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Review

Hydrogen–Natural Gas Mix—A Viable Perspective for Environment and Society

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Abstract: The increase in demand, and thus the need to lower its price, has kept C-based fuels as the main source. In this context, the use of oil and gas has led to increased climate change, resulting in greenhouse gases. The high percentage of eissions, over 40%, is due to the production of electricity, heat, or/and energy transport. This is the main reason for global warming and the extreme and increasingly common climate change occurrences, with all of nature being affected. Due to this reason, in more and more countries, there is an increased interest in renewable energies from sustainable sources, with a particular emphasis on decarbonisation. One of the energies analysed for decarbonisation that will play a role in future energy systems is hydrogen. The development of hydrogen–natural gas mixtures is a major challenge in the field of energy and fuel technology. This article aims to highlight the major challenges associated with researching hydrogen–natural gas blends. Meeting this challenge requires a comprehensive research and development effort, including exploring appropriate blending techniques, optimising performance, addressing infrastructure requirements, and considering regulatory considerations. Overcoming this challenge will enable the full potential of hydrogen–natural gas blends to be realised as a clean and sustainable energy source. This will contribute to the global transition to a greener and more sustainable future. Several international, European, and Romanian studies, projects, and legislative problems are being analysed. The mix between H2 and natural gas decreases fugitive emissions. In contrast, using hydrogen increases the risk of fire more than using natural gas because hydrogen is a light gas that easily escapes and ignites at almost any concentration in the air.

Keywords: hydrogen; environmental impact; social health; renewable energies; greenhouse emissions

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1. Introduction

For more than a century, oil has been the main resource for providing energy for the entire planet. At the same time, the chemical processing of oil has led to the development of the infrastructure and technologies we use most today. Therefore, it is understandable that many researchers and practitioners are asking what the world will look like without these finite resources and what needs to be conducted to ensure that people continue to improve their quality of life and make further technological progress. Global population growth is another reason the world's resources must be well managed and better targeted.

In terms of innovation, it is a challenge for energy and resource specialists to identify sustainable energy sources and techno-economically optimal technologies for accessing, transforming, and storing these forms of energy [1].

In the same context, the negative effects of greenhouse gases on the environment are a factor that supports the idea of a gradual transition to clean energy sources. Carbon emissions from burning fossil fuels [2,3] are causing global warming and extreme and increasingly common climate change, affecting all of nature. Hydrogen can be a clean source, and blending it with natural gas can be the transition to this type of energy. Based on these considerations, a graphical abstract of the unfolding of this review will be presented in Figure 1, taking into account the importance of this sensitive topic in the energy economy.

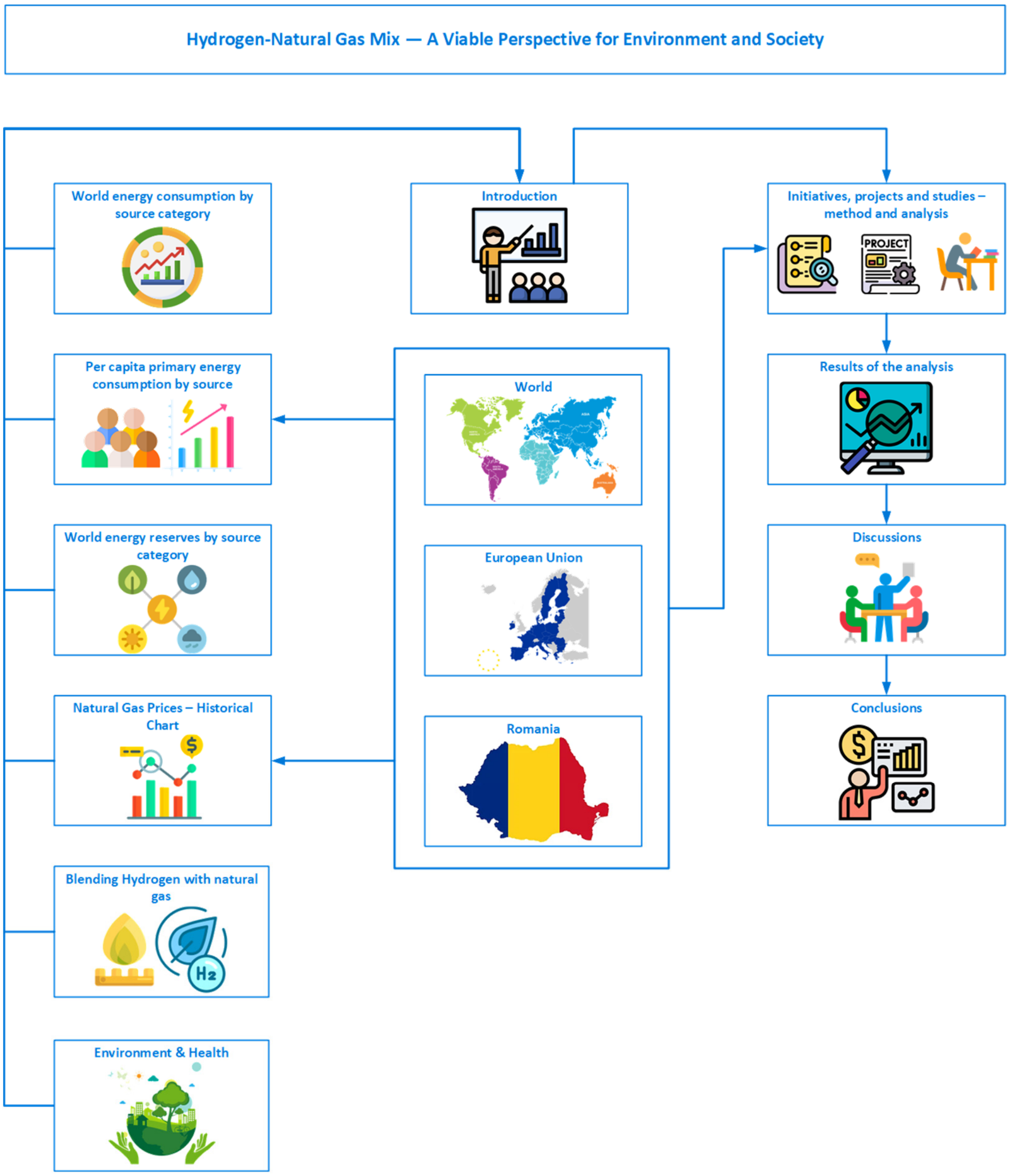


Figure 1. Graphical abstract (Source: Authors based on the content of this review).

However, statistics show that this transition is not easy to achieve, as the consumption of fossil resources is rising steadily alongside renewables [4,5]. Figure 2 shows the total world energy consumption by source category between 1971 and 2021.

