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The Transition to an Eco-Friendly City as a First Step Toward Climate Neutrality with Green Hydrogen

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Abstract: A city of the future will need to be eco-friendly while meeting general social and economic requirements. Hydrogen-based technologies provide solutions for initially limiting CO_2 emissions, with prospects indicating complete decarbonization in the future. Cities will need to adopt and integrate these technologies to avoid a gap between the development of hydrogen production and its urban application. Achievable results are analyzed by injecting hydrogen into the urban methane gas network, initially in small proportions, but gradually increasing over time. This paper also presents a numerical application pertaining to the city of Bucharest, Romania—a metropolis with a population of 2.1 million inhabitants. Although the use of fuel cells is less advantageous for urban transport compared to electric battery-based solutions, the heat generated by hydrogen-based technologies, such as fuel cells, can be efficiently utilized for residential heating. However, storage solutions are required for residential consumption, separate from that of urban transport, along with advancements in electric transport using existing batteries, which necessitate a detailed economic assessment. For electricity generation, including cogeneration, gas turbines have proven to be the most suitable solution. Based on the analyzed data, the paper synthesizes the opportunities offered by hydrogen-based technologies for a city of the future.

Keywords: green hydrogen; smart cities; CO_2 emissions

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1. Introduction

The share of the urban population is close to 57% of the total population of the globe, which exceeds 8.1 billion people [1]. Typically, urban agglomeration includes the population of a city or municipality plus that of suburban areas located outside the city boundaries but adjacent to it [2].

Conceptualizing a city of the future is a complex task, considering that this idea is constantly evolving and difficult to define in absolute terms [3]. However, one of the main goals remains to create a city with minimal or even absent pollution levels with effective control over its environmental impact. Pollution itself is a multifaceted phenomenon, involving various aspects that require specific approaches and future actions. Nonetheless, the reduction in or elimination of carbon dioxide emissions is already a well-defined and prioritized objective.

With all that makes them unique, these cities of the future are concentrated sources of energy consumption but also of the production of goods and services with associated pollutant emissions, primarily carbon dioxide. In 2023, compared to 2022 [4], primary energy consumption increased by 2% and carbon dioxide emissions by 2.1%. In 2022, carbon dioxide emissions associated with energy production were 35,129.6 million tons of CO_2, and those from gas combustion for household consumption were 317.4 million tons, out of a total emissions value of 40,417.9 million tons of CO_2. The EU's carbon dioxide emission trading scheme was priced at 85.17 EUR/ton of CO_2, in 2023 [4].

In 2023, according to the Energy Institute Statistical Review of World Energy 2024, the total hydrogen production reached 4834.9 thousand tons, of which green hydrogen accounted for only 147.6 thousand tons, and the rest was produced from fossil fuels, generating significant CO_2 emissions, namely 10 tons of carbon dioxide per ton of hydrogen (tCO_2/tH_2) from natural gas, 12 tCO_2/tH_2 from petroleum products and 19 tCO_2/tH_2 from coal [5].

The use of hydrogen as an energy carrier in the cities of the future is considered one of the reliable solutions, especially as hydrogen production costs continue to decline. According to [6], current hydrogen production costs (EUR/kg) vary depending on the technology used: 1.38–5.52 for natural gas reforming, 1.84–6.44 for reforming or gasification with carbon capture, 3.40–11.04 for electrolysis using onshore wind energy, 4.42–11.04 for electrolysis using offshore wind energy and 3.50–10.4 for electrolysis with energy from solar panels. The arithmetic average of the hydrogen production costs from various sources, in EUR/kg, is 3.45 for natural gas reforming, 4.14 for reforming with carbon capture up to 85–95% from natural gas, 7.22 for onshore wind, 7.73 for offshore wind and 6.95 for solar.

Even though the cities of the future, or smart cities, are characterized by a multitude of interactive activities [7], energy and pollution are omnipresent, so that through the complex use of hydrogen, the energy needs and climate neutrality are ensured.

The energy consumed in a city of the future is in the form of electricity, thermal energy, mechanical energy, pressure energy, etc. Moreover, transport is responsible for about 30% of the primary energy consumption and pollutant emissions. At the same time, the energy consumed for heating and food preparation has significant values, with corresponding high emissions.

Green hydrogen, produced by electrolysis using renewable energy sources, offers significant potential for reducing CO_2 emissions and decarbonizing various sectors, including transport, industry and residential heating [8].

Using green hydrogen in these areas can contribute to transforming cities into cleaner and more sustainable environments. Therefore, in the context of aspirations for a city of the future, the integration and promotion of hydrogen-based green technologies become essential for achieving an eco-friendly and sustainable urban environment. An integrated and collaborative approach between various stakeholders, including local authorities, the scientific community, industry and civil society, is needed to develop and implement innovative solutions, leading to a greener and healthier urban future. Producing green hydrogen represents a milestone in finding sustainable solutions for global energy needs. This form of green hydrogen is obtained by electrolysis of water into oxygen and hydrogen, using electricity generated from renewable energy sources such as solar or wind power [9].

The concept of green hydrogen has attracted the attention of the scientific community and industry as a potential carrier of clean and sustainable energy, capable of significantly reducing the carbon footprint of human activities. However, implementing green hydrogen in urban infrastructure poses numerous challenges. While production technologies have advanced significantly, transforming this form of energy into a viable and efficient solution for cities is still under development. Using green hydrogen in a city involves building

suitable production and distribution facilities as well as adapting existing infrastructure to enable its use in different sectors, such as transport, heating and industry. Currently, we are in a transition phase toward the widespread use of green hydrogen in cities. This transition period is essential for defining future directions and priorities. As research continues to advance and technologies improve, developing the necessary infrastructure to support the efficient use of green hydrogen in cities is crucial. Although the use of green hydrogen in cities is still in its early stages, it is evident that this energy form has the potential to play a significant role in transitioning to a sustainable and clean energy future [10]. By continuing to invest in research and development and actively involving local authorities and industry stakeholders, we can create greener and more resilient cities powered by renewable and clean energy sources [11]. The use of green hydrogen in a city aims to carry out carbon-free industrial, transport and social activities [12]. The initiative is in the initial phase, which includes theoretical studies, pilot-scale experiments and preparing society to accept and integrate into the new energy ecological concept. All this must ensure all areas that take into account the life cycle of hydrogen, production, transport, distribution and end use. If we consider the current state of green hydrogen production in the EU, we can say that there are still important steps to be taken.

