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Cost-optimal methodology for energy requalification of “raffaello” school in Pistoia

Keywords: existing school; energy requalification; sustainable school; energy saving

Abstract: In 2017, 46.5% of school buildings in Italy needed urgent maintenance regarding architectural usability and accessibility, but also concerning structural, energy and environmental aspects. 36% of the energy needs during the operational and management phase of the Italian school sector is required by secondary schools. The main objective of this paper is to propose an integrated (architectural, energy and environmental) redevelopment for the “Raffaello” School in Pistoia (Italy) aimed at improving the environmental and technological system and decreasing the building’s primary energy demand. Here, for the sake of brevity, we will only deal explicitly with energy rehabilitation. The results show that the replacement of the artificial lighting system with LED lamps alone leads to a 45% decrease in primary energy demand. Moreover, for the sake of completeness a cost-optimal analysis was performed referred to both heating and lighting system and technological solution for the external envelope. The cost-optimal analysis points out that the substitution of artificial lighting system is the upgrade measure that satisfy both economic and energy sustainability, confirming previous findings. Regarding external envelope redevelopment the more advantageous solution is the one with external insulation layer in wood fiber with aerated concrete blocks for load-bearing functional layer.

Introduction

The Italian school heritage is undoubtedly old, obsolete, inadequate and above all characterized by limited energy efficiency and poor environmental sustainability. Several problems characterize the existing schools, and they are linked not only to the internal organization, which does not at all meet the requirements of new teaching and pedagogical methods, usability, and safety, but also mainly to energy and environmental issues. This condition of the existing Italian schools is primarily related to the construction period of these buildings. Indeed the 63% of Italian schools are built before 1974 and the 23% before 1940, when there are not any standards concern energy saving, low environmental impact, and legislations about seismic construction.

Actually, school buildings are characterized by an excessive yearly primary energy demand (primarily energy needs for heating), mainly due to the non-use of renewable sources for energy production, inefficient heating and/or cooling systems and inadequate technological solutions for the external envelope. In Italy in 2018 only 1% of school buildings were in energy class A, while 45.3% were in energy class G ($EP_{gl,ren} > 3.50\ EP_{gl,nren,rif,standard}$) [1].

Due to this context and the ongoing climate change, it is essential complying with the requirements of "*2030 climate and energy package*", the *Paris Agreement* and the European *17 Sustainable Developments Goals* with the aim at obtaining safe and sustainably built schools. This aim can be achieved both by building new schools according to nZEB (Nearly Energy Building) and low-carbon standards and by planning suitable structural, energy and environmental upgrading of existing school's heritage. Certainly, this leads to a significant decrease in both primary energy demand and environmental impact during operational phase and consequently to the reduction of costs during building management for Public Administrations.

The main objective of this research work is to propose an integrated requalification (architectural, energetical and environmental) for the secondary school "Raffaello", designed by Luigi Pellegrin (1925–2001) and built by the company Fratelli Bortolaso of Verona in Pistoia in 1967, taken as a case study.

Here, for the sake of brevity, the chapter only deals specifically with the energy requalification. Once identified the possible energy and enviornmental requalification strategies to be used in the case study, mainly related to the external envelope technological solutions, a cost-optimal methodology was performed, with the help of BIM (Building Information Modeling) [2] especially to specify materials quantities.

This analysis makes it possible to define for the considered school building the better upgrade strategies considering both environmental and economic sustainability.

State of the art

As regard to existing school buildings, the analysis of the literature shows that many studies on existing school buildings (primary and secondary schools) deal with the evaluation of the best energy and environmental refurbishment strategies adopted to obtain a lower annual primary energy demand (especially in terms of energy demand for heating considering Italy). The Italian education sector energy needs is equal to 1 Mtoe/year (data from 2012) [3]. The 36% of the total energy demand is for public secondary schools, as for instance the level of the school considered as a case study. Regarding primary energy demand and upgrading strategies, some studies consider obviously the cost parameter as well.

Different analyses are used to outline the type of measure to carry out: the comparative cost-optimal methodology proposed directly by the European Directive 2010/31/EU [4][5][6][7] and combined very often with the calculation of the payback period and the CO_2 emissions released into the atmosphere [8].

The cost-optimality procedure allows to identify the possible requalification strategies to be applied on an existing building to obtain a better performance considering both energy and economic performance. Usually, the different energy measures are related in a graph to both the primary energy demand of the building [kWh/m^{2}a] and the global cost (initial investment, operational, servicing, substitution, energy and disposal) of the different measure applied [€/m^2].

For instance, Becchio et al. [9]for buildings, on the cost-optimal level. In Italy, the EPBD recast was transposed in a document (published in GU 2012/C 115 applied the cost-optimal methodology to evaluate the most energy efficient measure (mainly concerning external envelope and systems together to renewables for energy production) for an industrial building in northern Italy considering 21 different scenarios. They would change the intended use in house and office. They concluded that for a better performance an internal insulation layer for the external envelope must be used combined with condensing boiler and chiller with radiant floor for residential space and with fan coils for office building. With an appropriate global cost (of about 1000 €/m^2), the energy needs would be reduced by about 15 kWh/m^{2}a with these energy retrofitting measures.

Instead, some authors applied the cost-optimal procedure to evaluate the optimal thickness of insulation layer in building with different intended use and located in different climate zone [10][11]. For instance, Raimundo et al. considered 5 different intended use of building and different climate zone in Portugal in order to define the best solution of insulation layer (material and thickness) considering both economic and energy sustainability. They stated that the EPS (sintered expanded polystyrene) located in the middle of the external envelope stratigraphy is the best solution and the residential building required a higher thickness of insulation materials due to the permanent occupation of internal functional units.

In some cases, authors [12] resort to using BIM as a support tool for the cost-optimal analysis thanks to the parametric nature of the model it can be exploited to extract bill of materials ensuring reliable cost estimation. Moreover, because of its interoperability with energy simulation tools the model can be used for primary energy demand assessment.

Or to define the better upgrade strategy for existing buildings many authors performed the comparison through simulation in dynamic regime between the existing state and the design state with a proposal of upgrading according to nZEB standards considering the interventions also in terms of cost [13] and performing monitoring on the existing building to validate the simulation models [14] or through the life cycle assessment (LCA) or the application of certification protocols [15]. For instance, Elkhapery et al. [16] proposed a method to consider the cost-effective measure, especially for water and electricity savings, for 9 different schools in Dubai with respect to the level of LEED (Leadership in Energy and Environmental Design) energy certification (certified, silver, gold and platinum). They stated that there is not a significant difference in terms of cost between the 3 first levels along with the same energy savings and so they advised a requalification to gold level.

Instead, Doulos et al. [17] considering different energy retrofitting for a school building located in Pisa to evaluate the needed energy upgrade to obtain a nZEB building, according to current Italian standard, also evaluating the cost of each different requalification measure. If they considering a whole retrofitting action (for instance substitution of the external envelope, upgrade of artificial lighting system, installation of solar protection and retrofitting of heating, cooling and ventilation systems also using renewables), they obtain a decrease in both electric (70%) and thermal energy demand (48%).

