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Innovative use of Hydrogen in energy retrofitting of listed buildings

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Abstract

Existing buildings represent the major challenge in energy efficiency strategies applied to the building stock. Moreover, architectural and landscaping constraints related to listed buildings are further limitations to possible interventions. When listed buildings are used as museum, achieving the same effectiveness level of typical energy efficiency measures is very difficult and, if possible, very expensive. In order to couple preservation of cultural heritage and CO2 emission reduction, the approach would move to energy supply rather than modifications in building envelope or installation of new HVAC components. So, this study focuses on the opportunity to green NG supply of existing heating systems by means of Power to Gas option at district level. Thus, the recent advancements in Hydrogen enriched Natural Gas produced by RES electricity excess offer a zero-impact strategy to decarbonize the listed buildings using existing energy infrastructures. At the same time, the absence of changes in building features and the introduction of a renewable share in the supply address the sustainability issues of cultural heritage. In conclusion, a first original attempt was made towards the future crucial task of museum's deep energy refurbishment.

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Keywords: Power to Gas; historical buildings; energy efficiency; cultural heritage; existing building; energy transition.

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1. Introduction

Recently, many research activities are coping with the hot topic "energy efficiency in existing buildings". Within this matter, an interesting sub-topic is related to the listed buildings, characterized by further issues of interventions due to constraints such as preservation of architectural and landscaping values as well as cultural identity.

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Nomenclature

CHP	Combined Heat and Power
CO_2	Carbon dioxide emission
H_2	Hydrogen
H_2NG	Hydrogen and Natural Gas
RES	Renewable Energy Sources

Among those barriers, when a museum is established in a listed building, it represents the hardest challenge. This latter is identified by Todorovic et al. [1] as the future crucial task starting from the tracing phase towards a fully green construction status after a new way of Museum's deep energy refurbishment project. While, an immediate feasible intervention regards the outdoor thermal comfort. It was studied to improve historic buildings accessibility and fruition [2] but, the achieved energy efficiency goal can be considered sometimes negligible if compared to thermal and electrical energy needs.

Other research activities investigated on how to use cool materials to replace damaged building components made by stone [3]. This strategy could be used when there are not landscaping constraints because even the colour of materials must be preserved. Furthermore, a sustainable integration of the increasing RES share in energy mix results demanding for current energy systems so as to require particular attention to solve the mismatch between production and consumption profile by means of storage option at different scales [4]. In order to achieve the CO_2 emission reduction and to account for the aforementioned barriers, recent research lines focused on greening the energy supply by partial substitution of the fossil fuel such as Hydrogen enriched Natural Gas [5] or, if locally available, by total replacement with bioenergy [6]. It is noteworthy to point out that bioenergy availability and feasibility is strictly dependent on territorial features and their typology, sometimes being producer of higher GHG emissions amount than conventional fuels [7]. The increasing energy efficiency requirements for public buildings was set by EU Parliament through the Energy Efficiency Directive [8], aiming at reducing of 3% the CO_2 equivalent emissions every year. Listed buildings are excluded from this duty but, the growing environmental awareness drives research to find viable energy efficiency solutions, especially, when they are part of large building complex [9].

So, the authors of this study explored the decarbonisation potential of heating systems fuelled with H_2NG blends to meet the thermal energy needs of a listed building. The renewable energy integrated in this system comes from the Power to Gas option, i.e. Hydrogen produced by means of electrolysers fed by PV and, then, direct injected into Natural Gas pipelines. Different H_2 volumetric fractions in the mixtures were considered along with their environmental benefits in term of CO_2 emission reduction [10]. Well-established energy infrastructures are already present in a wide range of listed buildings due to the restoration activities carried out during the first decades of 20th Century, before the approval of an international minimum standard for cultural heritage preservation [11].

2. Heating systems terminals and restoration

Since all the interventions made to listed buildings contributed to its history, great part of heating systems installed at the beginning of 1900 were currently considered to be preserved, even if they are the outcome of disruptive measures. Especially for heating system terminals, they became part of the interior design but, sometimes they were also hidden by furniture or ornaments when no socially accepted. The first installed radiators were made by cast iron and placed on the floor due to their heavy weight as shown in Figure 1. Their color was immediately adapted to classical wall paper, i.e. dark tonality or bronze. The importance of their integration in the interior design was underlined by the ornaments in wrought iron. A further evolution was the implementation of a hole in the heating terminal to heat food up. Their importance in everyday life and the adaptation to the furniture gave them an historical value, not negligible for any restoration. Following the importance of traceability of historic stratification in cultural heritage, a viable energy retrofitting strategy could be limited to the analysis of reliability, maintainability and availability as essential features of the thermal energy plant to fulfill the heating demand [12]. This strategy involves the heat transfer fluid, the fuel burnt by the heating supplier and the centralized thermal power plant.

