

A Study on Retrofitting Proposals for an Historic School Building in the Energy Transition Perspective

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ABSTRACT

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In the current economic, energy and environmental situation, ecological and energy transition, would be achievable and effective if programmed over time by means of the use of advanced clean technologies for dealing with global warming. Our study was based on a systemic approach that requires taking into account the cultural, social, historical, environmental and energy context in any change or adaptation process of the building-plant system analysed. It was necessary to work out compromise solutions between architectural and landscape preservation, with the current mandatory regulations on ventilation and air quality in schools. The results showed a lower energy and environmental impact for those retrofitting solutions designed for a gradual switch off to energy transition in accordance with the energy consumption reduction, maximum possible integration of renewables, decarbonisation, reversibility and ease management of plant systems. Findings highlighted that the suggested retrofitting and refurbishment energy green/sustainable plant solutions can be a useful example and tool for designing and programming ecological and energy transition over time. This especially concerns public administration and school building managers, but also listed historic school buildings.

1. INTRODUCTION

The present global situation is influenced by interconnected factors: global warming, very high technological development (IoT, AI, DT, robots) which requires more and more energy, virus spread (e.g. pandemics), biodiversity reduction, building and plant design regeneration, territorial and energy context, rational use of energy by means of energy transition and maximum renewables integration, energy consumption reduction, sustainability and energy efficiency. In this context, it is important to rapidly reduce CO₂ equivalent emissions using existing infrastructures, technologies and systems with green economy. The European Directives refer to high savings, in particular, in the building sector, which accounts for 40% of final energy consumption. This is linked with balanced energy budgets together with the 2015 Paris agreement which increased efforts to net zero carbon for the existing building stock. All building and plant design have changed, but urban and territorial design are also based on a change of perspective that integrates climate resilience and health. This extends to one-health and eco-health, energy saving and integrated use of renewables, environmental impact of air conditioning and comfort.

It is well known how existing buildings, especially belonging to the historic and of cultural heritage, used as schools, are responsible for more energy consumption than newly constructed ones [1-4]. At the same time any intervention for building-plant system adaptation and energy refurbishment of schools is a complex task, because it must be interconnected with the guarantee of indoor air quality, effective ventilation and correct air changes per hour (ACH) and comfort. These aspects are crucial with significant impact

on student/teacher wellbeing, productivity, health safety, and performance but also on the national healthcare system. Therefore, in the present context of the post-COVID-19 era many recent studies have investigated plant systems adaptation and energy efficiency interventions [5-8]. Much literature has analysed some crucial questions: mechanical ventilation systems efficiency and efficacy, natural ventilation effect connected to physical distancing, CO₂ and occupancy monitoring, protection and prevention measures for people health and contamination risk reduction [9-12].

Many studies have provided different solutions, by means of experimental and numeric simulations of building-plant systems, for energy consumption reduction, e.g. hybrid ventilation and efficient thermal management proposals [13].

In particular, some authors have demonstrated that demand controlled ventilation combined with an HVAC variable air volume system, both in school and office buildings, can guarantee significant energy consumption reduction with high indoor air quality and effective ventilation [2-15]. The CIBSE document concerning COVID-19 air cleaning technologies, has foregrounded how scientific evidence suggests solutions with air purifiers to minimize the risk of contamination and infection only in specific situations. However, they are not a solution for reducing all the risks.

Effective ventilation, in terms of higher ACH, is the main measure to reduce indoor far-field diffusion. Anyway, purification systems may be suitable for those spaces where ventilation is not sufficient and cannot be improved.

Important literature on the subject has analysed and discussed different ventilation strategies and IAQ improvement in schools with the aim of airborne infection control, energy saving and human health protection [14-16].

The authors highlighted the importance of an effective ventilation system, shifting design solutions from comfort to health/safety bases. A holistic optimization approach, taking into account health-IAQ conditions and indoor environmental factors has been proposed. The guidance documents of national and international organizations have provided fundamental guidelines referring to the World Health Organization alerts (WHO) [16-19].