Hydrogen demand in end-use sectors includes the total final consumption of hydrogen and hydrogen-based fuels as well as the industrial hydrogen demand covered by on-site production within industrial facilities. Low-emission hydrogen trade as a share of production is the percentage of low-emission hydrogen produced (including commercial hydrogen and hydrogen produced on-site in industry and refining) that is exported from the region as hydrogen or as an energy product.

2. Objectives of Using Green Hydrogen

The Sustainable Development Goals (SDGs) established in 2015 as part of the United Nations (UN) 2030 Agenda for Sustainable Development [13] consist of the commitment of countries to eradicate poverty to find solutions for sustainable and inclusive development by 2030. The EU has made a positive and constructive contribution to the development of the 2030 Agenda.

Among the 17 Sustainable Development Goals (SDGs) outlined by the UN 2030 Agenda [13], very dedicated is Goal 7 on clean and affordable energy aims to ensure access to clean energy technologies and services, contributing to the global challenge of climate change. The European Union has put forward various policies that have made progress in reducing Europe's energy consumption and ensuring a sustainable energy supply. In the broader context of the European Green Deal, the EU has set itself the goal of carbon neutrality by 2050 [14]. Hydrogen, as a clean energy carrier and a storage medium, allows the integration of different sectors into a single energy market, thanks to the conversion of electricity into hydrogen chemical energy [15]. As renewable technologies enter the energy market, seasonal imbalances will become increasingly relevant, and hydrogen can balance intermittent supply, enabling the transition to renewable energy [16]. In addition to decoupling energy generation from demand (storage system), hydrogen can act as an energy vector for the decarbonization of heating, transport and industry.

It should be noted that Europe produces a total of 75.8 thousand tons of hydrogen compared to 4834.9 thousand tons worldwide, but 31.6 thousand tons of green hydrogen out of a total of 147.6 thousand tons, according to the Energy Institute Statistical Review of World Energy 2024 page 41 and Figure 1 [3].

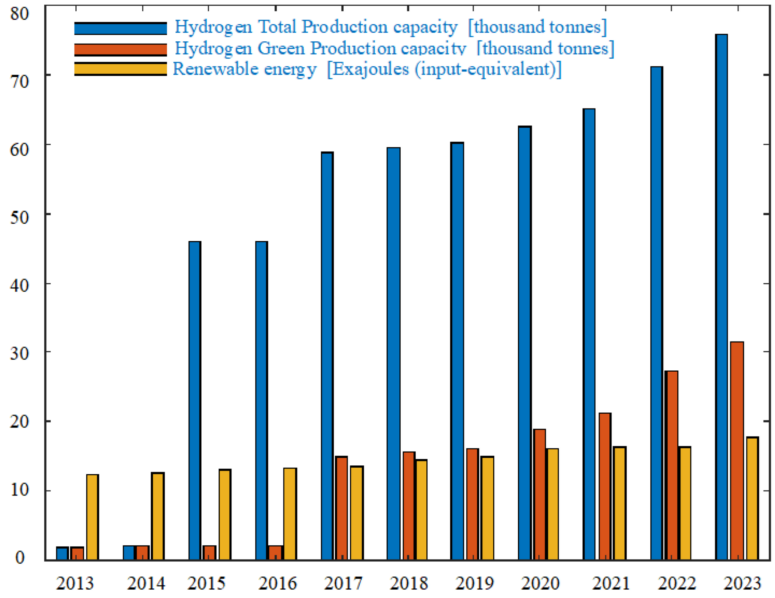

Figure 1. Production dynamics in Europe.

Global hydrogen production increased by 3.7% in 2023 compared to 2013 [4]. Global hydrogen demand reached over 97 Mt in 2023 and could reach almost 100 Mt in 2024, according to the IEA Global Hydrogen Review 2024, https://www.iea.org/reports/global-hydrogen-review-2024, accessed on 15 December 2024 [17]. Production remains predominantly dependent on fossil fuels without carbon capture. Hydrogen produced from natural gas accounted for 63% of the global total; from coal 20%; by-product hydrogen another 16%; and production from water electrolysis was below 100 thousand tonnes of hydrogen (kt H2), mainly in China.

The current production of hydrogen is used approximately as follows [5]: 11.7% for refining, 9.6% for ammonia, 3.7% for methanol, 1.3% for steel mills, 8% for consumption heat production and the rest for transportation and other uses such as fuel cells.

Hydrogen demand in 2023 was 12 EJ (97 Mt), produced almost exclusively from fiid fossil fuels used by industry for refining 45%, ammonia 34%, methanol 16% and steel 5% [18]. Secondary hydrogen from the chlor-alkali industry is not included.

In support of the development of the use of hydrogen, the European Union does not impose taxes on this fuel, except for VAT. Two European structures support the production and deployment of green hydrogen, namely the European Hydrogen Industry [19] and the European Hydrogen Bank [20]. As the production of green hydrogen is coordinated by the policy of the European Council and the governments of the EU Member States and the deployment of the use of green hydrogen in cities is a consequence of local policies, deviations may arise that must be theoretically anticipated and legally resolved. In Europe, the dynamics of total hydrogen, green hydrogen and renewable energy production are shown in Figure 1, processed based on available data.

Of the current global demand for hydrogen, around 21% is considered “pure”, with “pure” meaning that specific applications require hydrogen with low levels of additives or contaminants tolerated. The main applications of this hydrogen are oil refining and ammonia production, mainly for fertilizers. There is still about 14% demand for hydrogen as part of a gas mixture, such as syngas, with applications for methanol production and steel production. While today, a third of hydrogen demand is for applications in the wider transport sector, including refineries and for methanol used in vehicle fuel, only about 0.01 Mt per year of pure hydrogen is used in fuel cells.