Fig. 1. (a) First installation of decorated radiators; (b) radiator used as ornament; (c) radiator with a hole to heat food up.

As explained later in the Methodology section, a case study was selected to figure out the environmental benefits of partial fuel substitution of current heating supply with different H2NG blends. The case study is characterized by several features of heating systems terminals which encapsulate all the possible configurations present in listed buildings. Furthermore, specific constraints related to the distribution pipelines entail the exclusion of a sensitivity analysis on the typology of heat transfer fluid due to the absence of insulated channels together a low impact of any change.

3. Methodology

The authors explored the use of Hydrogen compatible with restoration issues. In particular, the contribution of H_2 in greening and decarbonizing conventional energy supply is widely investigated. This study focused on the addition of Renewable Hydrogen coming from Power-to-Gas solution directly injected into NG pipelines. It entails no changes in end-user devices, i.e. the heating supplier in the analyzed case study. So, no changes also in fuel distribution are required as demonstrated in recent EU projects [13].

In details, the heating demand of the considered listed building was assessed by on-site survey and collection of energy bills. Several scenarios were built to assess the influence of Hydrogen volumetric fraction in the blend. To calculate the CO2 emission, a proven model was used as in [14] and a subsequent allocation of those emissions was done as suggested in [15]. Then, it will be noteworthy to take into account a corrected CO_2 emission value.

Finally, the results were compared and discussed along with all the required measures related to each blend.

3.1. The case study

The selected case study is the “Vittoriale degli Italiani” building complex. It is located in Gardone Riviera, Northern Italy. This historic construction is now used as museum, while it was used as residential facility by the poet Gabriele D’Annunzio. It is composed by a main building and other minor facilities.

As depicted in Figure 2, the landscaping values associated to this case study do not allow any interventions which could modify its image or imply a fragmentation in the protected areas [16]. In Figure 2b, a view of the main building “La priora” is shown. Moreover, the architectural values do not regard only the building envelope but, interior design is an evidence of the beginning of 20th Century. In Figure 3, the plan of the “La Priora” main levels were reported along with the location of different kind of terminals and of the centralized thermal power plant.

Fig. 2. (a) The entire building complex; (b) the main building “La Priora”.

It can be noticed how the presence of radiators was accepted, even showing the naked pipes, or partially hidden so as to include them as decoration elements and part of the architectural identity of the building complex.

Fig. 3. Location of different radiators and their integration level in the interior design.

3.2. Hydrogen fraction in CO_2 calculation method

Having said, in order to calculate the carbon emissions amount expressed in kg/GJ, with changes in Hydrogen volumetric fraction in the proposed H2NG mixtures, Equation 1 was used [10]:

$$CO_2 = 20 \cdot f_{H2}^6 + 8.87 \cdot f_{H2}^5 - 11.7 \cdot f_{H2}^4 + 2 \cdot f_{H2}^3 - 16.4 \cdot f_{H2}^2 - 16.1 \cdot f_{H2} + 54.9978 \qquad (1)$$

where CO_2 is the amount of carbon emissions related to the H_2NG feeding. Then, the calculated amount in kg/GJ was converted in g/kWh and estimated for production of a single thermal energy output, i.e. 1 kWh. As documented in [4,10], a higher fraction of Hydrogen into the blend corresponds to an increase of the First Law efficiency. It comes from a higher energy output in terms of quality in CHP plant due to the increase of electrical efficiency [17], and in terms of quantity for the boilers due to the higher flame temperature.

To sum up, a reduction of specific CO_2 emissions is expected at increasing H_2 fraction thanks to the fuel substitution and the improvement of the combustion reaction.

3.3. Corrected CO_2 calculation method for the avoided electricity generator

If a Combined Heat and Power (CHP) plant could replace the installed boilers, it will provide an amount of electricity. This latter is function of the CHP Power to Heat ratio [17]. Since the thermal energy needs are the crucial point which drives the choice of the CHP typology, the authors analyzed the case of an Internal Combustion Engine, characterized by an electrical efficiency and a heat recovery efficiency equal to 0.3 and 0.5, respectively.