Common basic indications concern the management, control and maintenance of mechanical ventilation systems in offices, schools and public places. Microclimatic parameters (air temperature and relative humidity, CO₂ concentrations) must be controlled by continuous regulation systems. There must be no air recirculation, regular filter cleaning, extended operation times of controlled mechanical ventilation (i.e., starting at nominal velocity at least two hours before school/classroom usage, and switching to lower velocity two hours after) and the CO₂ set-point change for demand-controlled ventilation systems (DCV; i.e., to lower by up to 400 ppm to assure operation at nominal velocity, keeping the ventilation on 24 h for seven days, with lowered ventilation rates without occupants) [14, 15-19].

A recent study has demonstrated, by means of experimental monitoring and dynamic simulation, that a high efficiency air handling unit (AHU) combined with strong energy recovery from the expulsion air rates (i.e. using an air-to-water heat pump downstream of the recovery unit with hot water production at the condenser) in existing schools, can provide significant energy consumption and COVID-19 contamination reduction [15]. Many researches have shown that any sustainable green design should be based on a compromise between energy savings, plant system changeability and easy maintenance, as well as energy cost reduction [5, 6, 20, 21]. However, there are few studies concerning energy refurbishment of cultural heritage and listed school buildings. They are a particular case of buildings used as school with origin and functions often diametrically opposed to the complex issue of meeting the imposed requirements [20-26].

Other studies are oriented to historic building renovation towards zero-energy and net zero carbon together with IAQ and effective-health-oriented ventilation: e.g. the IEA Task 59, the International Scientific Committee on Energy and Sustainability within ICOMOS that developed fundamental guidelines for improving the energy performance of historic buildings, the World Heritage Centre-UNESCO that has highlighted the importance of world cultural and natural heritage protection and renewable energy projects.

The energy renewable sources and nZEB requirements for existing buildings are a complex task and even more difficult if they belong to the cultural heritage and therefore have protection and conservation constraints.

Starting from the aforementioned research and from further extension of recent investigations [25, 26] our present study proposes the identification and evaluation of possible transition projects to sustainable green design with renewable energy, for a historic school building belonging to the cultural heritage. Our findings showed the potential for development and application of green plant system solutions for energy transition (i.e. towards “all electricity”), especially if they are integrated in the urban and landscape, also with social, political and administrative context. The importance of our research concerns the assessment of the energy and environmental efficiency of historic school buildings retrofitting. Our research bridges the gap concerning the

energy efficiency and environmental impact reduction of historic and listed school buildings, with the objectives of green energy transition.

2. MATERIALS AND METHODS

Starting from some previous studies [25, 26], but in the light of the current economic, energy and financial situation and new legislation on the subject, some possible energy-efficient operations for building refurbishment and plant system retrofitting, were investigated and compared.

Various plant proposals were studied by means of transient simulation, taking into account both the conditions of school space occupation, imposed by the COVID-19 pandemic and regular school use with maximum people presence.

Transient simulation models were validated by means of a proposed index as normalized primary energy consumption. A historical high school building in Florence (Italy) was the case study.

2.1 Basic setting

The school building is the Dante High School, a cultural heritage building in Florence, built in 1876 and used as a school since 1921 (Figure 1).

It is a typical example of a historic building in which the original intended use (offices) has been changed (school) without any change in the distribution and functional structure. Some data: 22064 m³ total building volume, 4607 m² total floor area. The building and garden are protected/listed.

This means that any refurbishment intervention such as architectural feature modification, external cladding insulation system or solar thermal and/or photovoltaic system installation, are not possible due to the official constraints (Figure 1).



Figure 1. Dante school-photos: left-bottom, main entrance view, centre-bottom a typical classroom, right-bottom gym interior view

The load-bearing structure is stone masonry, the inter-storey floors are mixed iron and brick, a pitched roof with warping in wooden beams and mantle in brick tiles, and all the windows with a wooden frame and single-glass. Some thermo-physical properties of the building components are provided in Table 1 where dimensions of all the thermal zones are also shown.