It should be noted that hydrogen is not an energy source but an energy carrier, which means that its potential role resembles that of electricity. Both hydrogen and electricity can be produced through various energy sources and technologies, but they are versatile and can be used in many different applications. The use of hydrogen or electricity is completely environmentally friendly, with no environmental effects. For example, the hydrogen used in a fuel cell emits nothing but water. But, both hydrogen and electricity can have a high carbon dioxide intensity upstream if they are produced from fossil fuels such as coal, oil or natural gas. This disadvantage can only be overcome by using renewables or nuclear energy as an initial energy input or by equipping fossil fuel plants with carbon capture and sequestration. Overall, less than 0.7% of current hydrogen production comes from these sources, and today's hydrogen production is responsible for the emission of 830 $MtCO_2$/year.

The essential difference between hydrogen and electricity is that hydrogen is a carrier of chemical energy, being a molecule and not only from electrons. Chemical energy is attractive because it can be stored and transported in a stable way, as is performed today with oil, coal, biomass and natural gas. The molecules can be stored for long periods, are easily transported, burned to produce heat and use existing fossil fuel infrastructure and logistics. Due to its molecular nature, hydrogen can also be combined with other elements, such as carbon and nitrogen, to make hydrogen-derived fuels that are easier to handle and can be used as a feedstock in industry, helping to reduce emissions. The great quality and difference between hydrogen and electricity energy vectors involve the possibility of energy storage.

In the case of hydrogen, these losses can accumulate at different stages of the value chain (life cycle) and justify minimizing the number of conversions between energy carriers, that is, energy vectors [21]. As all transformations are loss-making, in the end, hydrogen is "more expensive" than the electricity or natural gas used to produce it.

In recent years, depending on the source and technology of hydrogen production, certain colors have been associated. Thus, for hydrogen produced from fossil fuels, the colors "black", "gray" or "brown" are associated. For the production of hydrogen from fossil fuels with low CO_2 emissions by using carbon capture, the color "blue" is used. For the production of hydrogen from renewable electricity, the color "green" is imposed.

The production of green hydrogen for climate neutrality will initially prioritize the supply of industry, with cities consuming only part of the production for the energy transition phase. In the later stages, the consumption of green hydrogen by cities will increase in line with environmental objectives.

Hydrogen contains three times more energy per unit of mass than natural gas or gasoline, making it attractive as a fuel for transportation.

However, hydrogen is the lightest element with a density 10 times lower than natural gas and, therefore, has a low energy density per unit volume, only 1/3. This means that larger volumes of hydrogen need to be displaced to meet identical energy requirements compared to other fuels. This can be achieved, for example, by using larger or faster-flowing pipes and larger storage tanks. On the other hand, the flame speed is eight times higher than that of methane, the auto-ignition temperature is approximately 2.7 times higher than that of methane and the auto-ignition energy is only 1/10 of that of methane.

Hydrogen can be compressed, liquefied or converted into hydrogen-based fuels that have a higher energy density, but any subsequent reconversion uses some energy.

Like other energy carriers, hydrogen presents certain health and safety risks that can slow down or even prevent the implementation of a new energy technology if the risks are not well communicated and managed. Being a light gas with small molecules, hydrogen requires special equipment and procedures to handle it, as it can diffuse into

some materials, including certain types of iron and steel pipes, and increases their risk of failure. It also escapes more easily through seals and connectors than larger natural gas molecules. Despite these issues, it is possible to use the existing natural gas infrastructure.

Hydrogen is a non-toxic gas, but its high flame speed, wide ignition range and low ignition energy make it highly flammable. This is partially mitigated by its high buoyancy and diffusivity, which cause it to dissipate quickly. It has a flame that is invisible to the naked eye and is colorless and odorless, making it more difficult for people to detect fires and leaks.

There are already many decades of experience in using hydrogen at an industrial level, including in large dedicated distribution pipelines, with established safety handling protocols, and hydrogen supply infrastructure exists. The widespread use in the energy system brings new challenges.

It is estimated that the demand for hydrogen will increase annually until 2050 by 166–240 Mt (Mega tons) of hydrogen [22]. This energy demand is closely related to population growth and total energy consumption per capita, Gigajoules per capita, which over the last decade has increased by 0.6% per year [4]. It should be noted that the total electricity generated, of 29,188.1 Terawatt-hours, had an increase of 2.5% per year, and that generated from renewable sources (solar, wind, hydro and other renewables), of 8988.4 Terawatt-hours, had an annual increase of 5.4%.

Today, significant efforts are being made to store hydrogen, an issue just as important as its production [23].

The primary energy source for green hydrogen production remains renewable energy sources. However, these sources are not located near urban areas, so the location of green hydrogen production, as well as its storage, poses complications for the necessary infrastructure, such as the grid's ability to transport electricity produced from renewable sources to the hydrogen production site.

The issue of seasonal storage and alternative carriers is discussed in the paper published in Int. J. Hydrogen Energy 2024, 52 Pt A, 1090–1100.

Each country has committed to an action plan for promoting hydrogen. According to Romania's strategy for 2030, which is set to be adopted, it plans to produce 152.9 kt of green hydrogen, which will be consumed as follows: 23.7 kt of green hydrogen in new industrial applications, 56.9 kt in the existing industry and 72.4 kt in transportation. To meet the hydrogen demand, 2130 MW of electrolysis capacity will need to be installed, and an additional 4261 MW of renewable energy capacity will be required to power this. Regarding green hydrogen used in a mix with natural gas, this is not included in the total estimated green hydrogen consumption for 2030. However, using a 2% volumetric mix of green hydrogen with natural gas to cover Romania's total natural gas consumption, the National Hydrogen Strategy estimates a required volume of 18.2 kt of green hydrogen.