Finally, many authors point out that to significantly reduce primary energy demand, it is necessary to work on the artificial lighting system and on the management of shading systems [18] [19].

Method

The methodology for the study of the energy requalification proposal (which is part of an integrated requalification process) is divided into 4 different phases:

- Identification of the energy strategies for the rehabilitation of existing schools. From the analysis of several case studies of secondary schools that are characterized by energy upgrading after 2008 and the state of the art, recurring energy strategies to improve the energy performance of an existing school building were defined.
- Detailed analysis of the case study. The energy performance of the existing state was defined through modelling of the school and energy simulation in a dynamic regime with hourly time step using Design Builder [20]. Heating, cooling, and lighting consumptions were considered because they are the most important contributions to the energy balance of a school building.
- Proposal for the energy requalification of the "Raffaello" School. First of all, different strategies for the energy requalification, according to the most recurrent ones in literature, have been proposed and validated through the energy simulations; replacement of the external envelope, replacement of the artificial lighting system (22 lm/W – fluorescent lamps) with a more efficient LED system

(120 lm/W with control on natural lighting), replacement of the existing heating system (gas boiler with 50% efficiency) and introduction of cooling one maintaining a natural ventilation of the rooms and two design proposals related to the system: design proposal 1 replacement of the boiler with an air-water heat pump (coefficient of performance = 3. 8 and energy efficiency ratio = 3.5) for heating and cooling with radiant panel as distribution system and design proposal 2 equal to design proposal 1 in addition to the replacement of the mechanical ventilation system (integrated with heat recovery with 60% efficiency) currently not working.

- To deeper study the external envelope in terms of different technological solutions to be applied, and some measures for lighting and heating system, a cost-optimal methodology [4] was performed to identify the retrofitting solutions that could ensure the best compromise between economic investment and energy saving.

The UNI EN 15459: 2018 [21] define the global cost with the following equation that lets considering both financial and macroeconomic scenario:

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

where: $C_G(\tau)$ is the global cost, referred to the first year $\tau = 0$, C_I are the initial investment costs, $C_{a,i}(j)$ is the annual cost for the year i for the component *j*, $R_d(i)$ is the discount factor for year *i*, $V_{f,r}(j)$ residual value of component *j* at the end of the calculation time, $C_{c,i}(j)$ is the cost of CO_2 emissions for the component *j*.

So, the initial investment cost for building materials was obtained recurring to price lists available on Italian Regional price list or other nationally trusted price list (for instance DEI prince list 2018) and, for the missing elements, referring to producers' websites. The cost of labor was included in the cost of the manufacturing. As it concerns the quantification of the amount of materials to be used in each of the alternative configuration, BIM models comprehensive of all the different stratigraphies to be compared were realized. An accurate calculation of materials was then provided thanks to the parametric nature of the model and the table sheets exported in Excel format.

As far as the period for the cost-optimality procedure concerns it was considered equal to 30 years as specified for public buildings in the Delegate Regulation n. 244/2012 [22]. Moreover, in the calculation of the annual cost for the year (i) for the component or measures (j) the cost of servicing for components maintenance, the cost of substitution of materials with lower service life than the period of calculation (for instance for the heating system) and the cost of energy for building operational phase are included. The cost for the substitution of the materials is considered equal to the initial investment costs while the cost of energy was defined with ARERA (Authority of Regulation for energy grid and environment) that gives costs of electricity and gas composed by a fixed part based on the Italian Region and by a variable part based on energy consumption of the building.

The discount factor for year depends on the real discount factor that was considered for both the economic scenarios: financial and macroeconomic. The difference is that for the first one the VAT and excise duties were considered but in the equation the cost of CO_2 emissions was not, by contrast for the second one the cost of CO_2 emissions for energy consumption was considered while VAT and excise duties were not. As the regulation detailed the cost of CO_2 emissions is equal to 20 €/tCO_2 within 2025, 35 €/tCO_2 until 2030 and 50 €/tCO_2 after 2030. In order to calculate the CO_2 emissions for energy consumption for both gas and electricity the following conversion factor referred to each energy vector are considered as reported in the ISPRA Report 317/2020: 0.201 kgCO_2/kWh for natural gas and 0.360 kgCO_2/kWh for electricity. For the value of VAT and excise duties the Italian standard was considered.

As previously mentioned, for completeness both financial and macroeconomic scenarios are considered, so the discounting factors are equal to 4% and 5% for the first scenario and 3% and 4% for the second one. In this way also a sensitivity analysis of data was performed, as required by the European regulation.

In the following table (Table 1) the different measures for the redevelopment of the existing school used for the cost-optimal methodology are showed, firstly the single upgrade and secondly a combination of some of them (5 different kind of combinations).

TABLE 1. **Differet upgrade measure for cost-optimal analysis**

Abbreviation	Upgrade measure description
GF_N1 + GF_N2	Insulation and waterproofing of the ground floor stratigraphy for the whole existing school building
EW_N1	Substitution of the external envelope with aerated concrete for load-bearing functional layer, rock wool insulation and advanced ventilated façade (thermal transmittance equal to the reference building)
EW_N1.1	The same of EW_N1 but characterised by half of the thermal transmittance
EW_N2.1	Substitution of external envelope with dry solution with rock wool insulation and gypsum fibre panel as external finishing (characterised by half of the thermal transmittance with respect to reference building)
EW _N3	The same of PPV_N1.1 but with wood fibre insulation
EW _N3.1	The same of PPV_N2.1 but with wood fibre insulation
EW_N3.2	The same of EW_N1.1 but with ETICS (External Thermal Insulation Composite System) external finishing
W_N1	Substitution of all windows in the whole building (Glazing + frame)
RF_N1	Insulation and waterproofing of roof stratigraphy with external finishing with gravel
RF_N2	Insulation and waterproofing of roof stratigraphy with technological solution of green roof

Abbreviation	Upgrade measure description
Syst_1	Substitution of gas boiler with condensing one characterised by a performance equal to 90%
Syst_2	Substitution of artificial lighting system with one more efficient (LED)
Combinations of upgrade measure	
1	EW_N3.1.2 + W_N1 + RF_N1
2	EW_N3.1.2 + W_N1 + RF_N1 + Syst_1
3	EW_N3.1.2 + W_N1 + RF_N1 + Syst_2
4	EW _N3.1 + W_N1 + RF_N1 + Syst_1
5	EW_N3.1 + W_N1 + RF_N1 + Syst_2

The different types of technological solutions proposed are more detailed in tables 7–12 and A.1-A.4 and figures 3–5.

