto di distribuzione e l'installazione dell'impianto fotovoltaico sul tetto; mentre l'EEM32 ha previsto le stesse misure impiantistiche dell'EEM20 con l'aggiunta dell'impianto di ventilazione meccanica controllata.

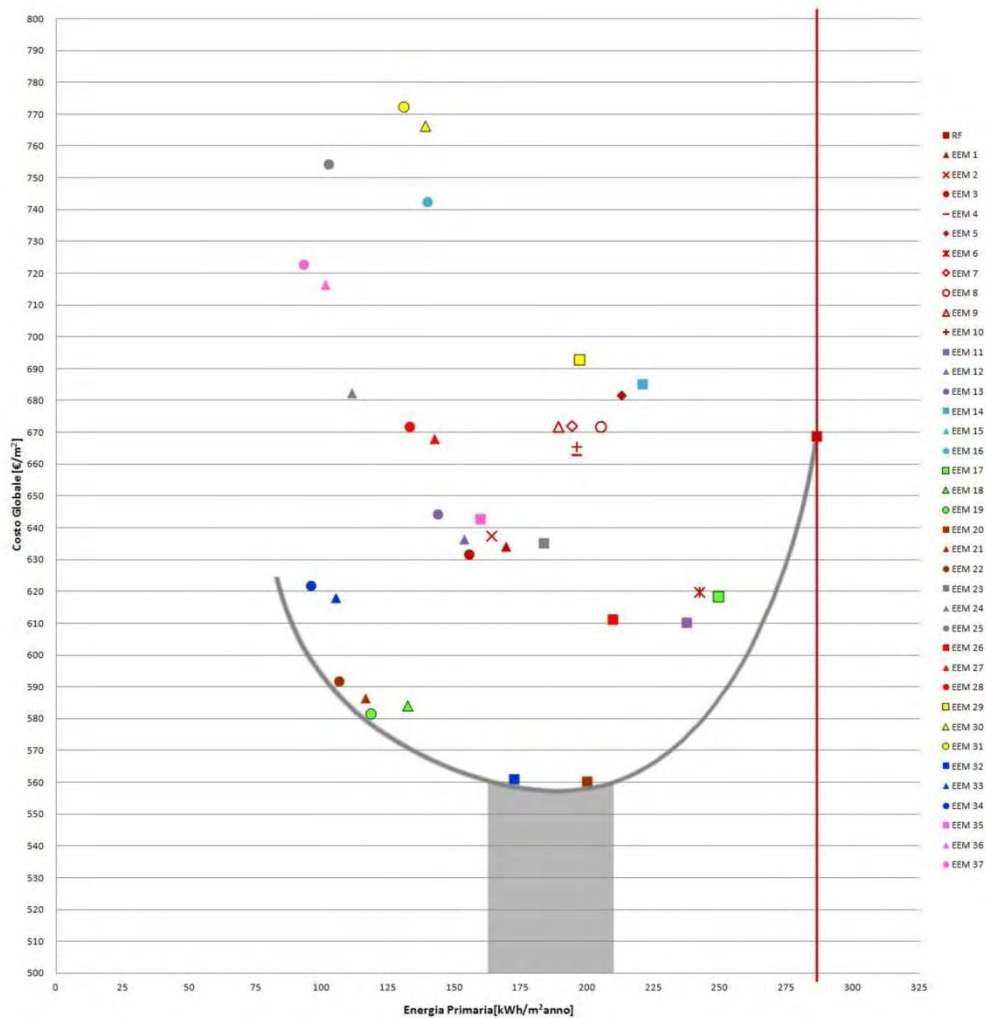


Figura 4. Valori di costo globale delle diverse misure di efficientamento energetico

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8. NOMENCLATURA

- C_G costo globale (corrispondente al periodo di calcolo τ) [€]
 C_I costo di investimento (all'anno τ_0) [€]
 $C_{a,i}(j)$ costo annuale all'anno i dell'elemento j [€]
 $f_{pv}(n)$ present value factor (for year n) [-]
 $V_{f,\tau}(j)$ valore finale del componente j [€]
 $R_d(i)$ tasso di attualizzazione per l'anno i [%]
 R_R tasso di interesse reale [%]
 R tasso di mercato [%]
 R_i tasso di inflazione [%]
 p anno in cui si considera il costo periodico [-]
 n numero di anni in cui si ripetono i costi annuali [-]
 τ periodo di calcolo [anni]
 τ_0 anno iniziale del periodo di calcolo [-]

SUMMARY

The Energy Performance of Buildings Directive (EPBD recast, 2010/31/EU) requires Member States to define minimum requirements of energy performance of buildings and building components with a view to achieving cost-optimal levels. In order to calculate the cost optimal level of minimum energy performance, Member States are required to create a set of Reference Buildings, at national or regional level, to be used in the calculations.