Sensible and latent thermal loads due to people (students and teachers), and lighting system and equipment were implemented as suggested in the study [27]. Technical data of the existing heating plant and time profiles of the classrooms and gym use, were provided by the technical office of the Environmental Department of the Metropolitan City of

Florence. In particular, the existing plant scheme is: heating system with a gas heat generator; natural indoor ventilation due to infiltration and manual handling; hydronic system for the main building and gym; terminal units with cast iron column radiators, operating at high temperatures; an air heater for the gym. The intermittent conduction regime has a pre-ignition in the morning and supplies different thermal zones in compliance with the study [27]. These thermal zones cover the circulation areas, administrative offices, classrooms, laboratories, attic, toilets, the gym, and changing rooms. Findings of the above mentioned studies [25, 26], that had provided an important energy saving of 45%, were the starting base of our present research.

Table 1. Thermo-physical feature and dimensions

Component	Thermal transmittance (W/m ² K)	
perimetral walls	1,91	
perimetral walls-first floor	1,903	
internal walls	2,391	
Roof	2,102	
slub-under-roof room	0,477	
slub-wattle	1,628	
windows (glass&frame)	5,68	
Thermal zone	Floor area (m ²)	Volume (m ³)
Basement	844	4218,5
ground floor	844	4471,7
first floor	844	4471,7
second floor	844	4471,7
under roof room	844	1190,8
Gym	388	3239,8

2.2 Transient simulations

Transient simulations were implemented by TRYNs commercial software. The simulation model of the existing building-plant system, described and validated, by means of a proposed index as normalized primary energy consumption in [25], were used for all the investigated proposals.

In particular, the real energy consumption for building heating demand was performed by the annual billing invoice data provided for two years 2012/2013 and 2013/2014 [25]. This real consumption only referred to the methane consumption for school heating during the winter period and not to hot water use, because there is no dedicated hydraulic system.

Since real energy consumption is strongly influenced by the external climatic conditions, it was normalized to the heating degree days (HDDs). The comparison between the real consumption, corrected by the corresponding real HDDs, and calculated energy consumption provided in the study [25] was a further validation of the reference simulation model used.

In particular, the normalized primary energy consumption index, expressed as the ratio between the total real consumption and the corresponding real HDDs, provided the reliability and validity of the numerical model [25]. It can be deduced that the difference between the index simulated the calculated one, using the real HDDs and real energy consumption for the year 2012/2013 and those for the year 2013/2014, were respectively 9% and 0%.

The boundary climate conditions, used for simulation, were derived from the test reference year (TRY) of Florence connected to the psychrometric diagrams for humidity and sky temperature. The tilted solar radiation was assessed using the Reindl model [28] and taking into account overhang and wing-wall shading effects. All the hourly set of TRY in compliance

with [29-31], was interpolated to allow a sub-hourly calculation time-step. The heat transfer functions solution, every quarter of an hour, provided a highly affordable model consistency. The TRNbuild library was used for the occupancy pattern and people behaviour, with differences between students in the classroom from those in the gym. Sensible and latent heat gains and those from artificial lighting, were implemented [27, 31].

Crucial references [12-14, 17] indicate that in the pandemic era, people density must be cut by at least 50%, but nowadays people density can be at 100% with all the safety measures and physical distancing.

As a consequence, in the calculation model, the number of students considered for each classroom and gym was both 50% and 100%. The building model was implemented considering three parameters variation as reported in Table 2.

This fact means: crowding rate, considered equal to, or half, of the suggested value [29,30]; ventilation rate, considered continuous with 4 vol/h, and attenuated with 2 vol/h; set point temperature for heating condition, considered continuous at 20°C and attenuated up to 16°C (Table 2).

Table 2. Ventilation rates and set-point temperature values for the considered occupation conditions

	100 % (2 m ² /person)	50 % (4 m ² /person)	No presence
Crowding index			
Ventilation rate [vol/h]	4	4	2
Set-point temperature [°C]	20	20	16

Simulations concerned the opening hours of the school i.e. 8.00 to 19.00 from Monday to Friday, and 8.00 to 14.00 on Saturdays. Due to the high thermal inertia of the building, the hydronic systems were designed out of phase by 2 hours in advance of people presence, while the aerualic systems coincided with it. An attenuated rather than intermittent conduction regime was implemented because it is more effective during night and weekends. The specific building thermal load was 150 W/m², to which thermal load for air treatment was added. The design conditions were set at 0°C for the external environment and 20°C for the internal one.