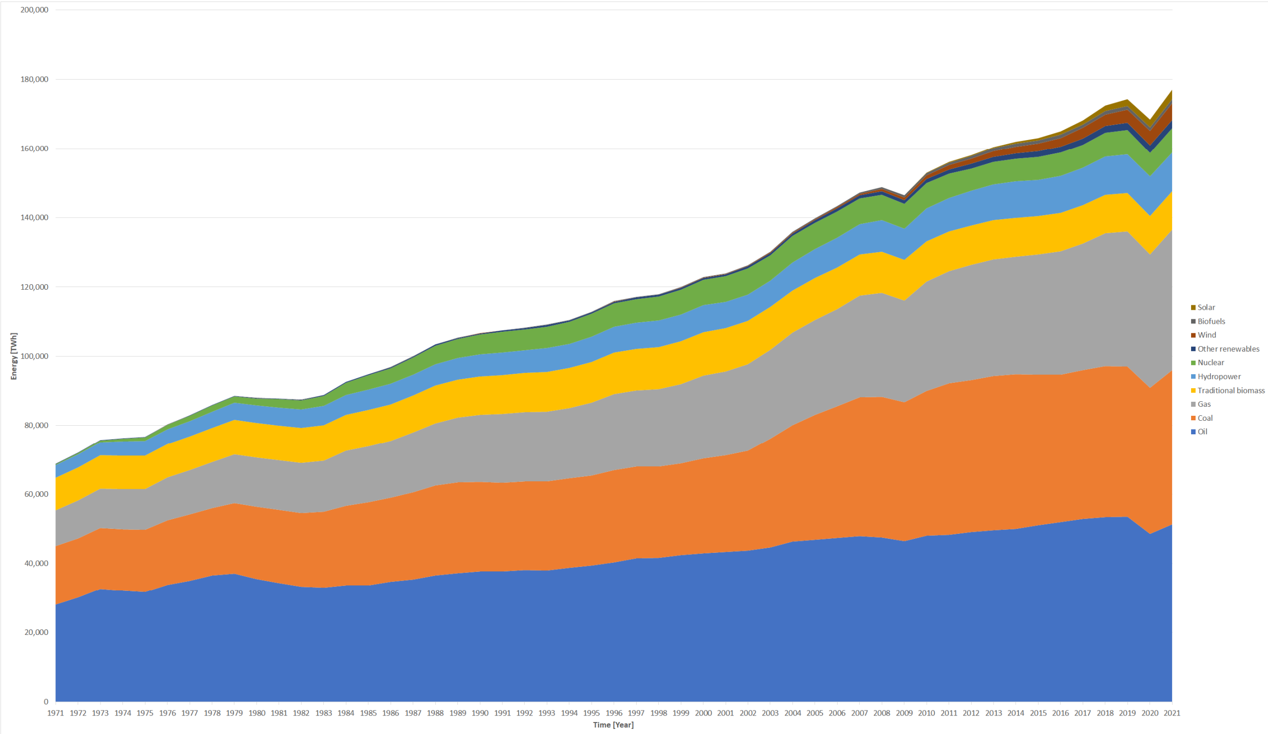
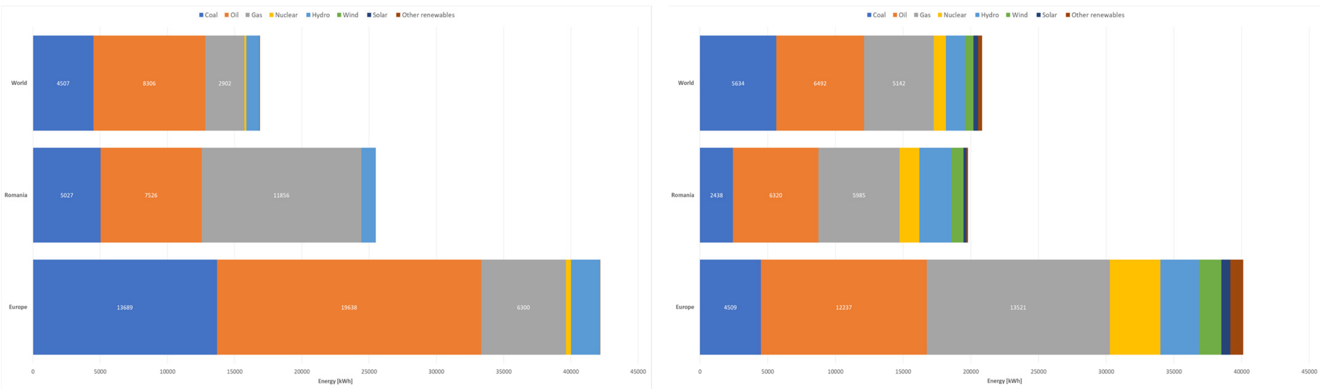


Figure 2. Total world energy consumption by source category between 1971 and 2021 (Source data adapted from reference https://ourworldindata.org/grapher/global-energy-substitution, accessed on 14 January 2023).

Figure 3 shows comparative primary energy consumption per capita in the world, Europe, and Romania by source for 1973 and 2021.



(**a**) (**b**)

Figure 3. Per capita primary energy consumption by source (world, Europe, and Romania): (**a**) 1973; (**b**) 2021. (Source data adapted from reference https://ourworldindata.org/grapher/global-energy-substitution, accessed on 14 January 2023).

By analysing the statistical data, the subsequent conclusions can be drawn. Overall, global, European, and national energy consumption has increased as mankind has progressed. Although renewable energy sources are increasingly used, they cannot meet the need. At the same time, the greatest attention is being paid to natural gas, whose share of consumption has almost reached that of coal and oil [4,5].

As is already known, oil resources are limited, and predictions have been made over time about the quantities of hydrocarbons available. Estimates can never be close to the truth as long as prolific new discoveries continue to be made.

Although the price of oil is volatile, with extreme variations due to political–strategic factors, the general trend is for the price to rise steadily as oil resources become harder and more expensive to access and reserves remain depleted. As evidenced in everyday life, the cost of services and products is reflected in the cost of oil, which is why alternative energy sources are important in order to gradually compensate and restore the balance [6].

In opposition, many energy specialists believe that the limits of oil reserves are irrelevant, as the oil price continues to rise and demand will disappear before the fields are exhausted—"a mineral industry runs out of customers before it runs out of minerals" [7].

The distribution of proven world reserves of crude oil, natural gas, and coal and crude oil consumption is shown in Figure 4. There is an uneven distribution of reserves and consumption; the data shows that in regions such as North America, Europe, and Asia-Pacific, consumption exceeds production capacity due to strong social development and industrialisation, particularly in Asia-Pacific countries.