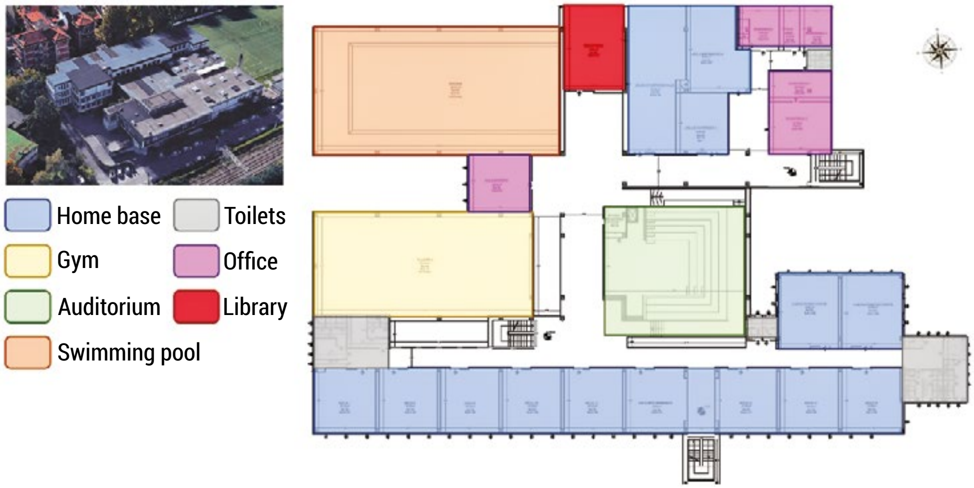

FIG. 1. **Aerial view (up on the left – https://www.google.it/maps) and plan of the standard floor of Secondary school Raffaello with the indications of the main functional units.**

The secondary school "Raffaello" built in 1967 is located in the municipality of Pistoia, belonging to the climatic zone D [23] with a degree day number equal to 1885. Italy, in fact, is divided in 6 climate zones based on the number of the degree day. The building is characterized by a very complex planimetric configuration that also includes a swimming pool, a gym and an auditorium, perfectly integrated with the remaining part dedicated exclusively to the school. Although the building is characterized by a very articulated architectural design, it can be inscribed in a rectangle with main dimensions of 80 m x 60 m; it has total surface area equal to 7196 m^2 and volume of about 37600 m^3. The architectural and structural design is based exclusively on the repetition of elements with a module of 1.20 m. The school develops on to 3 floors and a basement (Figures 1–2), which there is the central heating and air conditioning system.

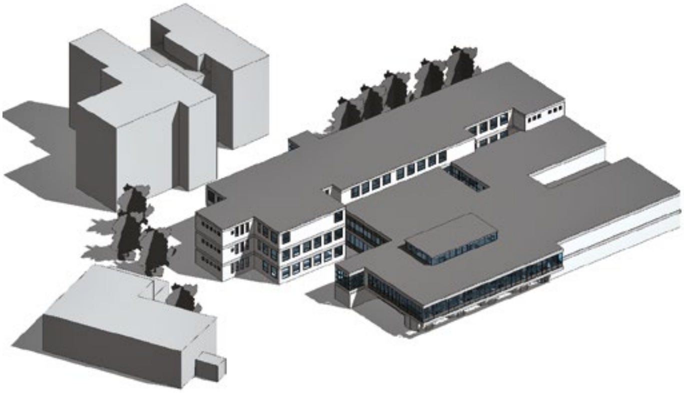

FIG. 2. **Axonometric view of the BIM model in Revit of the Secondary School Raffello.**

The existing building is characterized by a metal load-bearing structure and the only parts in reinforced concrete are the load-bearing structure of the stairs and auditorium. The external walls are mainly made of insulated precast reinforced concrete panel and the roof stratigraphy was characterized by a prefabricated panel in reinforced concrete 0.8 m thick (RAP patent) that was recurrently used in Italy during the period of construction of this school. For a better understanding of the current characteristics of the external envelope the following tables (tables 2–6) and corresponding figures (figures 3–5) show the detailed stratigraphy of each technological solution found in the building (from the external layer to internal one) and the main thermodynamic characteristics considering the requirements imposed by current Italian legislation. The thermal conductivity are mainly found, when they are not available, in the UNI 10351:2015 [24].

TABLE 2. **Existing ground floor stratigrafy (GF_E1) for gym functional unit**

Technological solution	Layer	T [m]	λ [W/mK]	R [m^{2}K/W]
Ground floor type 1 (Gym) – GF_E1	Brick slab	0.06		0.14
	Screed	0.05	1.910	
	Wood finishing	0.02	0.15	
Thermal transmittance [W/m^{2}K]				1.963

TABLE 3. Existing ground floor stratigrafy (GF_E2) for the whole building except gym

Technological solution	Layer	T [m]	λ [W/mK]	R [m²K/W]
Ground floor type 2 (Whole building) – GF_E2	Brick slab + reinforced concrete slab	0.26	–	0.35
	Screed	0.06	1.91	–
	Linoleum finishing	0.03	0.22	–
Thermal transmittance [W/m²K]				1.653

TABLE 4. Existing external wall stratigrafy (PPV_E1)

Technological solution	Layer	T [m]	λ [W/mK]	R [m²K/W]
External wall (prefabricated panel) – PPV_E1	Vibrated and reinforced concrete conglomerate panel	0.03	1.91	–
	Air cavity	0.10	–	0.15
	Resin foam	0.04	0.032	
	Aluminium sheet	–	–	–
	Gypsum laminate	0.018	0.21	
Thermal transmittance [W/m²K]				1.671
Periodic thermal transmittance [W/m²K]				0.57
Time shift [h]				1.90

TABLE 5. Existing roof floor stratigrafy (RF_E1)

Technological solution	Layer	T [m]	λ [W/mK]	R [m²K/W]
Roof floor – RF_E1	Waterproof sheet	0.003	0.5	–
	Resin foam	0.03	0.032	–
	Precast reinforced concrete slab	0.03	1.91	–
Thermal transmittance [W/m²K]				0.912

TABLE 6. Existing windows characteristics (W_E1)

Technological solution	Existing windows description
Windows – W_E1	The existing windows are characterised by a wooden frame and a single glazing (5 mm thick) with thermal transmittance that does not meet the Italian requirements

For performing cost-optimality methodology the following technological solutions for the external envelope in tables 7–12 and tables A.1–A.4 in the appendix A and figures 4–6 were investigated.