In this work, the global cost method is applied in compliance of the European Standard EN 15459, to a multi-family reference building to assess the cost optimal level of energy performance.

The reference building was selected from the Italian building typologies defined in the IEE project TABULA. It is an existing apartment building (Real Building), built in the '60s.

This research shows the comparison of 37 different packages of measures to improve the energy performance into the reference building selected in terms of the whole cost analysis. The packages of measures considered different level of thermal insulation of the building façade and different heating system to supply the energy demand of the building. Moreover the use of renewable energy sources was taken into account with the installation of photovoltaic panels on the building roof. In order to rate the energy performance, the building was modeled using the EnergyPlus software.

Paper V

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Cost optimal levels of energy requirements for nearly-ZEB: application to an Italian Reference Building for existing offices

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Abstract

The recast of the Directive on the Energy Performance of Buildings has set out that Member States must ensure that minimum energy performance requirements are set with a view to achieve cost optimal levels for buildings, building units and buildings elements. A cost optimal level is defined as the energy performance level which leads to the lowest cost during the estimated economic lifecycle. It must be calculated in accordance with a comparative methodology framework that is based on the global cost method. This one considers, for each energy efficiency measure, the initial investment, the sum of the annual costs for every year (including energy costs) and the final value, all with reference to the starting year of the calculation period.

In this study, the global cost method is applied to a reference building for existing offices customized to the Italian context to assess the cost optimal levels. In detail, different packages of energy efficiency measures, which consist in the implementation of envelope thermal insulation and the improvement of systems efficiency, were considered. Moreover, the utilization of renewable energy sources was taken into account with the installation of PV system on the building roof. Then, the energy consumptions of the reference building and the impact of the improvement measures were assessed. Finally, the costs of the different packages were estimated, according to the European Standard EN 15459:2007, in order to establish which of them has the lowest global cost and, consequently, represents the cost optimal level.

Keywords – cost optimal analysis; cost optimal levels; retrofit measures; minimum energy performance; dynamic simulation

1. Introduction

It is widely recognized that the building sector is one of the key consumer of energy. Buildings account for 40% of the total energy

consumption in the European Union [1] and the sector is expanding. In order to reduce the growing energy expenditure, the European Directive imposes the adoption of measures to improve the energy efficiency in buildings. The recast of the Directive on the Energy Performance of Buildings (EPBD recast) defines all new buildings will be nearly zero-energy buildings by the end of 2020 and the greenhouse gas emissions in the building sector could be reduced by around 80 – 90% by 2050. Consequently, EPBD recast [2] has set out that Member States (MSs) ensure that minimum energy performance requirements are set with a view to achieve cost optimal levels for buildings, building units and buildings elements. A cost optimal level is defined as the energy performance level which leads to the lowest cost during the estimated economic lifecycle. It must be calculated in accordance with a comparative methodology framework that is based on the global cost method. The methodology is addressed to national authorities and the cost optimal level is not calculated for each case, but for developing generally applicable regulations at national level. To apply this methodology MSs are expected to define a series of Reference Buildings (RBs) as baseline and representative models of the national building stock [3] that can be exploited as a basis for analysing national building stock and the potential impacts of energy efficiency measures in order to select effective strategies for upgrading existing buildings [4]. Additionally, MSs must define energy efficiency measures (EEMs) to be applied to RBs; EEM can be a single measure or constitute a package of measures. Finally, once estimated the RBs energy consumptions and the impact of the different EEMs, the costs of the different packages are estimated in order to establish which of them has the lowest global cost and, consequently, represents the cost optimal level. The global cost method considers, for each EEM, the initial investment, the sum of the annual costs for every year (including energy costs) and the final value, all with reference to the starting year of the calculation period. A measure or package of measures is cost-effective when the cost of implementation is lower than the value of the benefits that result, taken over the expected life of the measure. The cost-optimal result represents that retrofit action or combination of actions that minimized the global cost. From the variety of specific results, a cost curve can be derived. The lowest part of the curve represents the economic optimum for a combination of packages.