An all-air conditioning system was not proposed, due to the large size of ducts, hardly fitting into the listed building.

For this reason, the distribution scheme included medium temperature water risers, 50°C/40°C, connecting the heating plant and the Air Handling Units (AHUs) with horizontal air channels located in the false ceilings, with diffusion vents for each room.

The plant was simulated as a primary air system, with fan-coil hydronic units to compensate for the basic thermal load, and AHUs to supply air into the different rooms at the needed thermo-hygrometric conditions. This choice ensured the controlled mechanical ventilation effectiveness with IAQ conditions.

The design air flow rate, corresponding to 4 vol/h, was higher than that suggested between 2 vol/h and 3 vol/h for a standard crowding index [29, 30]. The requirements of the music classroom-workshops are less cogent, but they were always verified by transient simulations.

Referring to [16-19, 29, 30] the AHUs were treated a 100% external air flow rate, without recirculation. Sensible heat recovery units (cross-flow type) were installed. Their seasonal

average efficiency was 65% for continuous mode operating conditions and 75% for attenuated mode operating conditions. Different configurations of thermal power plant were analysed, taking into account all its parameter variations for the same internal primary air system. Heating plant and ventilation system were modelled by Trnsys [31].

The Building Automation and Control System (BACS) connected to the HVAC was implemented using TESS software components. This design choice with a proportional modulation of the HVAC devices, allows energy efficiency optimization and occupancy pattern variance reduction. The Trnsys solver uses the so-called “successive method”, for thermal capacity implementation, and differential equations solved by the “modified-Euler method” algorithm [31]. Simulations ran for one hour, with 0,5 s real-time, using a standard 2,5 GHz dual-core processor, without any over-clock.

2.3 New retrofitting designs

Considering the green energy design potential, all the plant refurbishment proposals were based on systems capable of adapting to changes in the energy market and therefore without structural rigidity with small size to reduce all the risks due to energy supply interruptions and to take into account the constraints imposed on historical heritage buildings. The first common proposal was the transition from natural to controlled mechanical ventilation. The studied configurations, differed in generator typology and energy carriers. The existing plant system (type A) and the retrofitting proposals (type from B to E), were:

- A) existing monovalent natural gas heat generator
- B) Monovalent biodiesel Heat Generator from a certified supply chain
- C) Bivalent hybrid gas HG / HP system
- D) Bivalent hybrid biodiesel HG / HP system
- E) Electric air-to-water heat pump (HP)

The air-to-water HP was installed in the school garden and adequately green screened in compliance with the landscape constraints. The local authorities do not allow groundwater use for hydrothermal applications.

A geothermal energy system with horizontal heat exchangers was not possible, due to the lack of suitable areas. The vertical exchangers system would have entailed higher construction costs. Due to the cold-humid winter period in Florence and the Mugnone rivulet proximity, the HP operating conditions were assessed taking into account all the defrosting cycles of the external heat-exchangers. As a consequence, the bivalent temperature, i.e. the switch temperature in the hybrid configuration with gas boiler/HP with alternating operation conditions for generators, was set at 7°C. This value was obtained by means of a sensitivity analysis of the transient simulation model based on the 3°C - 12°C temperature range. In particular, the COP mean seasonal value was evaluated in both monovalent and hybrid configurations (Table 3) as a function of the climatic data provided by different climatic stations (Consorzio Lamma, Test Reference Year–EnergyPlus, Italian Thermotechnical Committee CTI, Tuscan Region). The consequent results comparison can be read in Table 3.

Both gas and biodiesel boilers worked mainly during the night, and the electric HP during the day, precisely at those times when the external climatic conditions are the most favourable for the COP and defrost cycle reduction.

Table 3. COP mean seasonal values for monovalent and hybrid plant configuration

COP	Lamma Consortium	TRY	CTI	Tuscan Region
HP _{hybrid}				
T _{bivalent} 7°C	3,55	3,56	3,60	3,56
HP _{monovalent}	3,11	3,02	3,27	3,15

Conversion factors into primary energy and emission factors into CO₂ equivalent were used, as suggested [27], for all the energy vectors.