Traditional applications of hydrogen use include oil refining; raw material for the production of ammonia, methanol and other chemicals; reducing agent for producing alloy steel; and glass manufacturing or metal processing. Potential new applications include long-distance transportation; production of hydrogen-based synthetic fuels with 18.2 kt reduction; high-temperature heating in industry; energy storage and electricity generation; etc.

3. Methodology

In order to achieve climate neutrality in a city, the use of fossil fuels that produce carbon dioxide by burning must be reduced as much as feasible and economically possible. The possible directions of action consist of replacing fossil fuels with hydrogen. If we analyze the areas where this is possible, we note transportation, energy storage and residential heating. The reduction in carbon emissions in transportation is mainly achieved by switching to

electric vehicles, which essentially require electricity storage, or by using biofuel blends or direct hydrogen injection into internal combustion or compression engines, such as diesel engines, leading to a reduction in pollutant emissions [24,25].

The methodology of this study includes the transition from the production capacities for green H_2, along with its associated economic challenges, to its utilization through combustion in 5% and 10% CH_4 blends. A section addressing the technology for stable and high-performance combustion, tailored to the specific requirements of residential applications, was also introduced. These aspects were incorporated into an applicability study for a city with a population exceeding 2 million inhabitants. The data concerning combustion technology represent the theoretical and experimental results of the authors.

Energy storage and its impact on the grid and transportation sectors have expanded globally in recent years, as storage costs continue to decrease and new opportunities are being defined across a variety of industrial sectors and applications. The electrification of the transportation sector is driven by the availability of lithium-ion (Li-ion) batteries, which offer lower costs and higher performance for electric vehicles.

Energy storage does not have strict power constraints, allowing a variety of storage technologies to compete in providing flexibility services. Among the available storage technologies, batteries and the bidirectional hydrogen energy storage system (HESS) are the ones suited for application in the cities of the future. There are several HESS configurations that can be useful in different cases, but the preferred one is bidirectional storage using fuel cells. This configuration also involves the use of a PEM electrolyzer to generate hydrogen from water with an electric current (releasing oxygen as a byproduct) before compressing and storing the hydrogen. The hydrogen is later re-electrified using fuel cells to produce electricity. An HESS consists of three major components: the charging system, which includes electrolyzer modules, controllers, water treatment units, mass flow regulators, a management system, a compressor and a rectifier; he discharging system, which consists of stationary fuel cell modules, controllers, gas handling units, blowers, mass flow regulators, a fuel cell management syste and an inverter; and the storage system, which usually includes pipes, tanks or a cavern.

According to the 2022 Grid Energy Storage Technology Cost and Performance Assessment, at the level of the year 2030, the costs for an HESS with a capacity of 100 MW or 1000 MW depend on the duration of the reserve provision, respectively, 10 h or 24 h. For a 10 h reserve provision, the estimated costs for 2030 are (a) total installed cost approx. 101 EUR/kWh, respectively, 1010 EUR/kW; (b) operating cost for fixed OM—operations and maintenance—of approx. 14–16 EUR/kW/yr. The main performance parameters regardless of the capacity of the HESS system are round-trip efficiency (RTE) of 31%; cycle life unlimited; calendar life 30 yrs; and DOD—depth of discharge—of 80% [26].

For an urban area, the following areas of use of green hydrogen are identified: transportation with electric vehicles powered by fuel cells; residential and industrial heating; and energy for cooking.

Transportation is responsible for approximately 30% of the EU's total CO_2 emissions. Most importantly, CO_2 emissions from global transportation are expected to increase in the future under a normal scenario, as technical improvements to conventional internal combustion engines do not seem sufficient to reduce emissions from the continuously growing fleets of newly registered vehicles, service trucks, airplanes, trains and ships. The European Green Deal has set a target to reduce transportation emissions by 90% by 2050 [27].

Transportation and storage costs will play a significant role in the competitiveness of hydrogen. If hydrogen can be used close to where it is produced, these costs could be near zero. Long-distance transmission and local distribution of hydrogen are challenging due to

its low energy density. Compression, liquefaction or incorporating hydrogen into larger molecules are possible options to overcome this obstacle, but each option has its advantages and disadvantages. Blending hydrogen into existing natural gas pipeline networks could give a boost to hydrogen delivery technologies without incurring the investment costs and risks of developing a new hydrogen transport and distribution infrastructure. Updating and harmonizing national regulations that set limits on the allowed hydrogen concentrations in natural gas flows would help facilitate such a blending.

In the first stage, hydrogen will be injected into the natural gas supply network in a proportion of 5–15% (volumetric blending ratio, x = 0.05–0.15). As hydrogen infrastructure matures, this percentage will increase until it reaches 100% hydrogen [28]. For the production of electricity, current experience has shown that gas turbines offer the most practical solution for the use of hydrogen through direct combustion [29,30].

4. The Particularities of the Combustion of the Methane–Hydrogen Gas Mixture

Unlike methane, which forms combustion gases containing carbon oxides, water vapor, nitrogen and nitrogen oxides when burned with air, hydrogen is an environmentally friendly gas because, when burned with air, it only forms water vapor, molecular nitrogen and possibly nitrogen oxides. The gases resulting from the stoichiometric combustion of methane (CH_4) with air for energy production are nitrogen (N_2), carbon dioxide (CO_2) and water vapor (H_2O), according to Equation (1):

$$CH_4 + \text{air} \Rightarrow \text{energy} + N_2 + CO_2 + H_2O \quad (1)$$

However, the gases resulting from the stoichiometric combustion of hydrogen (H_2) with air for energy production are nitrogen (N_2) and water vapor (H_2O), according to Equation (2):

$$H_2 + \text{air} \Rightarrow \text{energy} + N_2 + H_2O \quad (2)$$

This highlights the absence of carbon dioxide in the combustion gases, which constitutes the ecological essence of hydrogen combustion.