2. Scope of the work

In a country like Italy where the building stock consists mainly of existing buildings, the specification of energy performance requirements for this sector becomes a key element of national energy policies. Therefore, in this paper the application of the cost optimal methodology [3], to a RB for existing offices customized to the Italian context is presented. Specifically, different EEMs involving the improvement of the building envelope thermal performances and the systems efficiency were considered. Moreover, the

utilization of renewable energy sources was taken into account with the installation of a PV system on the building roof. Then, the energy consumptions of the RB and the impact of the improvement measures were assessed with a dynamic simulation software tool. Finally, the costs of the different packages were estimated, according to the European Standard EN 15459:2007 [5], in order to establish which of them has the lowest global cost and, consequently, represents the cost optimal level.

Among the various studies that are being developed at each national level on this topic, this work is characterized by the use of dynamic simulation in order to accurately estimate the energy demand for heating, cooling, electric lighting, electricity from renewable sources, and especially the trade-off between heating energy and cooling energy, that is particularly important in an office building. Given the use of dynamic simulation and the inherent calculation times, a study based on a limited amount of technically feasible packages of energy efficiency measures, rather than a parametric study, was conducted.

3. The Reference Building

The main purpose of a RB is to represent the typical and average building stock in a certain MS, since it is impossible to calculate the cost optimal situation for every individual building [6]. Hence, it must be chosen to reflect as accurately as possible the present national building stock so that the methodology can deliver representative calculation results.

The case study hereby analyzed is a theoretical Reference Building [6] that is a fictional building composed of disaggregated statistical data related to the main building features gathered together to create a typical Italian office building. It is the results of a national survey [7] carried out by ENEA (Italian National Agency for New Technologies Energy and Sustainable Economic Expansion) and finalized to a quantitative and qualitative analysis of the Italian office building stock. The RB is representative of office buildings located in the North of Italy and built since 1970 until today.

The RB is a five-storey 2760 m² office building with an unconditioned basement and it is located in Turin. It is characterized by a total net conditioned area of 2300 m². The gross area of a typical floor is equal to 480 m², while its gross height is equal to 3.5 m. The building has a rectangular plan (16 m x 30 m), with an interior layout characterized by cellular offices on the perimeter areas and a central core for the services areas. It is oriented N-S on its cross-section. It has an aspect ratio of 0.33 m⁻¹, it is thus a quite compact building. The ratio of the transparent area to the opaque envelope is 38%.

It consists of a reinforced concrete structure, brick walls with insulation, plane insulated roof and double glazing windows with aluminum frame with thermal break and with internal blinds.

The primary system is constituted by a condensing boiler and a chiller with cooling tower; the terminals of heating and cooling system are four-pipe fan coil units.

4. Energy Efficiency Measures

In accordance with the EPBD Guidelines [3], MSs must define energy efficiency measures to be applied to the established RBs. The EEMs can regard the building envelope, passive techniques, building systems as well as the use of renewable energy sources. It is therefore recommended that measures be combined in packages of measures and/or variants, since meaningful combinations of measures can create synergy effects that lead to better results, regarding costs and energy performance, than single measures.

The definition of the EEMs, that are all technically feasible, was carried out on two stages. The EEMs were aimed first to the improvement of the building envelope performances and then to the improvement of systems efficiency and to the exploitation of renewable energy sources. The latter measures were applied to some of the previous models, and in particular, to the RB, which is the solution with the lowest global cost, and to the model which reported the lowest primary energy consumption.

The first set of 12 EEMs consists in an improvement of the thermal insulation of the building envelope. Since the RB is assumed to be located in Turin (climate zone E), the considered U-values correspond to the requirements established by the new regulations on energy performance of buildings in Piedmont Region [8]. Furthermore the EEMs concerning the retrofiting of the building envelope were also distinguished into “homogenous measures” that regarded all the building envelope or “not homogeneous measures” that concerned just selected building components. Three homogenous EEMs were defined (Table 1).

Table 1. Thermal features of the Reference Building and of the homogenous Energy Efficiency Measures involving the improvement of the building envelope thermal insulation

	EEM	U-value		EEM	U-value
RB	Walls	0.75	EEM2	Walls	0.24
	Windows	3.19		Windows	1.5
	Roof	0.81		Roof	0.22
	Ground slab	1.45		Ground slab	0.26
EEM1	Walls	0.33	EEM3	Walls	0.14
	Windows	2		Windows	1.2
	Roof	0.29		Roof	0.15
	Ground slab	0.30		Ground slab	0.16

The U-values applied for the EEM1 are the U-value limits set by the Piedmont Region regulation [8]; the U-values applied for the EEM2 are the optional U-value targets set by the Piedmont Regional regulation [8]; the U-values applied for the EEM3 are the optional U-value targets set by the Turin

city regulation [9]. Measures from EEM4 to EEM12 are indeed not homogeneous (Table 2).