In Table 4 the conversion factors for natural gas, biodiesel and grid electricity used, are provided: correspondently, $f_{p,no/ren}$ for primary energy into no/renewable energy, $f_{p,ren}$ for primary energy into renewable energy, and f_{CO_2eq} for CO₂ equivalent.

Table 4. The conversion factors used

Coefficients	$f_{p,no/ren}$	$f_{p,ren}$	f_{CO_2eq}
Natural gas	1,05	0,0	0,21 kg/Nm ³
Biodiesel	0,40	0,60	0,11 kg/kg
Grid electricity	1,95	0,47	0,46 kg/kWh

3. RESULTS AND DISCUSSION

For sake of clarity, Directive 2010/31/EU [32], concerning "nearly" Zero Energy Building (nZEB), and its crucial consequence i.e. that the residual energy needs of buildings, that must be covered mainly by renewable sources, were considered.

The term "residual" means the downstream of the implementation of passive air conditioning strategies.

Referring to the studied school building these strategies are limited to glass and fixture replacement and roof insulation, because of cultural heritage protection constraints.

In Italy, nZEB is defined as a building that simultaneously complies with [32-34].

This means a high performance building-plant system, whose cumulative energy needs for heating, cooling and domestic hot water production, are covered for at least 50% by renewable sources. Therefore, the transient simulation model was transposed into a steady-state condition to assess all the requirements imposed by [29, 30, 33, 34] and CEN-EPBD [32].

Results analysis showed that the energy refurbishment proposed never meets the nZEB requirements, for the following reasons: perimeter walls without any insulation system; no solar shading system; energy class 'A' is only reached with a biodiesel solution, monovalent or hybrid scenarios, as the building classification system takes into account the non-renewable share of primary energy.

The same scenarios are those in which the 50% threshold is reached for renewable energy sources. Building-plant system transient simulations were carried out for the time period between 1st November and 15th April, in compliance with [33]. For the rest of the year, the mechanical ventilation system was simulated in free-cooling mode, i.e. with all the heating/post-heating coils of the AHUs, at non-operating conditions. Twenty different calculation schemes were implemented, combining five thermal power plant configurations with a continuous and/or attenuated conduction regime in relation to 100% and / or 50% crowding rate (Table 5).

Table 5. Plant retrofitting proposals – boundary conditions

Thermal plant	continuous regime 100% people presence	continuous regime 50% people presence	attenuated regime 100% people presence	attenuated regime 50% people presence
A) gas boiler				Temp _{set-point} 20°C
B) biodiesel boiler			Temp _{set-point} 20°C	
C) hybrid system gas / HP	Temp _{set-point} 20°C	Temp _{set-point} 20°C		
D) hybrid system biodiesel / HP	Vent-rate _{set-point} 4 vol/h	Vent-rate _{set-point} 4 vol/h	Vent-rate _{set-point} 4 vol/h hours 8-19 / days 1-5 hours 8-14 / days 6	Vent-rate _{set-point} 4 vol/h hours 8-19 / days 1-5 hours 8-14 / days 6
E) electric areothermal HP	hours 0-24 days 1-7	hours 0-24 days 1-7	Temp _{back} 16°C Vent-rate _{back} = 2 vol/h hours /days- remaining	Temp _{back} 16°C Vent-rate _{back} 2 vol/h hours /days- remaining

Referring to Table 5, two result analyses can be deduced: using a vertical reading, the quantification and comparison between the efficiency of primary resources and the environmental sustainability of generators and energy carriers; using a horizontal reading, the energy savings quantification and comparison obtained with attenuated and continuous regime. For both cases, the average load factor for the air conditioning system is reduced by a few percentage points, ranging from a crowding index from 100% to 50%.

The four investigated plant retrofittings are now discussed and compared with the existing monovalent natural gas heat generator. From the environmental impact point of view, the benchmark is the non-renewable primary energy needs, in line with current national and EU regulations.

As shown in Figure 2, the most resource-intensive power plant configuration is the monovalent gas system. The latter is the existing heating system, entirely powered by fossil fuel.