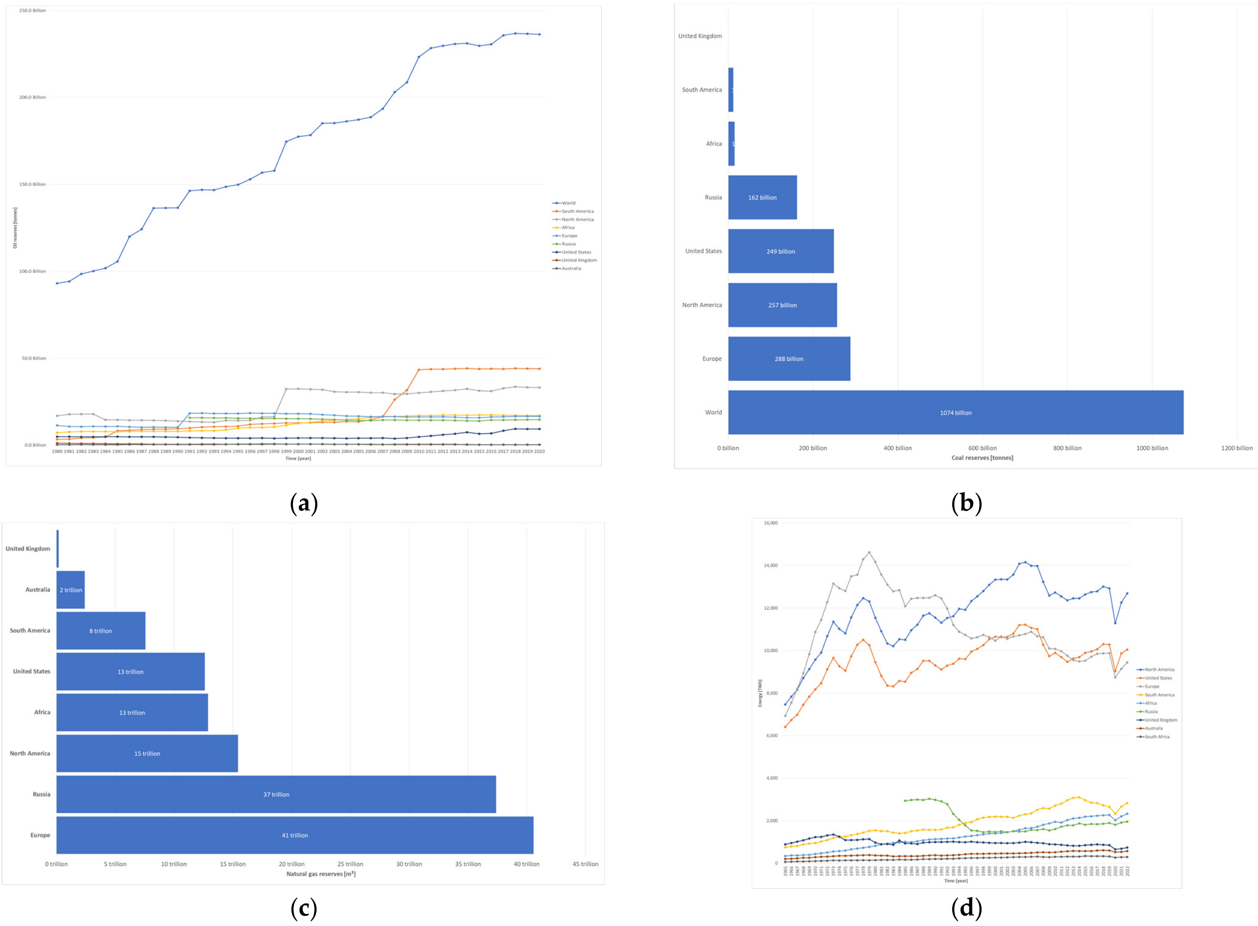


Figure 4. Total world energy reserves by source category between 1980/1965 and 2020/2021: (**a**) Oil reserves (Source data adapted from reference https://ourworldindata.org/grapher/oil-proved-reserves, accessed on 14 January 2023); (**b**) Coal reserves (Source data adapted from reference https://ourworldindata.org/grapher/coal-proved-reserves, accessed on 14 January 2023); (**c**) Natural gas reserves (Source data adapted from reference https://ourworldindata.org/grapher/natural-gas-proved-reserves, accessed on 14 January 2023); (**d**) Oil consumption (Source data adapted from reference https://ourworldindata.org/grapher/oil-consumption-by-country, accessed on 14 January 2023).

While reserves are still promising, and drilling and extraction technology is constantly developing, providing humankind with oil and gas for a long time, it is crucial to be proactive when exloiting unconventional resources. People need to be proactive in looking for and developing cost-effective alternatives to fossil fuels, which will gradually take on the role of substitutes.

In support of the above, in 2019, the oil and gas industry generated over 40% of global greenhouse gas emissions, directly or indirectly. Therefore, oil and natural gas are major contributors to climate change. Electricity generation, heat production, and energy transport are directly responsible for climate change [8]. Oil extraction and refining processes are part of the same category of pollutants that generate greenhouse gases.

Regarding the use of fossil fuels, there is a shift towards natural gas, partly because using natural gas to produce various forms of energy results in the lowest carbon emissions [9].

Strategies for decarbonisation are very ambitious, but as expected, the transition to renewable energy sources will be gradual [10], with oil and especially natural gas backing this trend [9,11]. This has given rise to the term "alternative energy sources," with conventional fossil-based energy sources now serving as the main global energy sources. The 19th century was a turning point in the use of energy sources. The same trend is still evident today in the trend to replace oil with alternative energy sources.

Decarbonisation is the most important task in Europe's climate neutrality strategy. Efforts by member states to reduce carbon intensity, i.e., decrease the gas emission quantity and concentration from burning fossil fuels, are reflected in various initiatives and plans. Moreover, there is an increasingly active use of renewable energy sources, which now produce a third of all energy capacity worldwide.

Thus, more and more countries show growing interest in renewable energy sources that can gradually replace energy produced by fossil fuels, especially coal and oil, which are the least environmentally friendly after combustion [7]. Therefore, in different parts of the world, such as the European Union and Japan, different strategies have been adopted with regard to this transition, with an emphasis on the term "decarbonisation." The aim is to have net-zero emissions from burning coal, oil products, and natural gas.

Increasing electricity production from renewable sources and accelerating the transition to clean energy can be exemplified by using natural gas–hydrogen mixtures [12]. Additionally, increasing the efficiency of the methods used to obtain and conserve different types of energy will prompt expectations, such as reducing the use of fossil fuels and energy market prices [13]. The most economically feasible method to transport substantial volumes of hydrogen is in a compressed state through a pipeline [14].

Given the current conflict in the region, the EU has launched RepowerEU, a new programme highlighting the need to act to ensure a just transition to affordable, secure, and sustainable energy sources.

RepowerEU is a research project based on the new generation of low-cost and highly efficient power-yielding systems based on hydrogen and other renewable energy sources [15]. The project is a collaboration between several universities, research institutes, and industry partners across Europe and is funded by the European Union's Horizon 2020 research program. The project will focus on the design, development, and testing of advanced power generation systems that can utilise hydrogen and other renewable energy sources, such as solar and wind power, to produce electricity, heat, and hydrogen for transportation and other uses. The new energy system faces issues with the voltage and frequency of the electrical network and with frequent power curtailments, especially in wind parks [16]. The ultimate goal of the project is to demonstrate the technical and economic feasibility of these advanced power generation systems and to support the transition to a low-carbon energy system in Europe [17]. The growing use and flexibility options for diverse types of energy sectors should be analysed [18].

Urgent actions in terms of reducing inflationary tendencies, storing gas to ensure consumption during cold periods, and taking immediate measures to reduce dependence on Russian gas imports are part of this new energy trend. These critical actions include accelerating efforts to access renewable energy sources by financing projects to increase solar panel areas and windmill farms, using heat pumps, and saving energy.