TABLE 7. Upgraded ground floor stratigrafy (GF_N1) for gym functional unit

Technological solution	Layer	T [m]	λ [W/mK]	R [m^{2}K/W]
Ground floor type 1 (Gym) – GF_N1	Brick slab	0.06		0.14
	Screed	0.05	1.91	
	Vapour barrier polyethylene	0.00005	0.40	
	Wood fiber	0.14	0.037	
	Lightweight Screed	0.04	0.25	
	Wood finishing	0.02	0.15	
Thermal transmittance [W/m^{2}K]				0.225

TABLE 8. Possible redevelopment measure for external wall (PPV_N1) with same transmitance of the reference building

Technological solution	Layer	T [m]	λ [W/mK]	R [m^{2}K/W]
External wall – PPV_N1	Advance screen façade	–	–	–
	Air cavity	–	–	–
	Aerated concrete	0.30	0.07	
	Gypsum fibre panel	0.015	0.3	
	Gypsum fibre panel	0.015	0.3	
Thermal transmittance [W/m^{2}K]				0.22
Periodic thermal transmittance [W/m^{2}K]				0.042
Time shift [h]				13.37

TABLE 9. Possible redevelopment measure for external wall with dry solution (rock wool insulation) characterised by the half value of the thermal transmittance of the reference building (PPV_N2.1)

Technological solution	Layer	T [m]	λ [W/mK]	R [m^{2}K/W]
External wall – PPV_N2.1	Cement board	0.013	0.13	
	Vapour barrier	0.0002	0.38	
	Rock wool	0.20	0.035	
	Gypsum panel	0.015	0.21	
	Rock wool	0.04	0.035	
	Gypsum fibre panel	0.015	0.3	
	Gypsum fibre panel	0.015	0.3	
Thermal transmittance [W/m^{2}K]				0.137
Periodic thermal transmittance [W/m^{2}K]				0.092
Time shift [h]				6.44

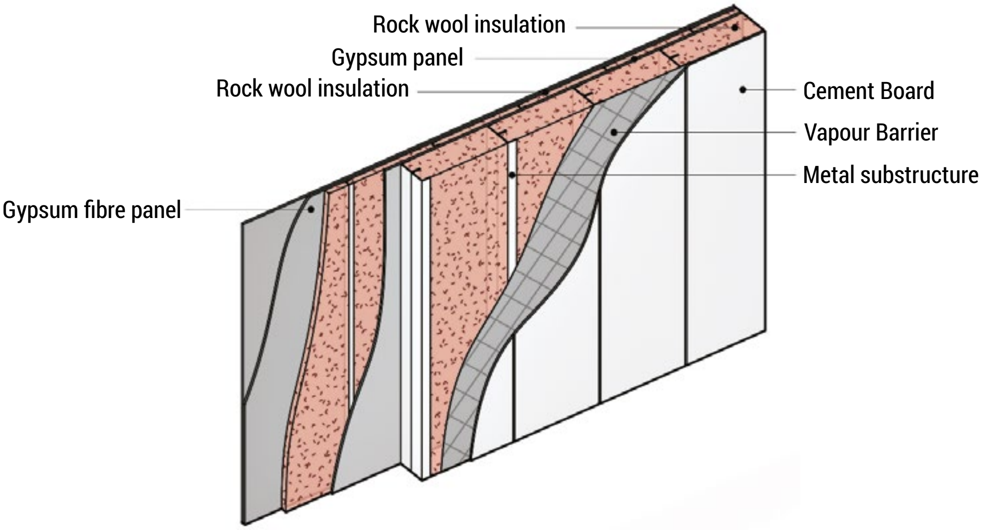

FIG. 3. Sketch of PPV_N2.1 stratigraphy

TABLE 10. Possible redevelopment measure for external wall characterised by the half value of the thermal transmittance of the reference building with ETICS as external finishing (PPV_N3.2)

Technological solution	Layer	T [m]	λ [W/mK]	R [m^{2}K/W]
External wall – PPV_N3.2	External plaster	0.03	0.43	
	Wood fibre	0.04	0.034	
	Aerated concrete	0.30	0.07	
	Gypsum fibre panel	0.015	0.3	
	Gypsum fibre panel	0.015	0.3	
Thermal transmittance [W/m^{2}K]				0.177
Periodic thermal transmittance [W/m^{2}K]				0.019
Time shift [h]				15.83

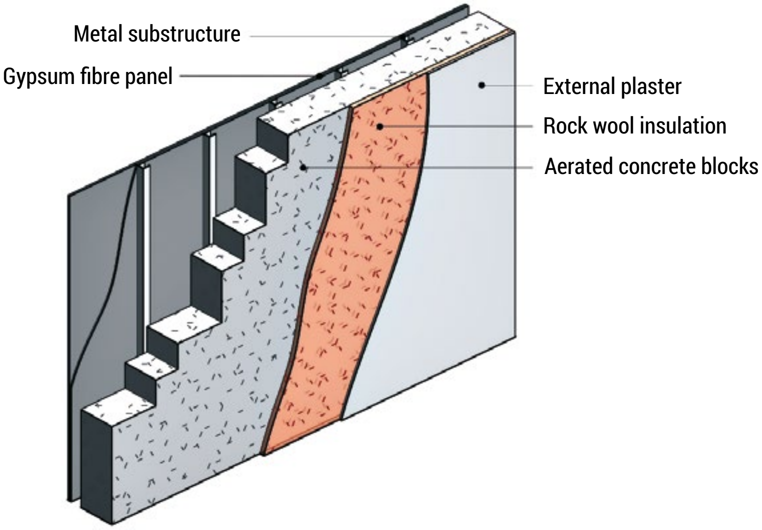

FIG. 4. Sketch of PPV_N3.2 stratigraphy

TABLE 11. Possible redevelopment measure for roof floor with gravel as fnishing layer (RF_N1)

Technological solution	Layer	T [m]	λ [W/mK]	R [m^{2}K/W]
Roof floor – RF_N1	Gravel	0.05	–	–
	Waterproof sheet	0.003	0.5	–
	Wood fiber	0.14	0.037	
	Vapour barrier	0.0005	0.4	–
	Precast reinforced concrete slab	0.03	1.91	–
Thermal transmittance [W/m^{2}K]				0.253

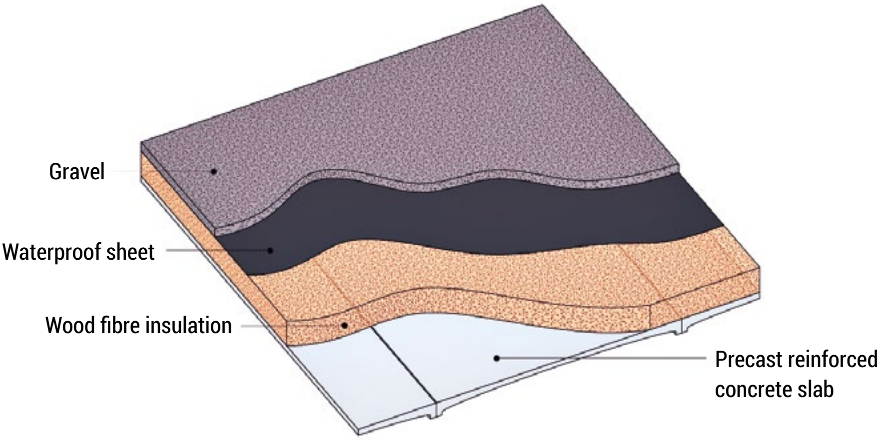

FIG. 5. Sketch of RF_N1 stratigraphy

TABLE 12. **Upgrade windows characteristics (W_E1)**

Technological solution	Existing windows description
Windows – W_E1	The new glazing is type AGC 66.2A(16AR)44.2A with solar factor equal to 31% and U = 1 W/m^{2}K

Results and Discussion

The main energy requalification strategies to obtain a reduction of primary energy demand identified in the study of the analyzed buildings and in the literature are: improvement of the shading system with both fixed and mobile solar shading ones, replacement of windows, creation of an external insulation layer for the external wall, integration with renewables, installation of more efficient artificial lighting system, use of rainwater collection systems, installation of a cooling system to maintain adequate internal comfort conditions even during the summer season.