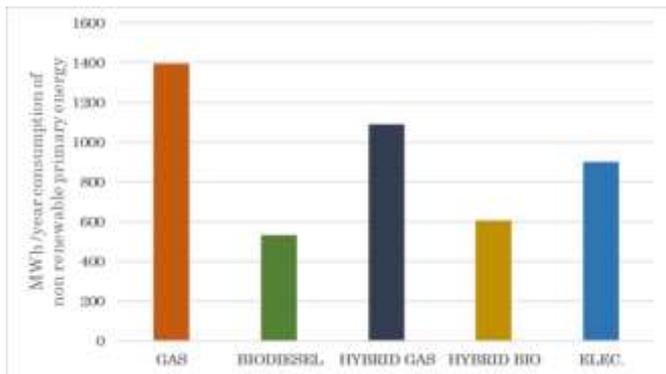


Figure 2. Primary energy consumption for each retrofitting proposal

Biodiesel and grid electricity carriers are partly renewable and partly non-renewable at different temperature levels.

Therefore, the environmental impact depends not only on the energy carrier used, but also on the technologies of use.

An aerothermal heat pump is strongly affected by external climatic conditions, so it has a higher seasonal COP albeit at hybrid, rather than monovalent, trim.

At hybrid trim operating conditions, it works during the mild periods of the winter season. At monovalent working conditions, it must be activated even under harsh climatic conditions. On the contrary, the combustion efficiency of a boiler can be considered constant, depending on the climatic parameters. The system load factor was also considered constant, under a performance correction coefficient, that

takes into account the condensation effect of the water vapour contained in the fumes.

In the proposed solution, the heating system, with hydronic and aeraulic circuit, was designed to work at medium temperature (50°C inlet-flow / 40°C return-flow), guaranteeing continuous condensation.

The simulation results show the best arrangement: i.e. the hybrid layout, due to a lower energy need compared with the monovalent electrical and biodiesel layouts (Figure 2).

In particular, the most efficient plant system is the biomass supply chain, because its energy vector has 0,60 renewable conversion factor.

But referring to total primary energy, a thermal plant with full electricity supply is the best with lower impact (Figure 2). The alternating temperature between the generators used, set at 7°C, was optimized in the range 5 - 9°C. In the hybrid layout the weight of renewable primary energy use was given by the sum between the amounts of renewable energy of biodiesel, grid electricity and heat from a natural thermal source (outdoor air at indoor environment conditions).

If simulation results are evaluated from the energy sustainability point of view, the benchmark is the direct and indirect CO₂ emissions, in agreement with current national and EU regulations.

Results confirm that the hybrid layout/setup is the best, due to the lower global emissions produced, as well as monovalent electrical and biodiesel layout (Figure 3).

From a local perspective, considering the air pollution and environmental loads in urban areas, 100% electricity configuration is the only way to eliminate combustion systems.

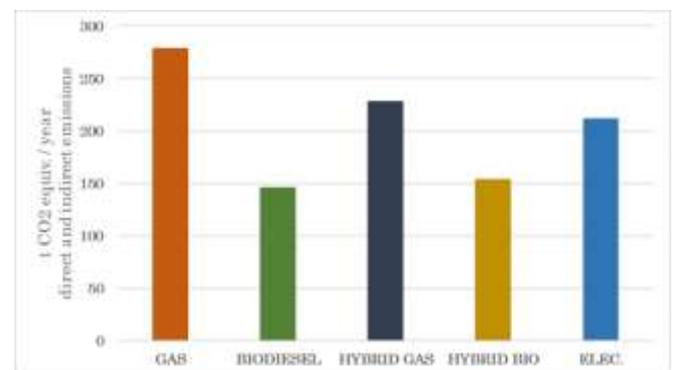


Figure 3. CO₂eq emissions for each retrofitting proposal

In addition, the emission relocation and the connected circular economy, were considered. As a matter of fact, its

purpose goes beyond the national power system, up to affect the entire EU energy mix [35, 36]. A progressive fuel-switch of the electric mix from fossil fuels to renewable sources is happening and in some cases it has been implemented, leading over time to the emission factor reduction of grid electricity.