Over time, the price of natural gas has fluctuated significantly due to the growth in global energy consumption, the volatile nature of the price of crude oil [19], the development of extraction technologies, economic conflicts between countries, etc. Figure 5 shows the evolution of natural gas prices on the Henry Hub market from 1995 to the present. It can be seen that the price increases considerably with demand. From the late 2000s on, as can be seen very easily, the price started to decrease gradually until 2020 with the onset of the pandemic. Then it increased with the start of Russia's special operation in Ukraine. These trends underline the effect of critical situations, i.e., that any events such as pandemics or belligerent actions are very important influencing factors that strongly sensitise the evolution of the gas market [20–22].

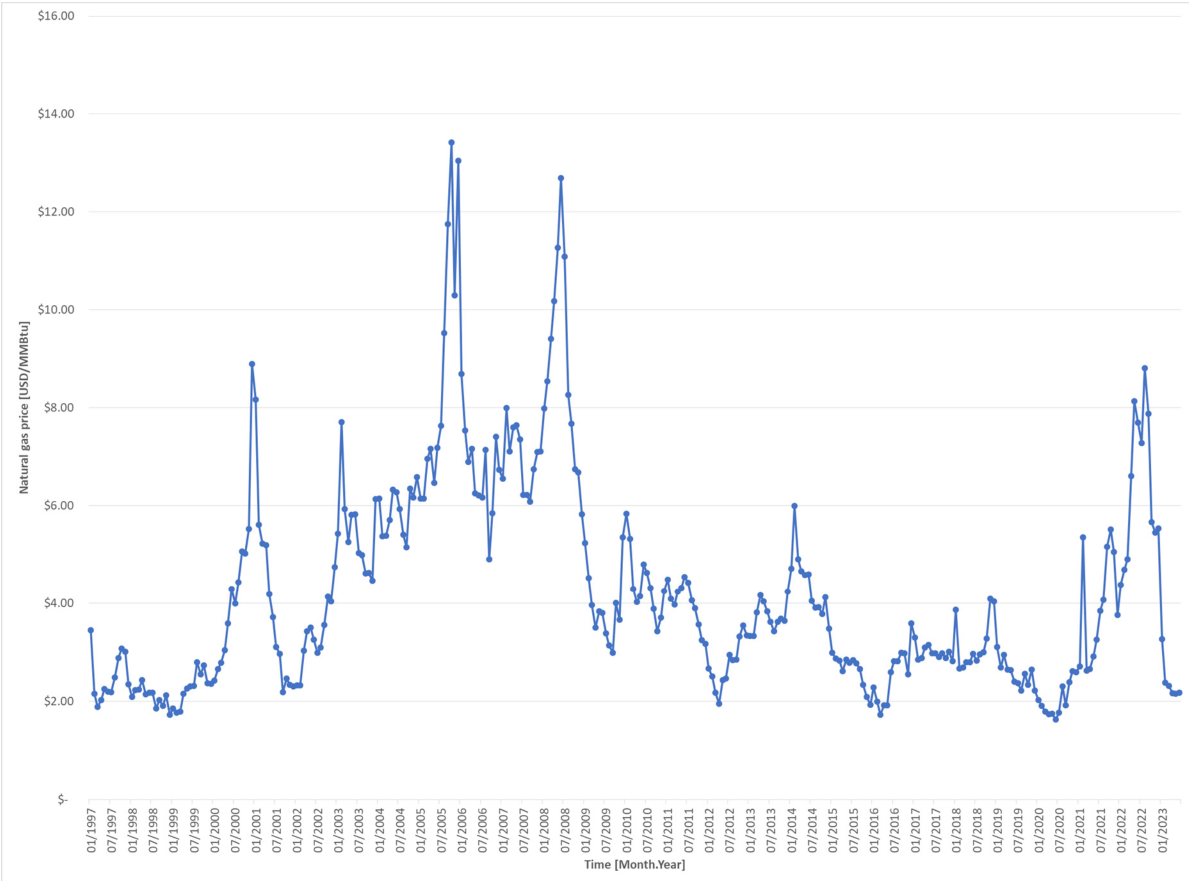


Figure 5. World Natural Gas Prices—Historical Chart (Source data adapted from reference U.S. Energy Information Administration, https://www.eia.gov/about/copyrights_reuse.php, accessed on 14 January 2023).

Phasing out COVID-19 pandemic restrictions has meant a resumption of economic activity globally, leading to accelerated demand for natural gas from economic consumers. On top of this, the context created by the prolonged winter of 2020–2021 has been superimposed in Europe, leading to the depletion of natural gas deposits. Last autumn, most European countries, including Romania, had low natural gas stocks. In order to reduce carbon dioxide emissions quickly and efficiently, the EU increased the price of carbon dioxide emission allowances, which doubled in 2021 compared to 2020, as part of its main strategy [23]. The immediate effect has been an increase in raw material prices, which are then passed on to final consumers in their bills.

In Romania, the market suffered at the end of 2021 partly because of insufficient gas reserves, considering the lower local production in 2020. According to Gazprom data, Romania's imports in 2021 will be more than 300% higher than in 2020, when the purchase price on the Russian market increased [23].

The situation is similar in Europe (Figure 6) and Asia, at least taking recent years into account. However, the social disputes between Russia and Ukraine have further accentuated gas prices in Europe and Asia, with the United States remaining energy independent in terms of natural gas.

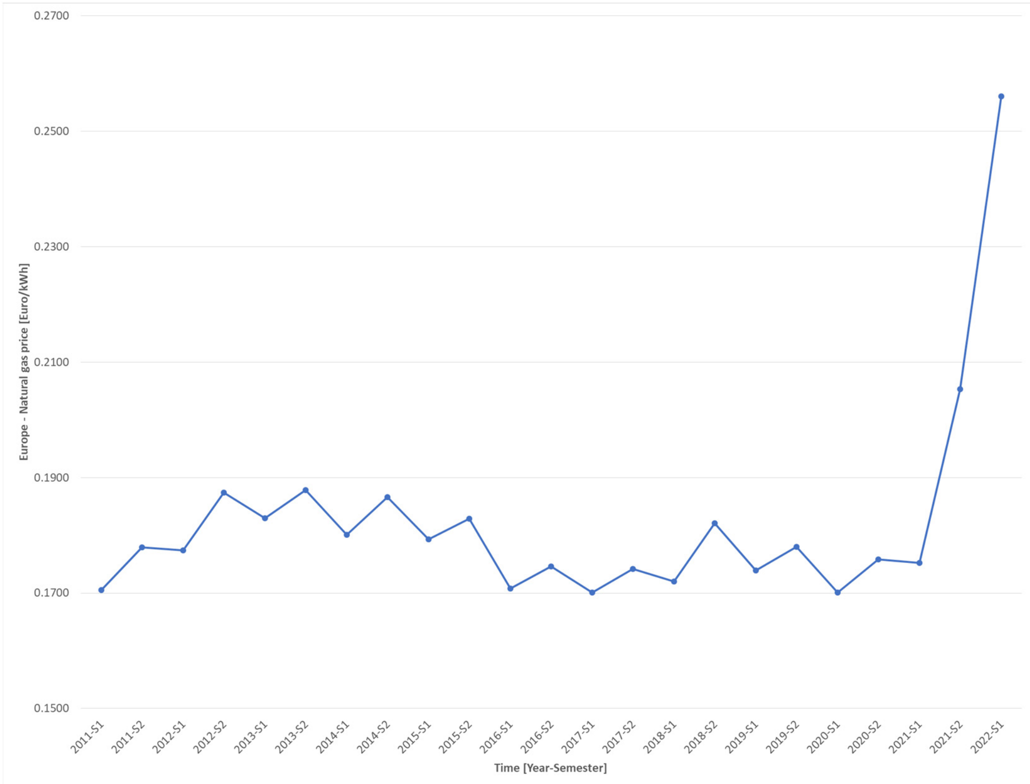


Figure 6. Europe Natural Gas Prices—Historical Chart (Source data adapted from reference EUROSTAT, https://ec.europa.eu/eurostat/databrowser/view/NRG_PC_202/default/table?lang=en and https://ec.europa.eu/eurostat/databrowser/view/NRG_PC_204/default/table?lang=en, accessed on 14 January 2023).