From an energy point of view, the analysis of the current state of the building highlights the following main problems: the technological solutions for the external wall are not verified in terms of thermodynamic properties and thermal transmittance as demonstrated in the values showed in previous tables about existing technological solutions, the artificial lighting system is outdated and obsolete and characterized by neon lamps with no automated control according to the level of illumination guaranteed by natural light. The heating system with gas boiler (peak power equal to about 1200 kW) does not guarantee the average minimum setpoint temperature of 20°C in the building, the mechanical ventilation system is currently not working, and therefore the air exchange required occurs only through natural ventilation. Consequently, the main proposals for the energy upgrading are: the replacement of the external wall made of prefabricated slabs with a solution characterised by a load-bearing layer made of aerated autoclaved concrete blocks (0.24 m), an insulation layer with rock wool (0.6 m) and an advanced screen façade with stoneware finishing, the replacement of windows that do not meet the requirements of current energy and safety regulations for schools, the replacement of the artificial lighting system and a double proposal for upgrading the system, as already described.

The graph in Figure 6 shows the annual energy demand in [kWh/m^{2}year] for heating, cooling, and lighting for the existing and design proposal 1 and 2.

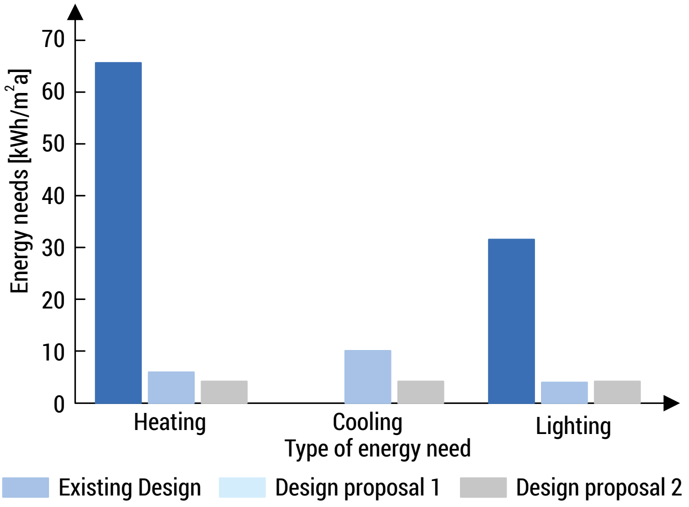

FIG. 6. **Energy needs [kWh/m^{2}year] for heating, cooling and artificial lighting.**

The graph shows that the energy requalification of the building leads to a significant decrease in both energy consumption for heating, by about 90%, and lighting, by about 85%. These results in a clear improvement in the environmental performance of the building during operational phase, with a decrease in CO_2 emissions of about 22 $kgCO_2/m^2$year (for heating alone). The energy demand for cooling obviously only appears in design proposal 1 and 2 and it is not significant, thanks to the use of solar shading systems on both the South and East façades of the building. Comparing design proposal 1 and 2, the former has a slightly higher value of energy demand for electricity. This is due to the presence of natural ventilation inside the rooms to ensure air exchange rates and the absence of heat recovery due to mechanical ventilation during the winter season.

The graph in Figure 7 shows the primary energy demand for heating, cooling and lighting for the existing state; design proposal 1 and 2; the replacement of the external envelope; the heating/cooling system and the artificial lighting system considered separately.

The graph (Figure 7) highlights that between the existing state and the design proposal 1 and 2 there is a difference for the primary energy demand, considering the conversion factors for each energy vector (gas or electricity from grid without renewables), equal to 66% and 79% respectively. As already pointed out, the decrease in primary energy demand in design condition 2 is due to the presence of mechanical ventilation with heat recovery. However, just the replacement of existing lamps with a more efficient lighting system with natural lighting control leads to a decrease in primary energy demand of about 45%.

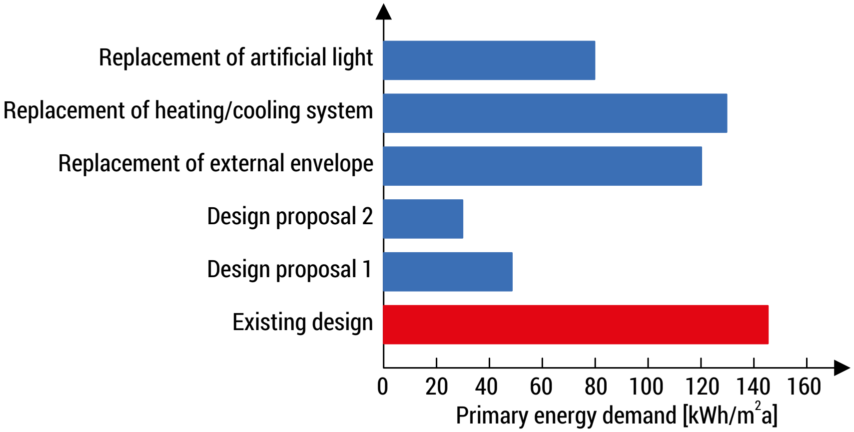

FIG. 7. **Primary energy demand [kWh/m^{2}year]. In red the yearly primary energy demand for existing design.**

As far as cost-optimal analysis concerns Figure 8 shows the results of the financial scenario of the cost-optimality methodology with the discount factor equal to 4%.

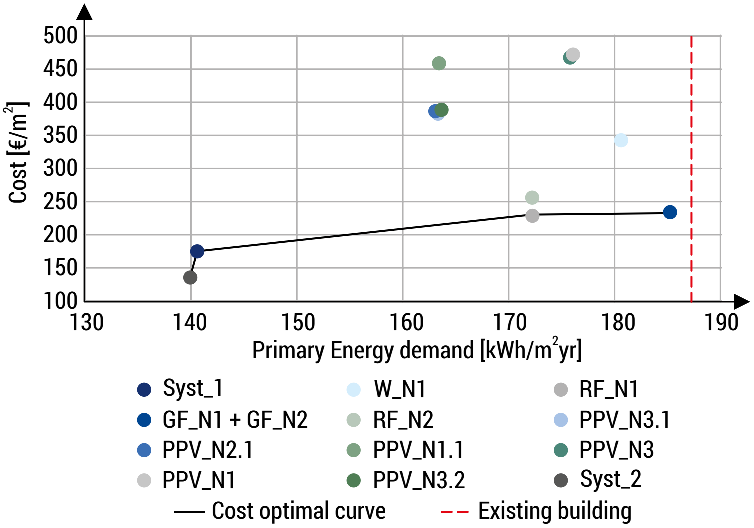

FIG. 8. **Cost-optimality method results for financial scenario and discount factor equal to 4%. The red line in the graph shows the primary energy consumption for existing building.**

Firstly, the graph highlights that all the solutions characterized by the external finishing with ventilated façade have higher cost with respect to other solutions linked to the used of metal substructure and the materials for the external cladding. Indeed, as regards energy performance in term of primary energy demand [kWh/m^{2}year], the ETICS solution and the ventilated façade are equivalent because they are characterized by the same thermal transmittance. So, the choice of technological solution with ventilated façade as external finishing is mainly related to an esthetical requirement of the designer or the administration.

