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Renewable hydrogen potential for low-carbon retrofit of the building stocks

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Abstract

Energy-related GHG emissions, mainly from fossil fuels combustion, account for around 70% of total emissions. Those emissions are the target of the recent sustainability policies. Indeed, renewables exploitation is considered widely the weapon to deal with this challenge thanks to their carbon neutrality. But, the biggest drawback is represented by the mismatching between their production and users consumption. The storage would be a possible solution, but its viability consists of economic sustainability and energy process efficiency as well. The cutting edge technologies of batteries have not still solved these issues at the same time. So, a paradigm shift towards the identification of an energy carrier as storage option, the so called Power-to-Gas, could be the viable solution. From viability to feasibility, a mandatory step is required: the opportunity to integrate the new solution in the proven infrastructures system. Thus, the recent studies on Hydrogen (H2) enrichment in Natural Gas, demonstrating a lower environmental impact and an increase in energy performance, are the base to build the hydrogen transition in the urban environment. The aim of this paper is to evaluate the environmental benefits at building and district scale.

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Keywords: Renewable Hydrogen; Energy Retrofit; Hydrogen-Methan mixtures; Cogeneration; H2NG; residential applications.

1. Introduction

The scarcity of fossil fuels, global warming and the ever increasing energy demand require a transition to a more sustainable energy system and to a large degree of climate resilience. The built environment plays a unique role in this transition stage. Especially at the scale of buildings and cities, the energy

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efficiency goals towards low or zero energy buildings and a climate resilience built environment are strictly linked. Several studies were conducted, but also due to the lack of appropriate test cases and the focusmainly on New Buildings, they ended with different outcomes. Indeed, the energy-efficiency and climate-resilience of a city worth being evaluated on Existing Buildings, in which appropriate importance should be given especially due to their high percentage (about 75-85%) of the building stock today and in the next fifty years. The relevant issues include at least the values preservation of historical buildings, the energy efficiency benchmark required by regulations in force dealing with climate change, the changing uses of the existing buildings due to the new needs in the contemporary society and the vital urban redevelopment so that to support the regeneration of brownfield areas to achieve higher sustainability goals [1]. To do so, it is crucial to take into account the existing energy infrastructures as part of the energy transition towards future smart energy systemsand building integrated RES production [2,3]. In this framework, Hydrogen can play a key role due to its double applicability: as direct fuel for conversion purposes by chemical process or combustion and as energy carrier for storing surplus energy coming from renewable sources [4].

Nomenclature

CHP	Combined Heat and Power	H_2NG	Hydrogen and Natural Gas
EU	European Union	NG	Natural Gas
GHG	Greenhouse gas	PV	Photovoltaics
H_2	Hydrogen	RES	Renewable Energy Sources

2. Methodology

The strict requirements to manage the energy transition scenario avoiding to postpone the solution to the deadline of EU protocols such as EU 2020, Green Paper 2030 and Roadmap 2050 entailthe use of a multi-disciplinary solution in terms of energy supply in which energy retrofitting, valorization of existing building stocks and feasible implementation of new technologies are consideredalong with matching the reliability requirements [5]. That combination has become hybridization of promising technologies and renewable energy sources such as solar and biomass [6] or hydrogen and biomass [7]within the distributed generation model. This model is the suitable energy layout to meet the new prosumer profile, composed of production and consumption on-site, and to achieve lower carbon and nitrous emissions [8].

In this framework, the H_2 addition to Natural Gas with different fractions has been investigated. Hydrogen is defined renewable when it is produced by electrical RES such as PV, wind, etc. Moreover, to achieve low environmental and architectural impacts, the production from RES has to be integrated in the building. For this reason, the study explores the opportunity to produce Renewable Hydrogen from Building Integrated Photovoltaics and add it to Natural Gas-based CHP to meet the energy demand of a detached house, a complex of four terraced houses and an apartment block with ten flats.

The location of the buildings is Central Italy. This data allows estimating the Direct Normal Irradiation to calculate the PV production. Then, an electrolyser fueled with PV produces Hydrogen.