To clearly explain that choice, it is possible to say that for each thermal energy unit, i.e. 1 kWh, 0.6 kWh of electricity would be available so as to reduce the energy import from the Grid along with the associated carbon emissions. This allocation method is consistent with the "Fuel Charged to Power" (FCP) method, or method of the avoided electricity generator. It is adopted from [18], to calculate the corrected CO_2 emission values and it reads as:

$$\delta_{CHP} = \delta_{hr} - \delta_{Avd} = \delta_{hr} - \left(\frac{\lambda'_t}{\eta_{g,ref}} \right) \cdot \left(\frac{\eta_{el}}{\eta_{hr}} \right) \qquad (2)$$

where:

- δ_{hr} corresponds to the specific emissions related to the thermal energy generation only;
- λ'_t is the specific emissions of the avoided electricity generator, i.e. the National Grid emission factor;
- $\eta_{g,ref}$ represents the reference electricity generator conversion efficiency, i.e. the National Grid efficiency;
- η_{el} is the CHP electrical efficiency;
- η_{hr} is the CHP heat recovery efficiency.

4. Results

In this section provided by Table 1, the calculated CO_2 emissions associated to the Hydrogen enriched Natural Gas with changes in H_2 fraction were presented. As aforementioned, a new electrical efficiency was calculated due to the thermodynamics effect of adding Hydrogen to the blends so as to highlight that beneficial outcome.

Having applied the formula shown in section 3.2, it is possible to appreciate the reduction in CO_2 emissions at increasing H_2 fraction. Big EU project as Natural-Hy [13] demonstrated that H_2 fraction up to 30% are acceptable for end-users devices like boilers, cookers etc., while big scale pipelines could accept up to 20%. As regards district energy grids, the percentage can rise to 30%. An average environmental benefit of 2 percentage points is associated to each 5% of Hydrogen enrichment. Moreover, when the method of avoided electricity generator is applied, the further reduction is due to the avoidance of electricity import from the Grid which is characterized by an average emission factor higher than thermal energy production: 400 g/kWh of electricity compared to 360 g/kWh of heat.

In the case of a CHP fueled with H2NG @30% vol., the corrected CO_2 emissions are 50% of a boiler fueled with NG. This result entails a profitable opportunity of the Distributed Generation (DG) compared to the Centralized generation, especially in those districts or protected areas threatened by new infrastructures construction [19].

Table 1. Carbon Emissions per thermal energy output for each H2NG blend

Fuel typology	Calculated Emissions (kg/GJ)	Calculated Emissions (g/kWh)	CO2 Reduction (%)	New Electrical Efficiency	Corrected Emissions (g/kWh)
Natural Gas	100.000	360.000	-	0.3	238.200
H2NG @5% vol.	98.453	354.433	-1.55%	0.305	230.603
H2NG @10% vol.	96.771	348.375	-3.23%	0.31	222.515
H2NG @15% vol.	94.933	341.760	-5.07%	0.315	213.870
H2NG @20% vol.	92.956	334.641	-7.04%	0.32	204.721
H2NG @25% vol.	90.813	326.929	-9.19%	0.325	194.979
H2NG @30% vol.	88.520	318.672	-11.48%	0.33	184.692

From Table 1, an immediate carbon emission saving results achievable, without modifying the energy generation appliances since, as demonstrated by [13], current cookers and boilers already work with methane blends. A crucial point refers to the real calculation of emissions as well as their allocation in order to correctly evaluate the benefits coming from poly-generation system installation [18]. The Hydrogen addition to Natural Gas for heating purposes by means of combustion in boilers or device substitution to CHP plant entails also again in electrical efficiency [15], as previously reported in Table 1. Feasibility and application to current constrained environment during transition phase make the solution suitable for heating purposes in listed buildings as well as promoter of Hydrogen economy.

5. Conclusions

The study highlighted the environmental benefits coming from Hydrogen addition to Natural Gas for heating purposes by means of combustion in boilers or device substitution to CHP plant. The electrical efficiency, as previously reported in Table 1, is affected positively by the Hydrogen fraction in H2NG mixtures to increase the advantages of the corrected calculation. Energy produced by fueling with H2NG blends is more environmentally-friendly due to a reduction of CO2 ranging from 1.55% to 11.48%.

Having identified fuel partial substitution as the driver to spread the distributed generation model and as the minimum intervention to retrofit listed buildings, the authors presented the advantages of Power to Gas integration in current energy systems. In this way, the constraints typical of protected building and areas are respected but, at the same time, a voluntary road to sustainability becomes viable and effective.

A further development of this study would be to analyze the carbon avoidance cost of this strategy at district level for different RES such as PV, wind, etc. to quantify the impact of H2NG applications.

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