Table 2. Thermal features of the not homogenous Energy Efficiency Measures involving the improvement of the building envelope components

EEM		U-value	EEM		U-value
EEM4	Walls	0.75	EEM9	Walls	0.24
	Windows	2		Windows	1.5
	Roof	0.81		Roof	0.81
	Ground slab	1.45		Ground slab	1.45
EEM5	Walls	0.75	EEM10	Walls	0.75
	Windows	3.19		Windows	1.2
	Roof	0.29		Roof	0.81
	Ground slab	0.30		Ground slab	1.45
EEM6	Walls	0.33	EEM11	Walls	0.75
	Windows	2		Windows	3.19
	Roof	0.81		Roof	0.15
	Ground slab	1.45		Ground slab	0.16
EEM7	Walls	0.75	EEM12	Walls	0.14
	Windows	1.5		Windows	1.2
	Roof	0.81		Roof	0.81
	Ground slab	1.45		Ground slab	1.45
EEM8	Walls	0.75			
	Windows	3.19			
	Roof	0.22			
	Ground slab	0.26			

Table 3. Description of Energy Efficiency Measures affecting the lighting system efficiency and the exploitation of renewable energy sources

EEMs Description		1 st stage EEM	ID
Package 1	ALC	RB	EEM13
		EEM3	EEM14
		EEM8	EEM15
Package 2	PV: 100% roof	RB	EEM16
Package 3	PV: 50% roof	RB	EEM17
Package 4	PV: 25% roof	RB	EEM18
Package 5	ALC PV: 100% roof	RB	EEM19
		EEM3	EEM20
Package 6	ALC PV: 50% roof	RB	EEM21
		EEM3	EEM22
Package 7	ALC PV: 25% roof	RB	EEM23
		EEM3	EEM24

The EEMs considered within the second stage (Table 3) consisted in the introduction of an artificial lighting control (ALC) and in the installation of PV panels on the plane roof. Three different configurations were studied for PV panels:

- covering of the entire roof (pick power: 38 kW_p);
- covering of one half of the roof (pick power: 21 kW_p);
- covering of one fourth of the roof (pick power: 11 kW_p).

5. Energy evaluation

The objective of the energy evaluation was to determine the annual overall energy use in term of delivered energy (divided by sources) and primary energy, which includes energy use for heating, cooling, lighting and equipment. In this study, the annual primary energy consumption for hot water (that is equal to 4.4 kWh/m²) was neglected.

The RB was modeled and simulated by the energy simulation software EnergyPlus (version 6.0).

The typical weather conditions of the Turin location refers to the IGDG Weather for Energy Calculation database of climatic data.

Each floor of the building office was divided into 5 thermal zones, one large core and four perimeter zones (Fig. 1). The model of the entire building is composed of 25 thermal zones plus the unconditioned basement. The interior partitions of the cellular offices were defined as internal mass.

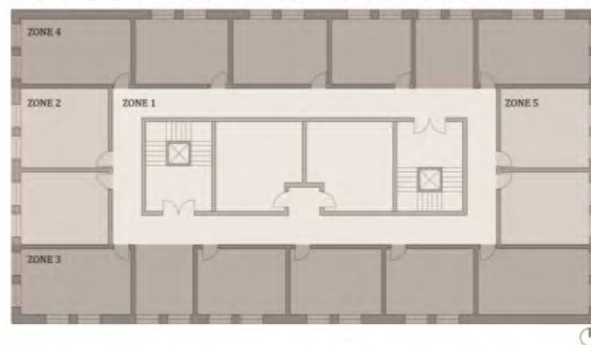


Fig. 1. Reference Building plan with the subdivision in thermal zones

The operational parameters were set to be consistent with the building typology. For the office areas, people per zone floor area were fixed to 0.06 pers/m² [10]. Lighting and appliances power densities were respectively defined to 13 W/m² and 10 W/m² for the office areas and 7 W/m² and 2.9 W/m² for the central core [11]. These densities were linked to the activities schedules carried out in the building during the weekdays and the weekends. A specific occupancy schedule [11] and a schedule related to the use of the lighting system [12] and of the appliances have been defined.