None of the simulated and assessed plant proposals can be defined as a 100% renewable solution. The constraints, to which the building and the surrounding area are subjected, do not allow the installation of solar photovoltaic and/or thermal systems. The use of grid electricity implies the energy vector question, which can coincide with thermoelectric power plants fuelled by coal, gas, fuel oil, etc. The biomass supply chain includes energy use and transformation phases, that can be hardly managed by means of renewable carriers (e.g. cultivation, cutting, transport of plant materials).

The hypothesis of solid biomass utilization (wood chips, pellets) was not considered, due to the connected problems of atmospheric pollution. Hydrothermal and geothermal sources are not feasible in the specific context due to the environmental impact and landscape constraints highlighted above.

Therefore, the environmental sustainability of the proposed plant retrofitting solutions must not be understood as "zero carbon" or a "100% renewable energy" condition.

The proposed solutions with new/clean technologies, could lead to optimal results only by means of a planned and gradual energy transition. As a matter of fact, the global CO₂ emissions obtained with the suggested plant designs are less than half, compared to those due to the existing monovalent gas-fired thermal power plant (Figure 3).

The Life Cycle Cost assessment (LCCA) was applied on the basis of a macroeconomic financial approach, due to the current uncertainty of the economic quotation of CO₂ emissions [37, 38]. The socio-health costs deriving from greenhouse gases emission, were implicitly included in the taxation applied to energy products.

Generally, the expected useful life of the main plant systems is 15 years, but it can be extended up to 20 years by means of revamping in the middle of the life cycle.

The revamping cost is approximately 1/3 of the initial investment cost. In accordance with [38], the annual maintenance cost was assumed to be 2% of all the plants value.

As a consequence, the calculation period coincided with the life cycle, without residual values or costs due to periodic replacements. The LCCA shows that the convenience of a scenario is given by the combination of fixed costs (investment) and variable costs (operating), discounted over 20 years. As a first approximation, a discount rate of 2.0% per year was used.

Operating costs include maintenance, revamping and expenses for the energy products purchase.

Due to the current international situation, the tariff trend, in particular for petroleum products, is rather uncertain.

Technologies cost will probably remain stable over time, but that of energy carriers will tend to increase, to a greater extent for petroleum products and less for the biomass supply chain.

The trend in the electricity costs is doubtful, currently linked to that of petroleum products, but in the future hopefully dictated by the development of photovoltaic and wind farms, in line with the political and programmatic action of the EU "Low carbon energy 2050". The average tariffs envisaged for the next 20 years, that were used for the operating cost calculation are provided in Table 6.

Table 6. The mean tariffs used for the operating cost calculation

Gas	Biodiesel	Electricity
1,20 euro / m ³	1,80 euro / litre	0,40 euro / kWh

Figure 4 shows that the hybrid configuration can reduce operating costs. Figure 5 shows that the monovalent combustion assets have a significantly reduced construction cost compared to heat pump systems. This fact is due to the system size and application of simple and small technologies.

The combination of investment and operating costs, discounted over a useful life of 20 years, shows the convenience of the hybrid configuration, with a better cost-benefit ratio, against the worst monovalent gas setup.

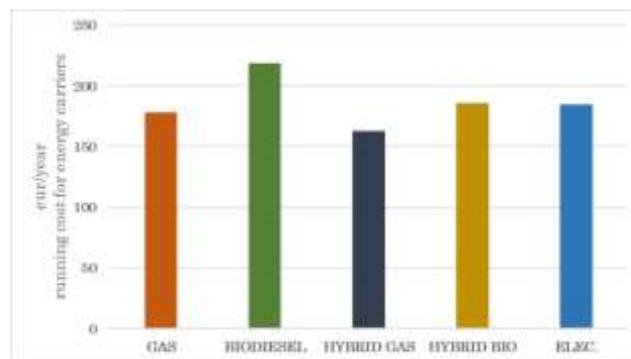


Figure 4. Annual purchase costs of energy products

Different values for type and size of the specific plant were applied to calculate the investment costs: 432 €/kW of installed thermal power for combustion generators, 780 €/kW for heat pump generators.