In Romania, both low consumption due to hot weather (and reduced industrial capacity operations) and the filling up of storage (well over 90%) have pushed the spot price of gas on the Romanian commodity market below the 40 euro per MWh record value of the last 15 months. Comparing two similar periods in 2022 and 2021 in terms of natural gas consumption, in 2021, a value of 220,000 MWh per day was recorded, while in 2021, the consumption was 270,000 MWh per day. On 1 November 2021, the underground gas reserve recorded by the operators Depogaz and Depomures was 2.963 bcm of gas consumption. Mc compared to 2019, when it was 2.966 bcm. On 2 November, the average energy price on the day-ahead market operated by OPCOM was 38.9 euros/MWh, while the intraday price fell to 35.6 euros/MWh. The situation has a high degree of similarity with other areas in Europe but with lower prices than in Romania: CEGH—the famous Austrian gas hub—had a spot price of 35.6 €/MWh (Figure 7).

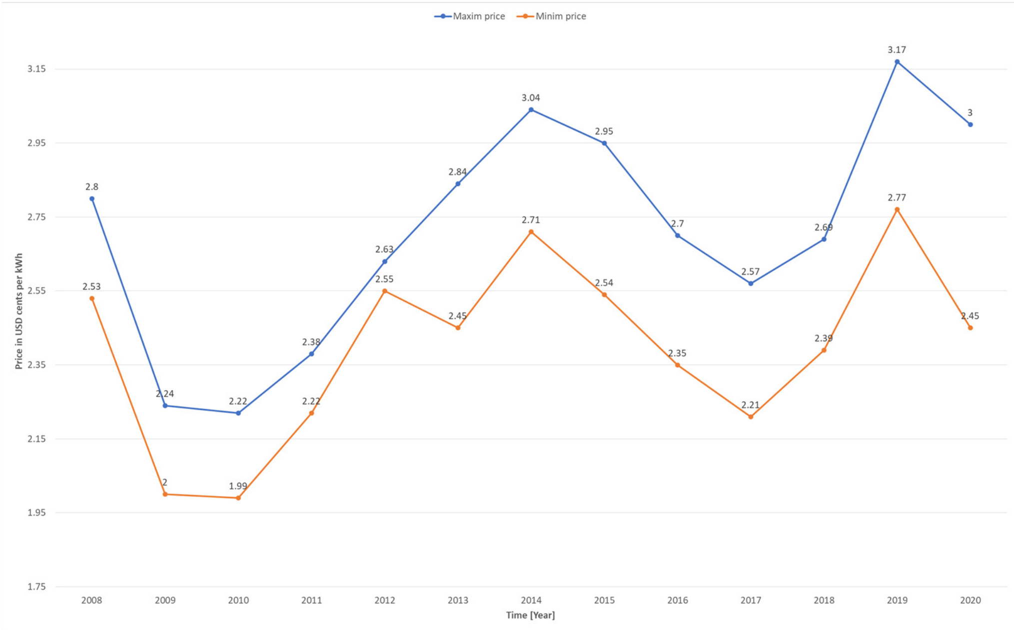


Figure 7. Romania Natural Gas Spot Prices—Historical Chart (Source data adapted from reference Statista, https://www.statista.com/statistics/595756/natural-gas-average-price-romania/, accessed on 14 January 2023).

Spot prices reached their lowest level on 9 August 2021, i.e., EUR 32/MWh. The same year saw a significant increase at the end of September to more than €180/MWh (5 times higher).

The evolution of natural gas prices at international, European, and national levels, the decarbonisation of natural gas combustion in final consumers, and the management of natural resources in general and of natural gas in particular are some of the reasons for the transition from natural gas to hydrogen and the introduction of their mix even in transmission and distribution systems (T&Dsys, Fort Worth, TX, USA).

Why use natural gas hydrogen energy mix?

Hydrogen combustion can decarbonise household energy sources for heating, domestic hot water, and cooking while removing certain technical and safety issues [24]. The use of the current natural gas transmission, distribution, and supply system to transport hydrogen or energy mixes between hydrogen and natural gas is a technological option that requires the intervention of central state authorities, parliament, government, and other energy regulators (NERA, SICBPVLI, etc.).

The first actions materialised by scale development demonstration projects for the new trend using hydrogen as an energy source are clearly starting points for further commercial deployment. This new technological method can be implemented in two ways: (a) through new projects when 100% hydrogen transport, distribution, and supply systems are being designed and built for certain categories of users; and (b) through existing projects when hydrogen is to be injected into existing transport and distribution networks. In this case, hydrogen energy mixed with natural gas is to be used up to a certain permitted limit [25–27]. Regardless of the technical solutions chosen, the legal framework for regulating and marketing gas will have to be amended and adapted to include hydrogen in the new energy concept [28]. It must be understood that even in the transitional phase [29,30], hydrogen and natural gas cannot be treated separately in a sustainable energy mix context, whether we are talking about transport, distribution, supply, trading, or end-users [31,32].

One proposed way of delivering hydrogen to end-users is to mix hydrogen in natural gas pipeline networks, while new technologies can be used for separation [33–35]. The use of hydrogen blending on a current gas grid is seen as an efficient way to rapidly accelerate the supply of hydrogen while reducing the need for pipelines and investments by end users [36–38]. Hydrogen delivery by blending into natural gas pipeline networks can offset the costs of building dedicated hydrogen pipelines or other costly delivery infrastructure in the early market development stage [39–42]. As a rebranding, until the 20th century and for a good period thereafter, hydrogen-rich gases (50 vol%), such as city street lighting gas or coke oven gas, were delivered to households in Germany, the US, and England via gas pipelines. The infrastructure elements installed at that time, such as pipelines, gas installations, gas fittings, burners, etc., were designed for hydrogen-rich gas and were later modified with the switch to natural gas [43–45].