For a methane–hydrogen mixture, in stoichiometric combustion with oxygen,

$$(1-x)CH_4\left[m_N^3\right] + xH_2\left[m_N^3\right] + (1-x)2O_2\left[m_N^3\right] = (1-x)CO_2\left[m_N^3\right] + (2-x)H_2O\left[m_N^3\right] \quad (3)$$

where *x* is the volumetric percentage of hydrogen in the mixture, resulting in a reduction in carbon dioxide emissions from

$$1\left[m_N^3\right]CO_2 \text{ to } (1-x)\left[m_N^3\right]CO_2 \quad (4)$$

Combustion with air, where the excess air is denoted by λ (excess is defined by the surplus of oxidant $\lambda > 1$), introduces the oxygen component from the excess air into the combustion gases and proportionally increases the amount of nitrogen. The material balance of the combustion depends on the excess air λ, as follows:

For methane,

$$\begin{aligned} 1\left[m_N^3\right]CH_4 + \lambda \quad & \cdot 9.5\left[m_N^3\right]\text{air} \\ & \Rightarrow \text{energy}\left(35,700\left[\text{kJ}/m_N^3\right]\right) + \lambda \cdot 7.5\left[m_N^3\right]N_2 + 1\left[m_N^3\right]CO_2 + 2\left[m_N^3\right]H_2O + (\lambda - 1) \\ & \cdot 1.9\left[m_N^3\right]O_2 \end{aligned} \quad (5)$$

For hydrogen,

$$1\left[m_N^3\right]H_2 + \lambda \cdot 2.4 \quad \left[m_N^3\right]\text{air} \Rightarrow \text{energy}\left(10,780\left[kJ/m_N^3\right]\right) + \lambda \cdot 1.90\left[m_N^3\right]N_2 + 1\left[m_N^3\right]H_2O + (\lambda - 1)\cdot 0.49\left[m_N^3\right]O_2 \quad (6)$$

Refs. [5,6] indicate that, for a unit of flow, the energy released by the combustion of CH_4 is more than 3.3 times higher than in the case of H_2 (the references and lower values pertain to the lower calorific value). The transition from the volume of oxygen required for combustion to the volume of air involves the following relationship:

$$2m_N^3 : 0.21 = 9.5m_N^3\text{aer} \quad (7)$$

Another pollutant element of conventional combustion is the emission of nitrogen oxides, NO_x. For a gaseous fuel, this emission is a one-to-one function exclusively of the maximum flame temperature, which is represented by the adiabatic flame temperature, T_{ad}, according to the following equation:

$$NO_x = f(T_{ad})\left[\frac{mg}{m_N^3}\right] \quad (8)$$

Since the adiabatic flame temperatures for excess air $\lambda = 1$ and stoichiometric combustion are very close $T_{ad} \cong 2000[^\circ C]$, with an additional value of about 55°C for hydrogen, this results in a very close proximity of NO_x emissions [31,32].

However, the thermal effect of using the methane–hydrogen fuel mixture is lower than that of the same amount of methane:

$$H_i^{mixt} = (1 - x)H_i^{CH_4} + x \cdot H_i^{H_2},\ MJ/m_N^3 \quad (9)$$

where x is the volumetric percentage of hydrogen in the mixture, $H_i^{mixt}\left[MJ/m_N^3\right]$ is the lower calorific value of the methane with hydrogen mixture, $H_i^{CH_4}\left[MJ/m_N^3\right]$ is the lower calorific value of methane, and $H_i^{H_2}\left[MJ/m_N^3\right]$ is the lower calorific value of hydrogen.

For a H_2–CH_4 mixture at the utilization level, reference is made to $m^3{}_N$, as combustion occurs in the gaseous phase. Mass-based references for hydrogen have economic implications because, even without mixing with methane, combustion takes place in the gaseous phase.

It should be noted that the lower calorific values vary within certain limits depending on the measurement method and the purity of the gas. According to the Energy Institute [4], $H_i^{CH_4} = 36\left[MJ/m_N^3\right]$, and that of hydrogen at atmospheric pressure is $H_i^{H_2} = 10\ \left[MJ/m_N^3\right]$ [33].

When referring to mass, the lower heating value is approximately 50 MJ/kg for methane and 120 MJ/kg for hydrogen. However, mass is specific to the solid or liquid state, which is not the natural state of these fuels nor the state during combustion.

For the analysis of carbon dioxide emission reduction during the combustion of the methane–hydrogen mixture, it is assumed that the thermal power generated is equivalent to the combustion of methane alone, and the system efficiency remains constant. The $H_i^{CH_4} = 36\left[MJ/m_N^3\right]$ emissions decrease based on the hydrogen-to-methane mixture ratio, x, according to the following equation:

$$CO_2\left[\frac{m_N^3}{m_N^3}\right] = (1 - x)\cdot\frac{H_i^{CH_4}}{H_i^{CH_4} - xH_i^{H_2}} \quad (10)$$

After the interaction of the gaseous fuel mixture with air, the burners are designed using two distinct technologies: (1) kinetic combustion or full fuel–air mixing; (2) diffusion

combustion, where the air is introduced exclusively at the flame level. Figure 2 illustrates the functional diagram of these combustion technologies.

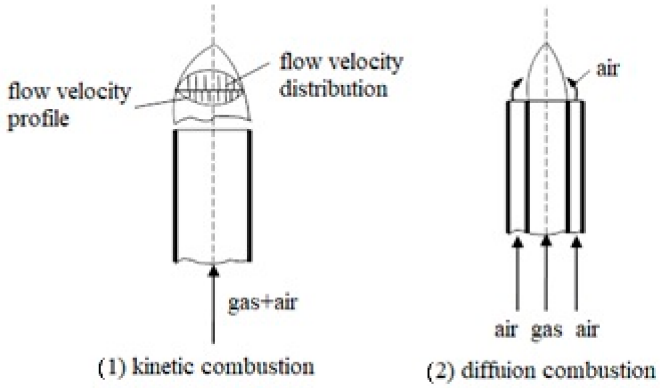

Figure 2. Types of gas burners.