Table 1. Building types and available surface for PV [9]

Building Type	Electrical Power Demand (kW_{el})	Roof Surface (m^2)	Parking Canopy Surface (m^2)	Direct Normal Irradiation (kWh/m^2)	Yearly Solar Radiation (kWh)
Detached House	5	100	8		164,052
Four Terraced Houses	15	200	30	1,519 [10]	349,370
Apartment Block	60	200	80		425,320

RES availability assessment is the first step to estimate the energy potential. The building surfaces considered for integration are the roof and the parking canopy. Each building typology entails a different layout of the area where is built. That area could involve isolated and aggregated parking surfaces. The assumption about those surfaces is that they could be covered by PV-integrated canopies and supply the produced electricity to the households. In order to calculate the yearly solar radiation, the location of the buildings was set in Central Italy. The data allows to estimate the Direct Normal Irradiation [10] so that to calculate the PV production. In Table 1, two surface values were estimated with the opportunity to install PV array on the parking canopies.Those building-parking layouts are representative of the building stock.

Then, as reported in Table 2, the PV array fueledan electrolyser to produce Hydrogen. This latter was used to enrich Natural Gas from Gas Grid. Each building scale entails a different Hydrogen production.

Table 2. Building types and Hydrogen potential

Building Type	Yearly-Solar Radiation (kWh)	PV array efficiency (-)	Gross Energy from Solar (kWh)	PV Hydrogen Production Rate (Nm^3/kWh)	Yearly Hydrogen Volume (Nm^3)
Detached House	164,052		24,608		591
Four Terraced Houses	349,370	0.15	52,406	0.024	1,258
Apartment Block	425,320		63,798		1,531

2.1. How to calculate the Hydrogen fraction

So, the Hydrogen fraction for the H_2NG blend is identified by solving Equation 1.

$$P_{H2NG} = \frac{1}{1-f_{H2}} \times \frac{E_{s}\times\eta_{PV}\times\eta_{H2}\times\eta_{CHP}}{t_0} \quad (1)$$

Where:

- P_{H2NG} is the electrical size of the hydro-methane power plant for each building typology;
- f_{H2} is the hydrogen volume fraction in H_2NG blend;
- E_s is the available solar energy;
- $\eta_{PV}$is the PV conversion efficiency considering operational time of 1,250 hours;
- η_{H2} is the electrolyser efficiency, accounting for overall system conversion efficiency;
- η_{CHP} is the CHP electrical efficiency of H_2NG blend;
- t_o is the CHP operational hours amount, it is equal to 1,650 hours per year, i.e. the winter season.

The CHP plant size (P_{H2NG}) was equal to the Electrical Power Demand of each buildingtypology.

Having substituted in Eq. 1 the Electrical Power Demand, i.e. the size of the electricity meter for residential applications, the Hydrogen volumetric fraction for H_2NG blend in the three case studies was calculated. Thus, a new electrical efficiency based on experiments carried out by Sapienza University of Rome [11], was evaluated.The last step consists of the calculation of associated carbon emissions to each blend and CHP size along with the carbon emissions saving [12].Finally, a comparison between the three micro-CHPs fuelled with H2NG and the traditional ones fuelled with NG in terms of carbon dioxide was done. The three scales allow evaluating the benefits coming from the Eco-fuels use in buildings.

3. Results and Discussion

The paradigm shift to renewable Hydrogen economy requires planning instruments. Those tools are related to energy infrastructures and established socio-economics towards the sustainable development [13,14]. A first attempt is done by evaluating at different building scales the environmental benefits, i.e. in terms of Carbon Emission reduction, associated to different Hydrogen-Natural Gas mixtures. The production of Hydrogen is linked to the local available resources, e.g. the solar potential to promote a Zero Kilometer Energy model [2]. This model could support transition stage by a current viable solution. Especially, for Natural Gas-based Countries and Coal-based Countries, which are substituting coal with NG for reducing emissions and pollutants, it is crucial to integrate systemic technologies, in order to deploy future smart energy systems.

In Table 3, the H2NG blends are summarized along with the electrical efficiency of the three CHPs. The Hydrogen addition has a double effect: a substitution effect and a leverage effect by improving the combustion process [15]. So, its addition entails a different electrical output compared to the NG one.