Many countries are now looking to add hydrogen to existing natural gas networks, although there are currently no standards or relevant experience in this area [46,47]. However, for scientific and technical reasons, it is considered possible to introduce between 2 vol% and 20 vol% hydrogen without any significant or negative impact on end-users, infrastructure, or pipelines. Several pilot projects, technical studies, and pre-normative approaches have been launched. For the same reasons, it is considered that higher additions of hydrogen would, in some cases, require costly conversions of pipelines, connections, sensors, and equipment [48–52]. This limit has been preliminarily fixed at 10% vol. in countries like Germany. In principle, gas concentrations up to 10% vol. hydrogen can be transported through the existing natural gas grid without any risk of damage to energy production facilities, infrastructure [53–55], distribution, etc. However, due to certain elements still being considered critical and generally unsuitable for use with such concentrations of hydrogen in terms of risks, the limit value currently authorised is also limited to 2 vol%, especially for CNG vehicles.

INiG—PIB determined the maximum hydrogen levels that can be safely added to natural gas (between 8% for explosion safety of devices operating in Ex-zones and 36% for gas from LNG regasification) [56,57], and in [58], there are other recommendations proposed. There are still a lot of things to analyse regarding the odorizing mixtures of natural gas with hydrogen without diminishing the safety of end users [59–61].

It can be assumed that many transmission networks, distribution lines, and gas storage facilities can be converted to pure hydrogen networks [62]. In Leeds (UK), for example, the possibility of converting the entire existing natural gas network in the region (mainly used to supply the municipality with heat) to a hydrogen network [63] has been explored. Given the existing infrastructure, especially the length of large gas networks, many countries are tempted to convert a gas network to a hydrogen network at minimal cost rather than build a completely new one. In Japan, an analysis of CO_2 emissions from the entire hydrogen supply chain was performed to anticipate the environmental advantage [64].

Adding hydrogen to gas networks can bring the following benefits:

- General: if hydrogen is produced from renewable sources, it will reduce greenhouse gas emissions [45].
- Potential: in automotive applications, from reduced oil consumption and imports, along with improved air quality through reduced sulphur dioxide, nitrogen oxides, and particulate emissions.
- For the environment: when a mixture of hydrogen and natural gas is used in existing equipment for heat production, cooking, or cogeneration, the environmental impact of natural gas combustion is reduced. Without the need to make significant changes in end-user equipment, such benefits are similar to increasing the renewable energy mix [65].

Burning the natural gas (methane gas) energy mix with hydrogen has the following disadvantages:

- Hydrogen, like methane, is not poisonous (but it can cause asphyxiation and is explosive!);
- Hydrogen's spontaneous ignition temperature is quite high, so it only needs a spark to ignite;
- Flammability limits are very high, which means it is easy to maintain a flame [66,67];

- Stabilises the flame because the flame-burning speed is much higher (300 cm/s) than for methane (30 cm/s) [68–71].

The crisis that member states of the European Union are facing stems from restrictions on a number of resources essential to meeting the decarbonisation targets. Therefore, the crisis experienced by the EU member states must send out a strong alarm signal about the unwillingness to accept innovative technologies and find sustainable alternatives to replace conventional resources in order to solve the current situation and prevent future crises.

Hydrogen plays an important role in the energy security mix among the innovative technologies mentioned in the previous paragraph because energy problems cannot be solved using only the sun and wind as resources. The crisis in energy production revealed that these sources may not be sufficient, even if they are necessary, and can only be a part of a secured energy mix.

The energy transition in Romania has been slow so far, although it is well under way in many European countries. A higher level of acceptance by both institutions and civil society of new technologies is needed if this country is to reach its energy security goals. In that case, hydrogen as well as some alternative energy sources such as wind or solar power, along with any of the new technologies like SMRs, would come into play.

At EU level, discussions have already been held on a hydrogen bank. The situation has moved at a rapid pace across Europe, with no significant changes taking place in Romania. The national debate on introducing a legislative framework for hydrogen inclusion has been reopened, and the strategy is expected to be finalised in late 2023.

The industry in Romania needs to redeploy hydrogen as a vector of energy and assimilate significant quantities of hydrogen produced without CO_2 emissions. Compared with the rest of the countries that have already put hydrogen strategies in place for several years, we have yet to spend any money from the estimated millions of euros on green hydrogen. From small demonstration projects in research to real industry, national projects already support the transition from the theory to the practice of hydrogen.

The bibliometric analysis was used to analyse the most relevant concepts in the field of this review, with the academic platform Web of Science providing the scientific articles that analyse the materials specific to the projects in the field of hydrogen introduction in the transport and distribution networks of natural bases. Therefore, the content of 500 highly cited articles related to this topic on the Web of Science platform was explored in order to highlight the structure of the scientific field using content analysis. This analysis focused on examining the most common words (hydrogen, environmental impact, social health, renewable energies, greenhouse emissions) and the connections between these words [72]. The pragmatic analysis shown in Figure 8 lists the most frequent words in the complete content of selected articles. However, it does not use any keywords, including "clean energy," "hydrogen and natural gas mix," "health," "social impact," and "emission."

Therefore, the use of the mix of hydrogen and natural gas is based on the transition to new hydrogen production technologies [73], storage, transport, and distribution of the mix. Sustainability in this sensitive area of energy is related to "technology," "environment," "innovation," "research," "change," and "economic growth" (Figure 8). Full protection of the climate and nature needs to be guaranteed, but this will require a sustainable way of life. Sustainability in terms of a clean energy transition reflects the future.

Hydrogen is a promising alternative energy source that can be used to power vehicles, heat buildings, and generate electricity. In view of the fact that it can be produced from a variety of sources, including water and biomass, it is considered a renewable energy source. Hydrogen's ability to generate no greenhouse gas emissions when burned as a fuel is one of its major advantages [74]. This makes it a potential solution for reducing carbon emissions and slowing climate change. However, hydrogen production can have environmental impacts, particularly if it is produced from fossil fuels like natural gas. Additionally, hydrogen fuel infrastructure is still being developed, which can make it difficult to access and use in some areas.

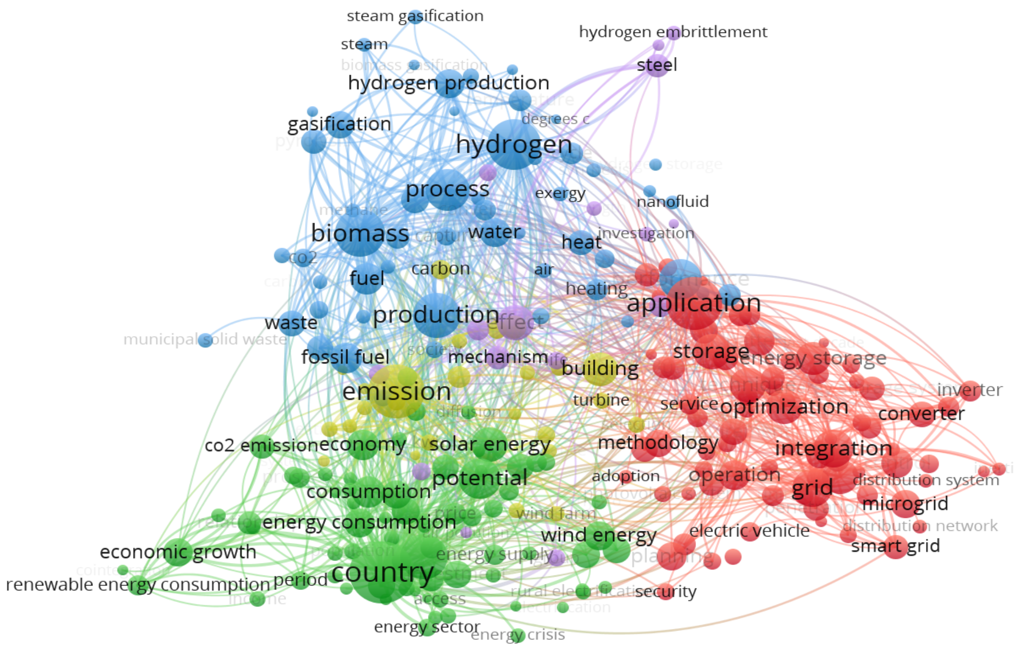


Figure 8. Word network in renewable energy transition scientific publications' content (Source: authors based on articles analysed).