At the same time, it is important to point out that all the upgrade measures for the external envelope are above the cost-optimal curve because of the higher cost of windows (frame and glazing) substitution. These measures result in a significant cost of all proposed redevelopment of the external wall.

Moreover, the graph shows that the solution GF_N1 + GF_N2 with waterproofing and insulation of the ground floor stratigraphy does not lead to a significant reduction in primary energy demand despite the cost of the solution. The same thing happens if we consider the only substitution of windows keeping the external wall the existing one, because this does not result in a considerable advantage in terms of energy performance.

Furthermore, regarding the technological solution for the external envelope, the solution PPV_N3.2 with ETICS satisfy the cost-optimal requirements of financial scenario, along with the same energy performance of PPV_N2.1 and PPV_N3.1.

Finally considering the cost optimal curve at 4% also the retrofitting measure related to the roof floor with gravel finishing (RF_N1) is not despicable as it lets achieving a decrease in annual primary energy demand with a lower cost than the upgrade measures for the external wall. As well as the same energy performance the solution with green roof finishing is characterised by a slight increase in cost.

Confirming previous findings, the Syst_2 upgrade measure with the redevelopment of the artificial lighting system is the better one because it is characterised by the lower cost along with the better energy performance.

The following graph in Figure 9 shows the sensitivity analysis of the cost-optimality financial scenario, considering a discounting factor equal to 5%. This analysis is fundamental to understand how the most variable parameters affect the global cost considering a range of time equal to 30 years.

The graph points out that the cost noticeably decreases for a value equal to about 25 €/m^2. The upgrading measure Syst_2 is always the better one but with respect to the others over time it is distinguished by a less decrease in cost due to the cost of maintenance of other solutions (for instance Syst_1) that considerably affect the global cost. Indeed, the LED solution does not have this component.

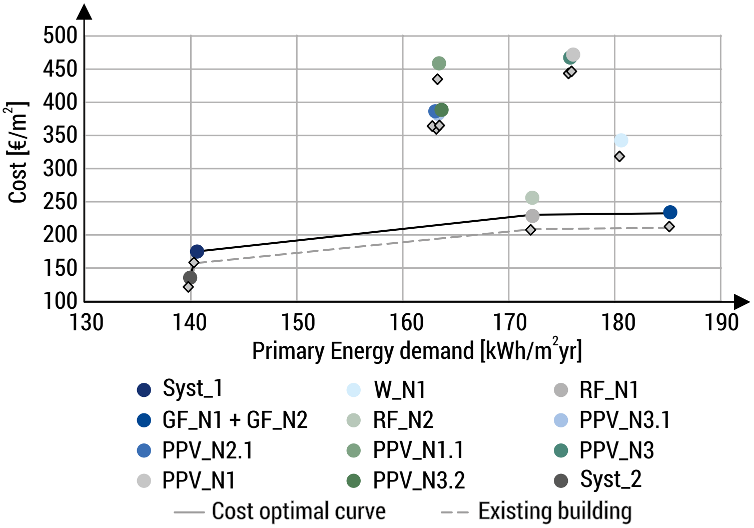

FIG. 9. **Cost-optimality sensitivity analysis for financial scenario and discount factor equal to 5%.**

Figure 10 shows the cost-optimality procedure considering some combinations of parameters (Table 1) as well to consider the variation in the period of the analysis (30 years) of the global cost for financial scenario with discount factor equal to 4%.

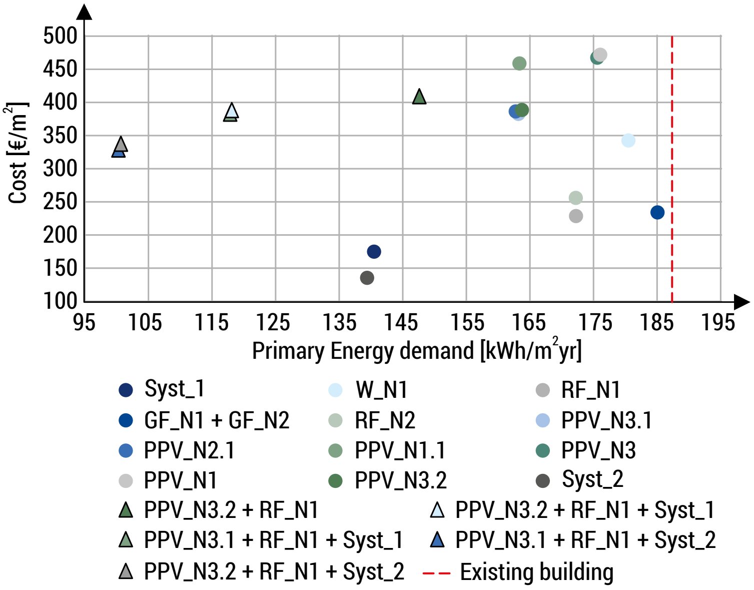

FIG. 10. **Cost-optimal results for financial scenario with discount rate euqal to 4% considering some combinations of parameters.**

As well as in previous graph in Figure 8, Figure 10 shows that combining some different solutions of upgrade measures for the external envelope, included obviously the substitution of windows, with retrofitting of systems, the higher cost of windows (both initial investment cost and maintenance one over time) significantly influences the results of cost-optimal analysis. Indeed, all the solutions with the retrofitting of the external wall are over the cost-optimal curve. The solutions PPV_N3.1 + RF_N1 + Syst_2 and PPV_N3.2 + RF_N1 + Syst_2, the first one with dry solution and the other one with the aerated concrete blocks, are the best combinations of parameters in terms of both cost and energy demand mainly related to the substitution of artificial lighting that lets to obtain a noticeable decrease in primary energy demand with affordable cost of initial investment.

For the sake of completeness, also the macroeconomic scenario was considered for the cost-optimality methodology. The graph in Figure 11 illustrates the sensitivity analysis of macroeconomic scenario for both values of discount factor: 3% and 4%.