The laminar burning velocities of stoichiometric methane–air and hydrogen–air mixtures under ambient conditions, according to various combustion reaction mechanisms, range from 33.5 cm/s [34] to 37 cm/s [35] for methane and from 203.64 cm/s [36] to 215.92 cm/s [37] for hydrogen.

The stability of kinetic combustion is achieved by matching the flow velocity with the combustion velocity, which is in the opposite direction of the flow. Kinetic combustion is primarily used in air-aspirated burners, with multiple residential applications such as cooking appliances, heaters, etc. This combustion technology has the lowest emissions due to flame cooling by the aspirated air, but it presents the risk of flashback (a highly dangerous process where the flame moves backward) when the combustion velocity exceeds the gas flow velocity. For this reason, kinetic combustion burners are equipped with flame stabilization systems as well as load limitation within the range of maximum stability. Based on extensive combustion research, the high combustion velocity of hydrogen requires low mixing coefficients, initially set at $x = 0.05$.

Diffusion combustion can be used in medium- and large-power burners and represents a forward-looking solution, as it can also be used with pure hydrogen fuel, 100% H_2. The use of diffusion combustion for predominantly hydrogen burning, either in a mixture with methane or pure hydrogen, is achieved through separate intake channels for the fuel and air, eliminating the risk of flashback.

The use of hydrogen for energy production through direct combustion creates infrastructure challenges in a city, even though initially, the hydrogen–methane mixture will be prepared outside the city, using only the existing methane pipelines for this purpose. One immediate consequence will be the flow rate through the pipelines, which will need to be adjusted to maintain the thermal power of the systems as the thermal power of the methane–hydrogen mixture decreases. Hydrogen's explosive limits in air, between 4.1% and 74.8%, compared to methane's limits of 4.4% to 17.0%, do not pose significant issues in ensuring adequate environmental protection when using hydrogen sources, within proportions of 5% to 15% hydrogen in methane.

5. Analysis of the Use of Hydrogen in a Future Eco-City

The development of a new hydrogen value chain depends on the successful completion and connection of the production, transportation, distribution, storage and end-use infrastructure. Mixing hydrogen into the existing natural gas infrastructure would avoid significant capital costs associated with developing a new transport and distribution infrastructure. Additionally, if the mixing was performed at low levels, while it might increase

the cost of natural gas delivery to consumers, it would also ensure reductions in CO_2 emissions. Mixing hydrogen would be much easier to implement if steps were taken to clarify existing national regulations regarding hydrogen in natural gas and to harmonize cross-border regulations.

There are nearly three million kilometers of natural gas transport pipelines worldwide and almost 400 billion cubic meters of underground storage capacity [32]. It is estimated that the economically viable transport distance through pipelines is up to 1500 km.

If part of this infrastructure could be used for the transport and utilization of hydrogen, it could provide a major boost to hydrogen development. For example, a 3% hydrogen blend by volume in the global natural gas demand would require almost 12 Mt of hydrogen. If most of this hydrogen was to come from electrolyzers, it would require approximately 100 GW of installed electrolyzer capacity, at a 50% load factor, which could offer a roughly 50% reduction in the capital cost of electrolyzers. If this energy comes from renewable sources, the hydrogen produced is referred to as green hydrogen.

Hydrogen can be stored in either gaseous or liquid form. The most suitable storage medium depends on the volume to be stored, the storage duration, the required discharge rate and the geographical availability of different options. In general, however, geological storage is the best option for large-scale and long-term storage, while tanks are more suitable for short-term and small-scale storage [38].

Local hydrogen distribution relies heavily on compressed gas trailer trucks for distances of less than 300 km. Liquid hydrogen tankers are often used instead where there is reliable demand, and liquefaction costs can be offset by the lower unit costs of transporting hydrogen. A single trailer can carry compressed hydrogen gas up to 1100 kg of hydrogen in lightweight composite cylinders at a pressure of 500 bar, but in practice, this weight is rarely achieved, as regulations around the world limit the permissible pressure, height, width and weight of the tubes that can be transported. Highly insulated cryogenic tankers can carry up to 4000 kg of liquefied hydrogen and are commonly used today for distances of up to 4000 km.

Residential use. The residential sector has specific applications focused on living conditions, particularly energy consumption for maintaining a comfortable ambient temperature, energy consumption for household appliances and gas consumption for cooking. Electricity can partially come from urban energy systems, especially if cogeneration is used, meaning the simultaneous production of electricity and heat.

For residential use, at the current stage, only the use of a methane–hydrogen mixture can be considered, with a blend ratio of up to 0.5–10%.

The Wobbe index is actually the correct representation of the heating value of natural gas arriving, from the gas line, at the orifice where a burner is located. The Wobbe index is as follows: (1) the heat output of a burner is proportional to the flow volume per time (given constant pressure and constant orifice size); (2) the flow velocity through a given orifice size at constant pressure is proportional to the specific gravity of the gas; and (3) the calorific value, or heating value, of a gas is proportional to its specific gravity.

In the EU, for the period 2024–2030, the installed capacity of electrolyzers is projected to reach up to 40 GW, with an estimated production of green hydrogen of 10^7 tH_2. For Romania, production is expected to stabilize starting with an installed capacity of 1.5 GW. Of the total H_2 production, approximately 65% is allocated to the chemical industry (mainly for ammonia), 25% to refining, 5% to metallurgy and 5% to the energy sector, including residential and agricultural consumption.

The operation of a burner when modifying the physical–energetic characteristics of a gaseous fuel requires compliance with the Wobbe number, $W_0 = \text{const}$, of the interchangeability of combustible gases [38].

$$W\left[\frac{MJ}{m_N^3}\right] = \frac{H_i\left[\frac{MJ}{m_N^3}\right]}{\sqrt{\frac{\rho_{gas}}{\rho_{air}}}} \quad (11)$$

where ρ_{gas} and ρ_{air}, in $\left[\frac{kg}{m_N^3}\right]$, are the densities of the gas and air under normal conditions.