Table 3. Building types and H2NG production

Building Type	Electrical Power Demand - P_{H2NG} (kW)	Electrical efficiency (-)	Electricity Production (kWh)	Heat Production (kWh)	Yearly Hydrogen Volume (Nm^3)	Hydrogen Fraction – f_{H2}(%)
Detached House	5	0.3	8,250	20,490	591	18.55
Four Terraced Houses	15	0.315	24,750	48,260	1,258	13.69
Apartment Block	60	0.325	99,000	162,650	1,531	4.5

3.1. Carbon Emission Analysis

In order to calculate the carbon emissions expressed in kg/GJ, with changes in Hydrogen fraction in the mixture, Equation 2 was used[4]:

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

where CO_2represents 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 the annual production. A higher fraction of Hydrogen into the blend corresponds to a lower carbon emission per energy output. As reported in Table 4 and Figure 1, the carbon emissions saving are about -50% compared to a traditional NG cogeneration. For optimal design, the increase of energy efficiency with the CHP size should be considered along with an extra PV array to produce Renewable Hydrogen.

Table 4. Carbon Emissions for each H2NG blend

Building Type	New Electrical Efficiency (-)	Calculated Emissions (kg/GJ)	Calculated Emissions (g/kWh)	Annual Emissions(t)	Annual Emissions BAU (t)	CO2 Savings (%)
Detached House	0.318	51.45	185.22	1.5281	2.97 [16]	48.5
Four Terraced Houses	0.328	52.49	188.96	4.6767	8.91 [16]	47.5
Apartment Block	0.33	54.25	195.29	19.3337	35.6 [16]	45.7

A new electrical efficiency was calculated due to the thermodynamics effect of adding Hydrogen.

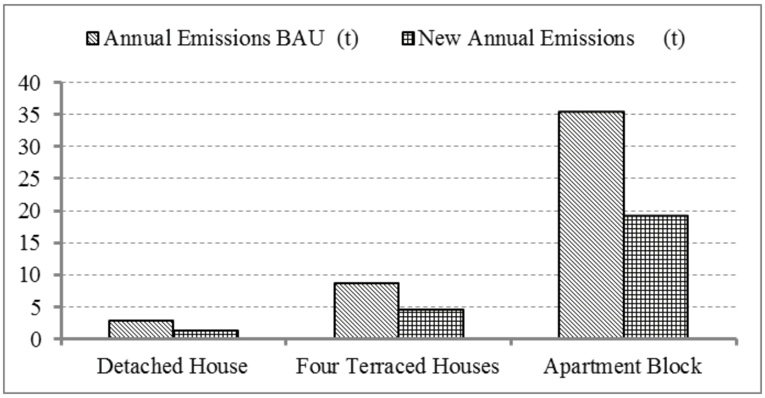

Fig. 1. Carbon emissions for each building typology in BAU and H2NG scenarios.

4. Conclusion

The study highlighted the environmental benefits coming from Hydrogen addition to Natural Gas CHP. The electrical efficiency, as previously reported in Table 4, is different for each size and it is affected by the Hydrogen fraction in H_2NG mixtures. Energy produced by micro-CHP fueled with H_2NG blends is more environmentally-friendly due to a reduction of CO2 ranging from 48.5% to 45.7%.

Having identified micro-cogeneration as the driver to spread the distributed generation model, the opportunity to integrate a new fuel into well-proven local energy systems allows managing a transition scenario, avoiding the planning, economic and grid issues related to a new energy infrastructure.

The further step would be to analyze the impact in those aspects to verify the feasibility of H_2NG applications.That study would assist the Urban Energy Planning phases for local RES valorization.

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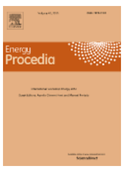

Biography

Architectural and Building Engineer. His research is focused on the role of Eco-Fuels in the transition towards future smart energy systems, in a new relation between urban and rural environment for low carbon city and society. Expert of Sustainable Energy Action Plans, renewable energy technologies and their integration in urban and agricultural planning.