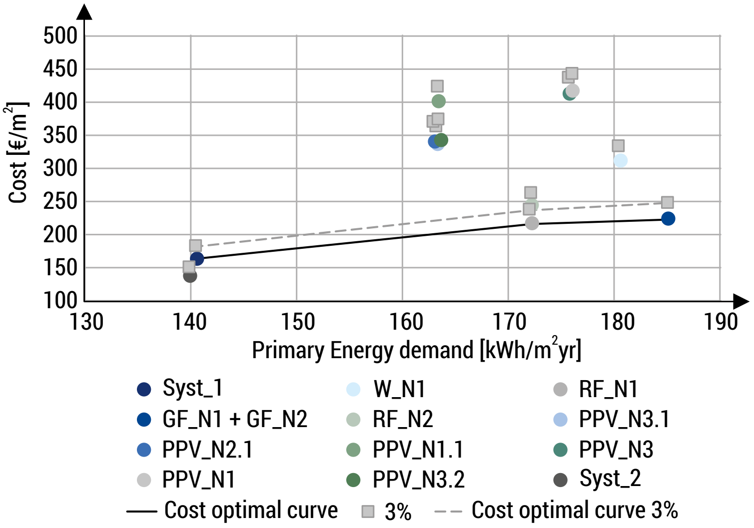

FIG. 11. **Cost-optimality method results for macroeconomic scenario and discount factor equal to 3% and related sensitivity analysis at 4%.**

It is possible to affirm that in general for each improvement measures proposed, the global cost of the cost-optimality methodology decreased in this macroeconomic scenario with respect to financial one. This is mainly due to the VAT and excise duties that in this scenario were not considered as required by legislation. In this case the cost of CO_2 emissions were included but they have less influence than taxes because they are applied exclusively to energy consumption. Indeed, the graph shows that the cost of the solutions with many components (for instance the dry solution for the external envelope) significantly decrease because of there are not taxes for materials components. For instance, for the solution with ventilated façade the cost of the financial scenario is equal to about 450 €/m^2, by contrast for the macroeconomic one is equal to about 400 €/m^2.

Moreover, as it possible to see in table in Figure A.1 and A.2 with respect to the existing building, the solution Syst_2 is the better one in terms of cost-optimal for both scenarios because it halves the global cost over time. If we consider the macroeconomic scenario, it is also possible stating that all the considered retrofitting measures lets to obtain a decrease in CO_2 emissions over time (30 years) and this is fundamental taking into account the European aim at achieving carbon-free economy within 2050, especially for a public building with this intended use.

Conclusion

In conclusion, the main energy redevelopment proposals of the case study concern 3 main aspects: the external envelope, the artificial lighting system and the plant system (heating, cooling and mechanical ventilation). A complementary economic assessment was not carried out to determine the economic sustainability of the different proposed interventions. For this reason, the benefits obtained by considering separately the 3 main aspects of the proposed energy requalification were analyzed, as for hypothesis even only one of the 3 could be carried out without involving the others. The one that has the greatest benefit in terms of primary energy demand is the replacement of the neon lighting system with LED lighting, which leads to a reduction of about 45% in annual primary energy demand. The replacement of the external envelope and the heating/cooling system results in a reduction of 17% and 11% respectively. The energy requalification defined as “design proposal 2”, although the most expensive in terms of cost of the interventions, is certainly the one that ensures adequate conditions of well-being for the occupants, a correct air exchange and certainly an undoubted advantage from an environmental point of view during the operation and management costs of the building: the primary energy demand can be reduced to about 39 kWh/m^{2}year compared to the existing design of the building which needs 145 kWh/m^{2}year.

The cost-optimal analysis confirms the results of the energy simulations because the solution Syst_2 with the retrofitting measure of the artificial lighting system and the substitution of the existing one with more efficient one it is possible to achieve both economic and energy sustainability. Indeed, there is a significant decrease in primary energy consumption along with an affordable initial investment cost.

With respect to the performed cost optimal analysis the upgrade measures that consider the substitution of the external envelope with the inclusion of windows retrofitting are the most expensive solution, by contrast the influence on energy demand is not noticeable comparable with global cost.

Moreover, the calculation of both financial and macroeconomic scenario let to point out that the global cost is more influence by VAT and excise duties rather than the cost of CO_2 emissions over time. But in the context of the Paris Agreement all the proposed retrofitting measure significantly decrease the environmental impact over time with respect to the existing building.

The research can be deepened considering both other retrofitting measures for the existing building and another building with the same intended use in order to make a comparison between 2 different buildings in the same climate zone. At the same time, it is important to consider the evaluation of more efficient system for heating and cooling (for instance heating pump) and the integration with renewables for energy supply.

Finally, since it is an existing school building dates to 1967, a comparison between two different scenarios, and so demolition and construction of a new school building or combination of retrofitting measures for the existing one, would be evaluated in terms of both economic and environmental sustainability also considering payback period and the possible economic advantages due to renewables.

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Appendix A

TABLE A. 1. Possible redevelopment measure for external wall characterised by the half value of the thermal transmittance of the reference building (PPV_N1.1)

Technological solution	Layer	T [m]	λ [W/mK]	R [m^{2}K/W]
External wall – PPV_N1.1	Advance screen façade	–	–	–
	Air cavity	–	–	–
	Rock wool	0.04	0.035	
	Aerated concrete	0.30	0.07	
	Gypsum fibre panel	0.015	0.3	
	Gypsum fibre panel	0.015	0.3	
Thermal transmittance [W/m^{2}K]				0.175
Periodic thermal transmittance [W/m^{2}K]				0.019
Time shift [h]				15.30

TABLE A. 2. Possible redevelopment measure for external wall characterised by the half value of the thermal transmittance of the reference building with advanced screen facade as external finishing (PPV_N3)

Technological solution	Layer	T [m]	λ [W/mK]	R [m^{2}K/W]
External wall – PPV_N3	Advance screen façade	–	–	–
	Air cavity	–	–	–
	Wood fibre	0.04	0.034	
	Aerated concrete	0.30	0.07	
	Gypsum fibre panel	0.015	0.3	
	Gypsum fibre panel	0.015	0.3	
Thermal transmittance [W/m^{2}K]				0.177
Periodic thermal transmittance [W/m^{2}K]				0.019
Time shift [h]				15.83

TABLE A. 3. Possible redevelopment measure for external wall with dry solution (wood fibre insulation) characterised by the half value of the thermal transmittance of the reference building (PPV_N3.1)

Technological solution	Layer	T [m]	λ [W/mK]	R [m^2K/W]
External wall – PPV_N3.1	Cement board	0.013	0.13	–
	Vapour barrier	0.0002	0.38	–
	Wood fibre	0.014	0.035	
	Gypsum panel	0.015	0.21	
	Rock wool	0.04	0.035	
	Gypsum fibre panel	0.015	0.3	
	Gypsum fibre panel	0.015	0.3	
Thermal transmittance [W/m^2K]				0.186
Periodic thermal transmittance [W/m^2K]				0.083
Time shift [h]				8.72

TABLE A. 4. Possible redevelopment measure for roof floor with green roof as fnishing layer (RF_N2)