The Wobbe number values for methane range between 47 and 53 and for hydrogen between 40 and 48. For a mixing ratio below 15%, the Wobbe index remains practically constant [39]. This leads to the conclusion that for all consumers in the methane–hydrogen mixed network during the transition period, there are no issues regarding burner performance characteristics. As a result, household consumers will not be significantly affected for a certain period. Problems start to arise as the hydrogen proportion increases. In the first stage, issues will appear with distribution systems, flow measurement and safety systems, representing the second stage of hydrogen use in urban environments when burner replacement will also be necessary.

For electricity generation in units located within the city perimeter, the use of gas turbines is the most easily applicable and suitable solution, as there are already successful implementations of these turbines operating with hydrogen-rich fuel. It is worth noting that the use of gas turbines allows for cogeneration, partially meeting residential heating needs. Gas turbines have already adapted to using the current methane–hydrogen mixture within the limits of the energy transition. Moreover, gas turbines designed for pure hydrogen have already been developed [40], generating 1516 kW and producing 1.07 tons of steam per hour for residential heating, with a hydrogen consumption of 2215 mN^3/h.

Also, the SGT-400 model from Siemens Energy, with a power of about 14 MW, has been tested for operation with 100% hydrogen [41].

For gas turbines, combustion in the combustion chambers results in nitrogen oxide emissions being reduced below the 50 ppm/m^3N limit. Future developments will enable the creation of competitive gas turbines designed to operate with pure hydrogen, representing an efficient solution for a zero-emissions city.

A notable increase in the performance of high-power steam boilers, integrated into a cycle for district heating, has been observed. Gas dynamic studies of the methane–hydrogen mixture flame indicate the need to increase the flow rate, which, in order to obtain a stable flame, must correspond to the much higher hydrogen combustion rate. For this variant, there is also a future need to replace burners designed exclusively for methane.

6. Simulating Hydrogen Consumption in Bucharest, a Future Eco-City

A simulation of hydrogen consumption during the transition to a zero-emission city was carried out for Bucharest, Romania. According to data provided by the city hall [41], the population of the city on 1 January 2023 was 2,160,169 people, of whom 1,011,128 were men and 1,149,041 were women. The residential market in 2023 includes 803,794 house holds, of which 733,864 have natural gas heating.

It should be noted that both natural gas and hydrogen are gases under normal pressure and temperature conditions, so their properties will be reported per normal cubic meter. As is known, hydrogen has a very low density, resulting in a low energy power reported per volume (about 1/3 of that of methane gas, but three times higher if we consider the energy power reported per mass).

This means that for the same amount of stored energy, a tank or pressure three times higher than for methane gas is needed. Currently, hydrogen storage for direct use can be conducted in gaseous form at pressures of about 300 bar or 700 bar and normal temperatures or at atmospheric pressure but cryogenic temperatures of about 20 K. All this brings additional costs of about 15% of the amount of energy stored in hydrogen.

To begin with, we considered using a mixture of methane gas and hydrogen for domestic consumption, a mixture transported through existing pipelines, so that specialized storage is not required. We considered a feasible proportion x of 5% and 10% hydrogen in methane gas.

Green hydrogen consumption during the energy transition phase includes the following: domestic consumption for cooking, centralized heating and urban transportation.

For domestic cooking, the average annual natural gas consumption per household is 200 $\left[m^3_N/year\right]$. With 5% hydrogen mixed with methane, the average annual hydrogen consumption per household would be 10 $\left[m^3_N/year\right]$, and at the city level, this consumption would become 7.34 $\left[Mm^3_N/year\right]$. For a 10% mixture, this consumption becomes almost 14.7 $\left[Mm^3_N/year\right]$ [42].

To determine the consumption of green hydrogen in the district heating sector, the average living area of households based on comfort class was calculated. In 2023, the average living area in apartments was 63.07 m^2 while for individual households, the average area was 107 m^2.

A suggestive presentation of the types of housing considered for various consumption values is shown in Figure 3.



Apartments with district heating | Apartments with central heating with individual boilers | Individual households | Restaurants preparing food

Figure 3. Types of housing considered.

These values are based on data from research conducted by the authors in this field. Table 1 presents the residential heating consumption by type of housing and the three variants of gaseous fuel: (1) pure methane; (2) a mixture of 5% hydrogen and 95% methane; and (3) a mixture of 10% hydrogen and 90% methane [2]. The total number of households was divided among those with district heating, those with central heating using individual boilers and individual households. Fuel consumption also includes domestic hot water [43,44]. The data in Table 1 come from the consumption statistics in Romania. District heating helps to average the amount of heat for all apartments in a building, leading to a reduced consumption. (In parentheses, the collection flow rates are indicated to produce the same amount of energy, considering the lower calorific value resulting from the introduction of H_2 in CH_4).

Table 1. Gaseous fuel consumption by household type.

Type	Average Surface Area [m^2]	Simple CH_4 Methane Gas Consumption [m^3_N/year]	H_2 Consumption in a Mixture of 5% Hydrogen and 95% Methane/Methane Consumption [m^3_N/year]	H_2 Consumption in a Mixture of 10% Hydrogen and 90% Methane/Methane Consumption [m^3_N/year]
Apartments with district heating	63.06	900	46.3/879.6	96.2/865.8
Apartments with central heating with individual boilers	63.06	1030	53/1006.7	110.1/990.8
Individual households	107	1550	79.7/1514.9	165.7/1491.1

Regarding CO_2 emissions, it is specified the following:

- During the combustion of $1m^3_N CH_4$, $1m^3_N CO_2$ is emitted;
- When mixed with 5% H_2, the combustion of one unit of gas results in 0.95 $m^3_N CO_2$. The correction to maintain 1 m^3_Ngas and, respectively, 1.07 m^3_Ngas for a 5 and 10%H_2 mixture will lead to an actual reduction of 0.022 $m^3_N CO_2$ and 0.037 $m^3_N CO_2$, respectively, relative to the energy released by combustion of CH_4.

Table 2 presents the values of gas required for the entire city for heating and cooking. Among the 803,794 households, the city also includes spaces for institutions, restaurants and food preparation units.