In spite of these challenges, hydrogen has the potential to play an important role in moving towards a low-carbon economy, according to numerous experts. Research and development into hydrogen production and use are ongoing, and new technologies and methods are being developed to make it more efficient and cost-effective.

Overall, hydrogen could be an energy source with a clean and renewable nature that can help reduce greenhouse gas emissions and improve social health [75–77]. To ensure the future viability of hydrogen, it is important to keep investing in R&D [78,79].

2. Method

The method used in this review is materialised by studying the main initiatives and studies in the literature on this issue, presenting the most important studies and projects at international, European, and Romanian levels, and then structuring them by areas of interest (see Figure 9), namely the transport and supply of natural gas in a technological mixture with hydrogen in order to achieve the goal of "clean energy."

Mixing hydrogen and natural gas can have several benefits, such as increasing energy efficiency and reducing emissions from combustion engines and power plants.

Some gas properties suffer modification due to the addition of hydrogen to natural gas, which directly impacts utilisation. These properties include the Wobbe Index, Net Calorific Value (NCV), Gross Calorific Value (GCV), density, thermal efficiency, and flame propagation [80,81]. The impact is different depending on the parameter and the type of gas utilisation. The influence of hydrogen concentrations is quite significant for density and GCV and small for the Wobbe Index. The Wobbe Index has a bigger influence on housing utilisation, whereas, for industrial processes, it is used in the composition of non-combustion applications [82–84]. The effect of injecting hydrogen into gas grids [85] using a large number of gas network models has been analysed in a presentation on the deployment of hydrogen into natural gas distribution networks [86–88]. The mathematical models for hydrogen–natural gas mix in gas transport and distribution systems need to take into account a lot of factors, such as pressure, hydrogen rate, gas flow rate, distance, ambient temperature, pipeline geometry, etc. [89–91].

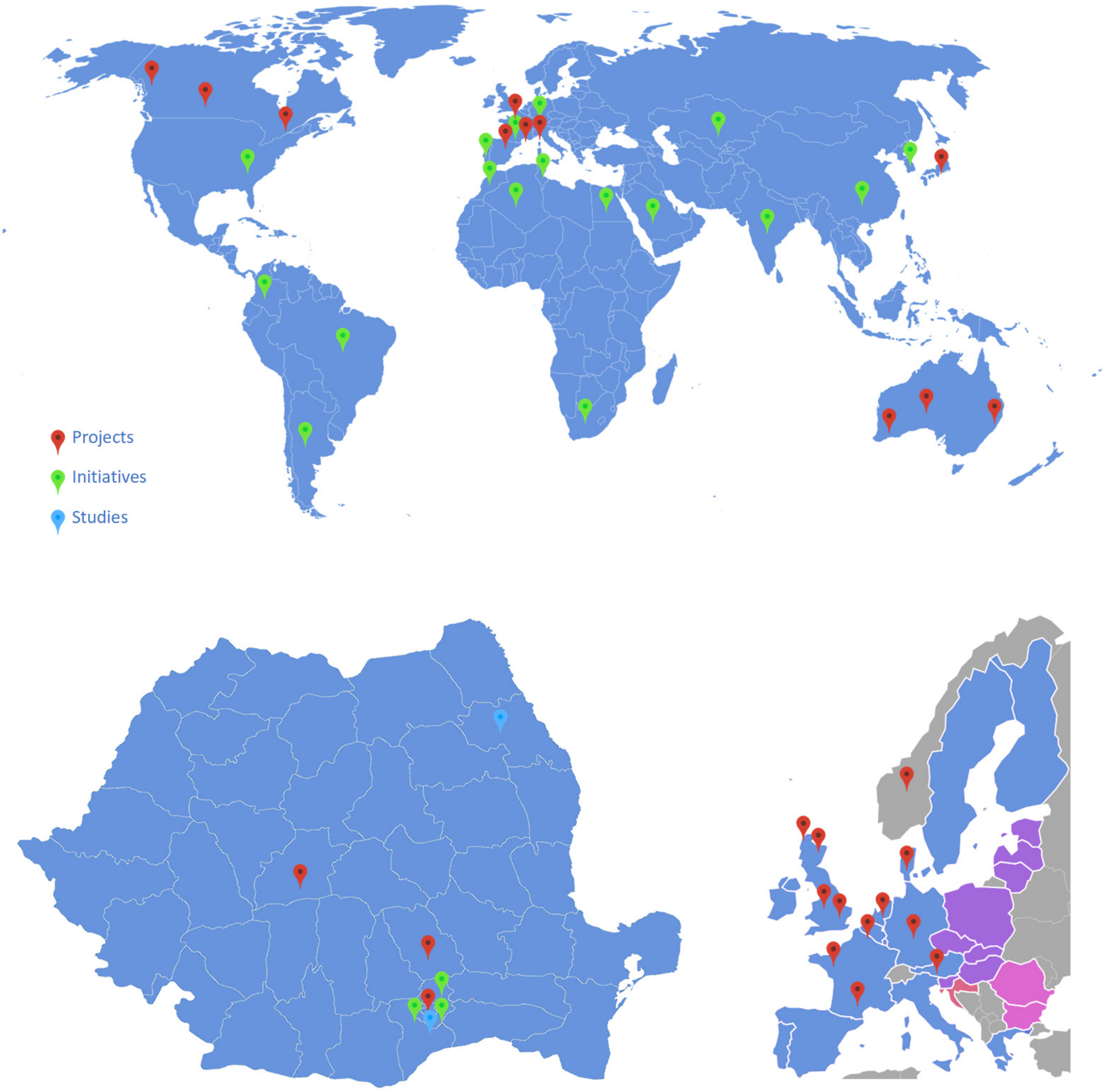


Figure 9. Projects at international, European, and Romanian levels—geographical distribution of hydrogen projects. (Source: Authors based on the method used).

As hydrogen is the lightest element and a good energy carrier, it can be used to enhance the combustion of natural gas, leading to higher combustion efficiency and lower emissions of carbon dioxide and other pollutants. Additionally, blending hydrogen into natural gas pipelines can also help increase the utilisation of existing natural gas infrastructure for the transportation and storage of hydrogen. However, there are also potential challenges to be addressed. These include the need for new materials and technologies to handle the high reactivity and corrosiveness of hydrogen and the cost and safety issues associated with hydrogen production, transport, and storage.