The control of the solar shading is done on the basis of the total solar radiation incident on each window (above 300 W/m² internal blinds are

shut). The control of the artificial lighting is done on the basis of the daylighting illuminance levels in each zone with a continuous/off regulation type.

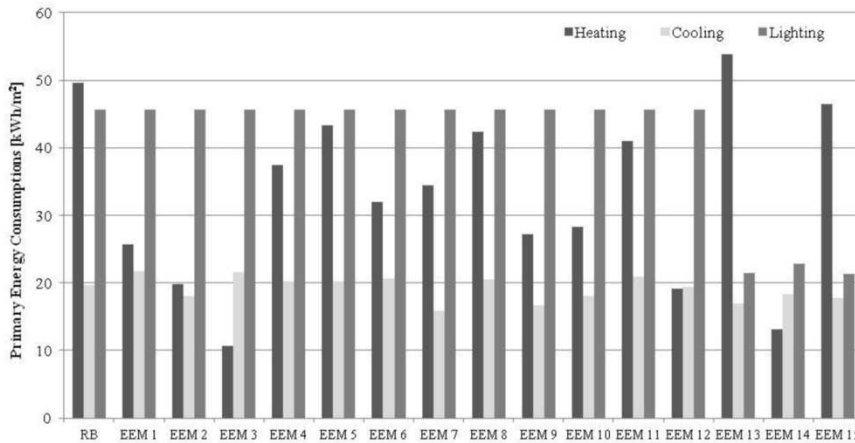


Fig. 2. Annual primary energy consumptions for space heating, cooling and lighting

The heating system has been assumed to be active from the 15th of October to the 15th of April in compliance to the Italian regulations for the climatic zone E (Turin). The cooling system has been set to operate during the remaining period due to the high presence of internal gains. During weekdays, the heating and cooling setpoints were set respectively to 21.5 °C and 26 °C from 5 a.m. to 7 p.m.

During weekdays, the outdoor air flow rate is set at 11 l/s per person operating from 5 a.m. to 7 p.m.

In Figure 2 primary energy consumption of RB and EEMs are reported.

6. Economic evaluation

In accordance with the EPBD, global cost calculations result in a net present value of costs incurred during a defined calculation period, taking into account the residual values of components with longer lifetimes. Following the procedure described in the European Standard EN 15459, global cost is directly linked to the duration of the calculation period τ and it can be written as:

$$C_G(\tau) = C_I + \sum_j \left[\sum_{i=1}^{\tau} (C_{a,i}(j) \cdot R_d(i)) - V_{f,\tau}(j) \right] \quad (1)$$

where $C_G(\tau)$ represents the global cost referred to starting year τ_0 , C_I is the initial investment cost, $C_{a,i}(j)$ is the annual cost for component j at the year i (including running costs and periodic or replacement costs), $R_d(i)$ is the discount rate for year i , $V_{f,\tau}(j)$ is the final value of component j at the end

of the calculation period (referred to the starting year τ_0). The discount rate R_d is used to refer the costs to the starting year; it is expressed in real terms, hence excluding inflation, and it depends from the real interest rate.

In this research, the calculation period was set as equal to 30 years. According to the Guidelines [3] the real interest rate was fixed equal to 4%. The investment costs of EEMs were evaluated by referring to the price list of the Piedmont Region of 2012 [13].

With regard to periodic cost of replacement of building envelope components, it was assumed to replace only the windows, for which it has been considered an average lifespan of 25 years. In the case of the Reference Building, however, since it is an existing building, it was assumed to replace them after 13 years (about half of 25). With regard to the data on the duration of the system components reference was made to Appendix A of EN 15459:2007. This Appendix reports also the annual maintenance costs of systems components (expressed as a percentage of the cost of the component) that were used in this analysis.

For RB and for each EEM the costs related to energy consumption for space heating (natural gas), for space cooling, for the auxiliary of heating and cooling system, for lighting and for appliances (electricity) were considered. In detail:

- natural gas cost: 0.083 €/ kWh;
- electricity cost: 0.16 €/ kWh;
- electricity tax: 100 €/kW.

About the PV system, the following assumptions were made:

- feed-in tariff: 0.171 €/kWh (11 kW_p) or 0.157 €/kWh (21 and 38 kW_p) taken for 20 years [14];
- incentive for the electricity consumed on site: 0.089 €/kWh (11 kW_p) or 0.075 €/kWh (21 and 38 kW_p) taken for 20 years [14];
- feed-in tariff from the 21st to the 30th year: 0.03 €/kWh.