The LCCA application highlighted the discrepancy between energy-environmental value and economic convenience. LCCA directs any project towards the electrification of the final uses of energy, in line with the EU policy.

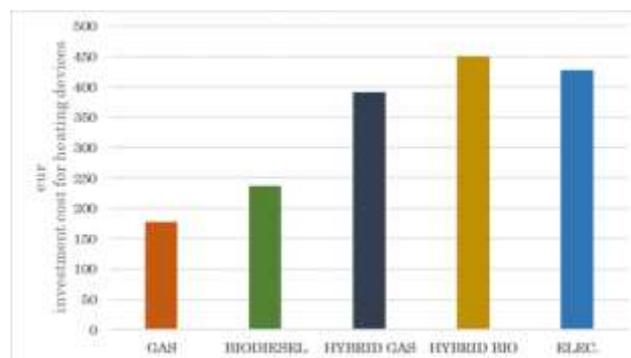


Figure 5. Initial investment costs of thermal power plant

The energy-environmental analysis directs any project towards the fuel-switch, i.e. from fossil fuels to renewable sources, always in line with EU energy policy.

If the mix of EU electricity generation translates from thermo-fossil prevalence to wind/photovoltaic, it will be possible to obtain a complete convergence between all the performance parameters that were analysed in this article. At these conditions, their convergence is evident, because the conversion factor into primary energy and the CO₂ equivalent emissions of grid electricity will tend to decrease. However,

the current market for technologies and energy products does not seem ready for an “all-electricity” scenario.

4. CONCLUSIONS

Any retrofitting intervention for a historic building, such as the one studied, is really complex, referring to the CO₂ emission reduction by 55% in 2030 and total decarbonisation in 2050. This task leads to a different design of plant systems, that is the basic condition for energy transition: small, easily removable and maintainable, reversible and integrated with current advanced clean technologies.

From a thermodynamic point of view, a heat pump system has a higher efficiency than a combustion system.

However, the impossibility of installing renewable electricity sources on-site (photovoltaic or mini-wind), and the prevalence of fossil sources in the energy mix of electricity grid, today make a thermal plant with HP really uncompetitive from the green transition point of view. The “all-electricity” strategy diverges from “low-carbon” programming.

Based on the current parameterization of primary resources and environmental impacts, the combustion of biodiesel prevails. Off-site renewable electricity source installation (e.g. relocated ground-based solar system) could be a solution, as long as the impact on the urban-man-made area does not cause damage to the ecosystem and biodiversity.

Our results showed a lower energy and environmental impact for those retrofitting solutions in which the use of existing technologies was designed for a gradual switch off to the energy transition in accordance with energy consumption reduction, maximum possible integration of renewables, decarbonisation, but above all real and contextual feasibility of the interventions.

Furthermore, the results obtained show how the energy transition and 100% renewable energy condition is not immediately achievable. At this stage, it is almost impossible to eliminate methane gas use. Optimal and thermodynamic use of thermal renewable energy, could be achieved addressing the issue of the high costs of raw materials, overcoming and modifying the current electricity tariff regime, as well as simplifying the access requirements to incentive mechanisms and overcoming their time limits, at least up to 2030.

The importance of our research concerns the assessment of the energy and environmental efficiency of plant system retrofitting. There are numerous examples of how to build new school buildings, according to ZEB criteria and to the guidelines of the National Plan for Recovery and Resilience (i.e. PNRR belonging to Next Generation EU-NGEU) dedicated to Education and summarized in the document “Future, the school for Italy of tomorrow”.

Our present research bridges the gap concerning the energy efficiency and environmental impact reduction of historic and listed school buildings, with the objectives of green energy transition. This research suggests a useful comparison between the possible plant solutions for ecological and energy transition, that can be achieved in compliance with the architectural and landscape constraints to which the historical building heritage must respond.

Findings can be a valid tool for public administrations (e.g. Provinces and Municipalities) to rethink and redesign refurbishment and plant management planning for the existing historic school buildings of which they are often both owners and managers. It is also a useful reference tool for local

authorities that will certainly have to rethink planning and programming for the protection of cultural, building and landscape heritage in relation to the ecology green energy transition.

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