Technological solution	Layer	T [m]	λ [W/mK]	R [m^2K/W]
	Earth	0.12	–	0.3
	Filter layer	0.001	–	–
Roof floor – RF_N2	Accumulation layer (EPS)	0.04	–	0.71
	Waterproof sheet	0.003	0.5	–
	Wood fiber	0.10	0.037	
	Vapour barrier	0.0005	0.4	–
	Precast reinforced concrete slab	0.03	1.91	–
Thermal transmittance [W/m^2K]				0.253

SOLUTION	Initial Investment Costs	Substitiution costs	Annual costs [€/yr]				Annual costs over the reference period [€/m^{2}yr]	Residual value	Primary Energy demand [kWh/ m^{2}yr]		
			Heating	Electricity	Maint.	Total			Heating	Electricity	Total
Existing building	-	-	30,787	43,103	-	73,890	1,277,712	-	104.95	82.23	187.18
W_N1	719,551 €	- €	28,830	43,103	7,011	78,944	1,365,105	- €	98.25	82.23	180.18
PPV_N1	1,520,173 €	- €	27,505	43,103	7,011	77,619	1,342,189	- €	93.71	82.23	175.94
PPV_N1.1	1,504,310 €	- €	23,836	43,103	7,011	73,950	1,278,744	- €	81.15	82.23	163.39
PPV_N2.1	1,066,181 €	- €	23,728	43,103	7,011	73,843	1,276,887	- €	80.79	82.23	163.02
PPV_N3	1,498,462 €	- €	27,440	43,103	7,011	77,554	1,341,075	- €	93.49	82.23	175.72
PPV_N3.1	1,047,866 €	- €	23,796	43,103	7,011	73,910	1,278,054	- €	81.02	82.23	163.25
PPV_N3.2	1,075,006 €	- €	23,885	43,103	7,011	73,999	1,279,593	- €	81.32	82.23	163.55
GF_N1 + GF_N2	152,913 €	- €	30,186	43,103	-	73,289	1,267,315	- €	102.89	82.23	185.12
RF_N1	196,924 €	- €	26,406	43,103	-	69,509	1,201,960	- €	89.95	82.23	172.19
RF_N2	349,671 €	- €	26,412	43,103	59	69,575	1,203,095	- €	89.97	82.23	172.21
Syst_1	20,853 €	9,517 €	17,159	43,103	417	60,679	1,049,272	3,214.76 €	58.30	82.23	140.53
Syst_2	31,228 €	- €	34,487	11,971	-	46,457	803,343	- €	117.61	22. 31	139.92
PPV_N3.2 + RF_N1	1,271,930 €	- €	19,464	42,726	7,011	69,201	1,196,629	- €	66.19	81.51	147.70
PPV_N3.2 + RF_N1 + Syst_1	1,302,301 €	9,517 €	10,871	42,726	7,428	61,026	1,055,255	3,214.76 €	36.78	81.51	118.29
PPV_N3.2 + RF_N1 + Syst_2	1,303,158 €	- €	23,075	11,971	7,011	42,057	727,244	- €	78.55	22.31	100.86
PPV_N3.1 + RF_N1 + Syst_1	1,275,161 €	9,517 €	10,834	42,726	7,011	60,572	1,047,406	3,214.76 €	36.66	81.51	118.16
PPV_N3.1 + RF_N1 + Syst_2	1,276,018 €	- €	23,004	11,971	7,011	41,986	726,024	- €	78.31	22.31	100.62

FIG. A. 1. Summary table of cost-optimal methodology for financial scenario with discount rate equal to 4%

SOLUTION	Initial Investment Costs	Substitiution costs	Annual costs [€/yr]				Annual costs over the reference period [€/m^{2}yr]	Emissions		Residual value	Primary Energy demand [kWh/m^{2}yr]		
			Heating	Electricity	Maint.	Total		CO$_2$ [ton]	CO$_2$ costs [€]		Heating	Electricity	Total
Existing building	-	-	24,048	32,753	-	56,801	982,202 €	196.151	250,092	-	104.95	82.23	187.18
W_N1	589,796 €	- €	22,519	32,753	5,747	61,019	1,055,146 €	188.368	240,170	- €	98.25	82.23	180.18
PPV_N1	1,246,043 €	- €	21,485	32,753	5,747	59,984	1,037,250 €	183.099	233,451	- €	93.71	82.23	175.94
PPV_N1.1	1,233,041 €	- €	18,619	32,753	5,747	57,119	987,703 €	168.511	214,851	- €	81.15	82.23	163.39
PPV_N2.1	873,919 €	- €	18,535	32,753	5,747	57,035	986,253 €	168.084	214,307	- €	80.79	82.23	163.02
PPV_N3	1,228,248 €	- €	21,434	32,753	5,747	59,934	1,036,380 €	182.843	233,125	- €	93.49	82.23	175.72
PPV_N3.1	858,907€	- €	18,588	32,753	5,747	57,088	987,164 €	168.352	214,649	- €	81.02	82.23	163.25
PPV_N3.2	881,153 €	- €	18,658	32,753	5,747	57,157	988,366 €	168.706	215,100	- €	81.32	82.23	163.55
GF_N1 + GF_N2	148,417 €	- €	23,578	32,753	-	56,331	974,083 €	193.760	247,044	- €	102.89	82.23	185.12
RF_N1	161,413€	- €	20,627	32,753	-	53,380	923,044 €	178.732	227,884	- €	89.95	82.23	172.19
RF_N2	286,615 €	- €	20,632	32,753	49	53,433	923,970 €	178.757	227,915	- €	89.97	82.23	172.21
Syst_1	17,093 €	7,801 €	13,405	32,753	342	46,500	804,081 €	141.965	181,005	2,635.05 €	58.30	82.23	140.53
Syst_2	25,596 €	- €	26,937	9,113	-	36,050	623,376 €	156.769	199,880	- €	117.61	22. 31	139.92
PPV_N3.2 + RF_N1	1,042,566 €	- €	15,205	32,466	5,747	53,419	923,716 €	150.474	191,854	- €	66.19	81.51	147.70
PPV_N3.2 + RF_N1 + Syst_1	1,067,460 €	7,801 €	8,495	32,466	6,089	47,050	813,589 €	116.308	148,292	2,635.05 €	36.78	81.51	118.29
PPV_N3.2 + RF_N1 + Syst_2	1,068,162 €	- €	18,025	9,113	5,747	32,885	568,641 €	111.393	142,027	- €	78.55	22.31	100.86
PPV_N3.1 + RF_N1 + Syst_1	1,045,214 €	7,801 €	8,466	32,466	5,747	46,679	807,181 €	116.161	148,106	2,635.05 €	36.66	81.51	118.16
PPV_N3.1 + RF_N1 + Syst_2	1,045,916 €	- €	17,970	9,113	5,747	32,829	567,688 €	111.113	141,699	- €	78.31	22.31	100.62

FIG. A. 2. Summary table of cost-optimal methodology for macroeconomic scenario with discount rate equal to 4%