7. Cost optimal levels of energy consumptions

In order to find the cost optimal level, the primary energy consumption (that includes also the energy for lighting and for equipment) was plotted versus the global cost (Fig. 3). Both quantities are divided per the net conditioned floor area.

In the graph, in correspondence to the RB a vertical line that represents the maximum primary energy consumption was drawn.

The energy efficiency measures allow savings from 6 to 97 kWh/m²y (primary energy) in absolute terms; in percentage terms, savings are between 4 and 58%. In particular, EEMs 8, 5 and 11 (characterized approximately by an energy consumption of 160 kWh/m²y and a global cost of 449 €/m²) allow to achieve the minimum energy savings that can be obtained with the analyzed efficiency actions. These measures considered different levels of roof and ground slab thermal insulation. Instead, the minimum value of

consumption is achieved with the EEM20 (69 kWh/m²y and 557 €/m²), which combines the maximum level of thermal insulation of the whole envelope with the introduction of the artificial lighting control (ALC) and the installation of PV panels covering the entire roof.

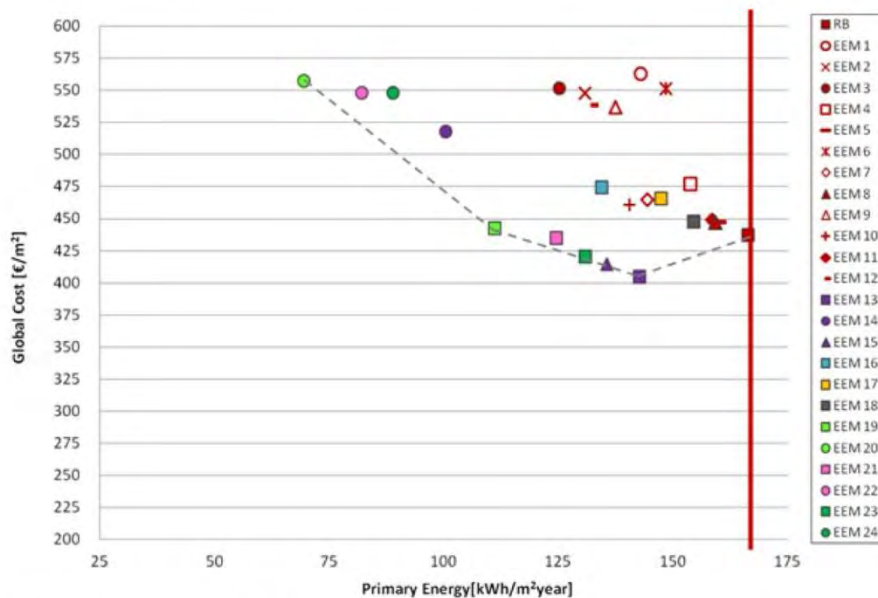


Fig. 3. Global costs of the Reference Building and of the different Energy Efficiency Measures as a function of the primary energy consumption

With regard to the global cost, EEM 1 and EEM 13 represent respectively the uppermost (563 €/m²) and the lowest (405 €/m²) extreme points. EEM 1 consists in a thermal insulation improvement of the whole building envelope according to the current Italian regional regulation; EEM 13 doesn't deal with building envelope efficiency measures but consists in the installation of ALC on the Reference Building.

The graph underlines that EEMs have both lower and higher global cost values compared to the RB. Global cost values higher than RB tend to be the ones of the envelope EEMs, because the investment costs for the different efficiency measures cannot be repaid by the economic savings associated with energy savings obtained.

The position of the EEMs that were studied permitted to draw the trend of dotted broken line that represents the cost curve, the minimum of which may be considered as the cost optimal level [3]. Global costs lower than the cost of the RB tend to be associated with EEMs concerning the systems. EEMs 13, 15, 21 and 23 have approximately the same value of global cost, that ranges between 405 and 435 €/m². EEM 15 consists in the improvement of roof and ground slab thermal insulation (according to the optional U-values targets set by Italian regional regulations) and in the introduction of

ALC; while EEMs 21 and 23 are characterized by the installation of ALC and different PV system configurations. The EEM with the lowest global costs is EEM 13 and has a primary energy consumption of 143 kWh/m²y. It does not improve the thermal insulation of the building envelope but considers only the introduction of ALC.

Further studies are needed to simulate different EEMs which combine various levels of thermal insulation for the envelope components (windows, walls, roof, slab) and EEMs related to the building system, and to carry on sensitive analyses on the discount rates and, in particular, on the escalation of energy price.

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