Table 2. Total gas fuel consumption by household type.

Type	Average Surface Area 10^6 m^2	Simple CH_4 Methane Gas Consumption 10^6 m^3_N/year	H_2 Consumption in a Mixture of 5% Hydrogen and 95% Methane 10^6 m^3_N/year		H_2 Consumption in a Mixture of 10% Hydrogen and 90% Methane 10^6 m^3_N/year	
			H_2	CH_4	H_2	CH_4
500,000 Apartments with district heating	31.53	450	23.1	439.8	48.1	432.9
200,000 Apartments with central heating with individual boilers	12.61	180	9.3	175.9	19.1	173.2
104,000 Individual households	11.1	161	8.3	157.4	17.2	154.8
Total 804,000 gas-powered homes	55.2	791	40.7	773.3	84.5	750.5
803,794 Homes currently powered by biomass	56	-	52	-	90	-

Since the combustion of methane produces, according to chemical relations, the same volume of CO_2, a decrease in emissions results proportional to the volume of methane–CH_4 consumed.

In 2023, the Bucharest Transport Company had a fleet of 1.527 buses, with an average of 992 buses in operation on regular working days. It is worth noting that the company also owns 523 trams and 265 trolleybuses, which provide emission-free transport. At the end of 2023, the company acquired 2023 electric buses, in addition to the 130 hybrid buses already in use since 2019. With a consumption of 70 kg of hydrogen per bus per day, for 360 working days per year, the total consumption amounts to 2.52×10^9 kg/year or 25.2×10^9 m^3_N/year. This quantity will need to be stored at a charging station located

outside the city or on the outskirts for safety reasons. A hydrogen transition usage scenario for a city of 2.1 million inhabitants indicates the following consumptions, classified by size, as shown in Table 3.

Table 3. Hydrogen consumption for Bucharest, an ecological city of 2.1 million inhabitants.

Type	H_2 Consumption in a Mixture of 5% Hydrogen and 95% Methane $10^6 \cdot m^3_N$/year	H_2 Consumption in a Mixture of 10% Hydrogen and 90% Methane $10^6 \cdot m^3_N$/year
Consumption for food preparation	7.34	14.7
Consumption for heating homes	40	80
Consumption for urban transport with 100 buses	25.2	

The urban distribution network for the hydrogen–methane mixture will include only the consumption for food preparation and households with district and individual heating, excluding the 500,000 apartments with district heating supplied by a separate network associated with thermal power plants. The hydrogen flow rates resulting from this scenario are, in $10^9 \cdot m^3_N$/year, 25.12 for 5% hydrogen and 50.24 for 10% mixture.

For the 10% H_2 in CH_4 limit, current estimates consider insignificant costs for the distribution and metering network including for the safety of use. It is understood that the production and storage of hydrogen involve costs not associated with residential installations. Raising the proportion of H_2 will have to be studied not only from a technical but also from an economic point of view.

It is worth mentioning that from 2023 to 2024, tests regarding the use of green hydrogen were conducted in Romania in two communities, one with 50 households and the other with 51 households. No issues were reported regarding distribution, ignition, monitoring or thermal effects for gradual doses of up to 30% [45].

Analyzing the simulation results, it is evident that the main issue is related to the annual consumption of green hydrogen. This consumption affects not only the production of green hydrogen but also the urban distribution network, storage and compression. The economic impact is another major obstacle for the community. However, costs are in a dynamic state, with a tendency to decrease.

The number of buses that will need to be electric or hydrogen-powered in the future is very large. In the simulation carried out, considering future possibilities for hydrogen implementation, a total of 100 buses was taken into account. This includes not only buses running on hydrogen but also the annual consumption, reflected in a charging station.

7. Conclusions

Reducing emissions in a future city is vital for combating climate change and improving the quality of life in urban environments. In this regard, the use of green hydrogen represents one of the most promising solutions. Green hydrogen is produced through the electrolysis of water using renewable energy sources, such as solar or wind power, meaning it is completely carbon-free during the production process.

To achieve an economic transition to green hydrogen, it is essential to implement global policies that promote its efficient use. These policies could include subsidies for the production and use of green hydrogen, tax incentives for investments in green infrastructure and regulations that encourage the shift from fossil fuels to renewable energy sources.

At the same time, it is crucial for cities to develop their own local strategies and policies for the adoption of green hydrogen. These policies could involve investments in infrastructure for the production, storage and distribution of green hydrogen as well as promoting its use in the industrial, transport and residential sectors. Additionally,

collaboration between cities and regions to exchange best practices and experiences can accelerate the local adoption of green hydrogen.

By adopting an integrated approach both globally and locally, cities can significantly reduce their emissions and move toward a more sustainable and environmentally friendly future based on the efficient use of green hydrogen.

CO_2 emissions are reduced by 2.2% when H_2 is mixed with CH_4 at a 5% proportion and by 3.7% for a 10% mixture.

A complex analysis of the possibilities for using hydrogen in a future eco-friendly city indicates that green hydrogen production has an initial availability for rapid use through the introduction of hydrogen into the urban natural gas network. However, immediate difficulties arise in the storage and dosing systems of hydrogen within the methane network. Other challenges occur in safety systems and flow measurement, especially after the mixing ratio exceeds 0.15.

This partially addresses the challenges presented by residential heating and cooking, which can use existing equipment designed for methane, as well as for electricity production, including cogeneration. Gas turbines represent the most favorable technological link for the use of pure hydrogen in electricity production, including cogeneration.

In the transport sector, fuel cells have already received a positive response, especially in public transportation. Extending their applicability to personal transport depends on local refueling systems, an action currently under development in all cities. This initial stage of hydrogen consumption implementation in urban environments, already applicable in the short term, will be followed by further stages, targeting a higher proportion of the hydrogen–methane mixture. All these achievements will require numerous studies and research, followed by standards and technologies for implementation and operation to support the increasing use of hydrogen.

The economic aspects have not been analyzed in the current paper, as they are intended to be addressed in a subsequent study.

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