Mixing hydrogen and natural gas in a network of pipelines and storage facilities can be a way to increase the use of hydrogen as a clean energy source. Hydrogen is a versatile fuel used for transportation, heating, and power generation, but it is not currently extensively used because it is difficult to transport and store. Mixing hydrogen with natural gas allows the hydrogen to be transported and stored more easily, and it can also be used to supplement natural gas in existing infrastructure [90,92]. However, it should be noted that there are safety concerns associated with mixing hydrogen and natural gas, as hydrogen is highly flammable [93].

Global Hydrogen Industry

The global hydrogen industry is a rapidly growing sector involving the production, distribution, and use of hydrogen as an energy source. Hydrogen can be used for a variety of purposes, including transportation, power generation, and industrial processes. The industry is still in its early stages but is expected to grow significantly in the coming years as more countries invest in hydrogen infrastructure and technology. Some of the key challenges facing the industry include the high cost of hydrogen production and the lack of a comprehensive infrastructure for hydrogen storage, transportation, and distribution. Economic calculations showed that if the market share of hydrogen increased to 10%, building these systems would be economically feasible [94]. Despite these challenges, many experts believe that hydrogen has the potential to play a major role in the global transition to a low-carbon economy.

There are several global hydrogen industry projects currently in development or operation. These include:

- Hydrogen Council's global hydrogen production and distribution project. Also, the Hydrogen Council is a global CEO-led initiative to accelerate the development of the hydrogen economy.

The Hydrogen Council is an initiative for hydrogen to foster the clean energy transition and reach decarbonisation goals through diversifying energy sources worldwide. The Hydrogen Council is promoting collaboration with governments, industry, and investors while guiding how to accelerate the deployment of hydrogen solutions worldwide, given that hydrogen plays a crucial role in achieving our decarbonisation goals [95].

The main objectives are: increasing visibility and recognition that hydrogen is a critical tool for energy system decarbonisation; identifying the places where hydrogen solutions bring value through decarbonisation, energy security, resilience, and sustainability; and consulting for the business community, policymakers, and international agencies. In order to achieve these objectives, the Hydrogen Council coordinates and funds hydrogen studies to support the hydrogen industry's further development, using key regional partners in America, Europe, and Asia for strong, global action. The Council also works with the global investment community to explain the essential role of hydrogen in an energy transition [95].

- The HyP Murray Valley project is a large-scale renewable energy project aiming to produce and store green hydrogen from solar energy in the Murray Valley region of Australia [96].

The project is being developed by the Australian energy company Neoen. It is expected to have a capacity of up to 500 MW of solar power and up to 50,000 kg of hydrogen production per day and will involve the installation of large-scale solar panels that will generate electricity to power electrolysers that split water into hydrogen and oxygen. The hydrogen produced will be stored and transported via existing gas pipelines to markets where it can be used as a clean energy source for a range of applications, including industrial processes, transport, and power generation.

Due to the potential for hydrogen produced by renewable energy sources to substitute fossil fuels in a wide range of sectors, the Murray Valley HyP project is seen as contributing significantly towards Australia's decarbonisation. It is also expected to create jobs and stimulate economic development in the Murray Valley region.

The Jemena West Sydney project involves the construction of a new gas pipeline in western Sydney, Australia [97].

The pipeline will run from the existing gas network at Eastern Creek to the new gas network at Hassall Grove, connecting up to 33,000 homes and businesses to natural gas.

The project also includes constructing a new gas gate station at Horsley Park to regulate the gas supply. The pipeline is expected to increase the reliability of the gas supply and bring economic benefits to the local community.

- The Fort Saskatchewan Hydrogen Project is a joint initiative between Air Products Canada Ltd., a leading hydrogen producer and distributor, and the Government of Alberta, with support from the City of Fort Saskatchewan [98,99].

The project aims to build a new hydrogen production facility in Fort Saskatchewan that will use innovative technology to produce low-carbon hydrogen from natural gas, with carbon dioxide (CO_2) captured and stored underground. For a variety of uses, such as transport or industrial processes, the hydrogen generated will be used as fuel. This project will reduce up to one million tonnes of GHG emissions annually, creating new jobs in the region. The Fort Saskatchewan Hydrogen Project is part of Alberta's broader strategy to expand its economy and bring down its carbon footprint.

The Cummins-Enbridge Hydrogen Project is a joint venture between Cummins Inc. and Enbridge Inc. to develop a hydrogen production facility in Canada [99,100].

The goal of this project is to produce green hydrogen using renewable energy sources such as wind and solar and to supply the hydrogen to customers in a variety of industries, including the transportation and industrial sectors. The proposed production facility will be located in Edmonton, Alberta, and will have a capacity of 10 megawatts, producing up to 1000 kg of hydrogen per day. It is hoped that this project will play a major role in reducing greenhouse gas emissions and supporting the transition to a low-carbon economy.

- European Union's Hydrogen Backbone Infrastructure Project.

The aim of the ″European Hydrogen Backbone″ project is to provide an opportunity for a large-scale competitive hydrogen pathway for the European market by adapting equipment and using new, appropriate technologies to minimise the risks associated with hydrogen exploitation [101,102]. It is a network of pipelines and facilities for producing, transporting, and storing hydrogen that uses green hydrogen from offshore wind energy in The Netherlands and has the potential for European expansion. The network will supply industrial consumers in German industrial areas [103]. The project comprises three development phases. By 2030, the aim is to connect major industrial clusters via a 6800 km infrastructure in order to extend the grid to cover significant areas of western Europe by 2035 [101]. A preliminary analysis has identified 11 corridors in the NTS that can be included in the future European hydrogen transport system (see Figure 10). The proposed corridors provide interconnection with all the neighbouring countries of Romania, namely Hungary, Serbia, Bulgaria, Ukraine, and the Republic of Moldova, and also provide access to existing natural gas storage facilities.

- Hydrogen Europe initiative is a collaboration between European Union countries to promote hydrogen as a clean energy source and develop a hydrogen economy.

More than 400 member states in the European Hydrogen Association represent the hydrogen industry and its interested parties, as well as 25 EU regions and 30 national associations. Hydrogen Europe's mission is to accelerate the European hydrogen industry by bringing together national hydrogen associations, regional public authorities, industry players, enterprises, and non-governmental organisations [104]. In order to achieve net zero economic growth, the Association also supports international policies and initiatives aimed at helping develop hydrogen technologies and coordinate research, development, and innovation of clean hydrogen technologies.

- Hydrogen Mobility Europe project (H2ME) aims to deploy hydrogen-powered fuel cell electric vehicles and refuelling infrastructure in several European countries.

The project was the flagship for fuel cell electric vehicle drivers' access to hydrogen refuelling stations. Their first project, which started in 2015 and finished in 2020, culminated in an increase in the number of fuel cell electric vehicles and started creating a hydrogen fuelling station network spread across many countries. Over 300 vehicles and 29 new refuelling stations were built during the project. A second project, which has been running since 2016, was launched to verify the technical and business readiness of vehicles, fuelling stations, and hydrogen production techniques with a view to developing recommendations on possible shortcomings that may compromise the full introduction of this technology [105]. After this project, many European countries focused on projects for HRS [106,107]. For example, the north of Spain will be linked with the south of France through the H2PiyR project [108].

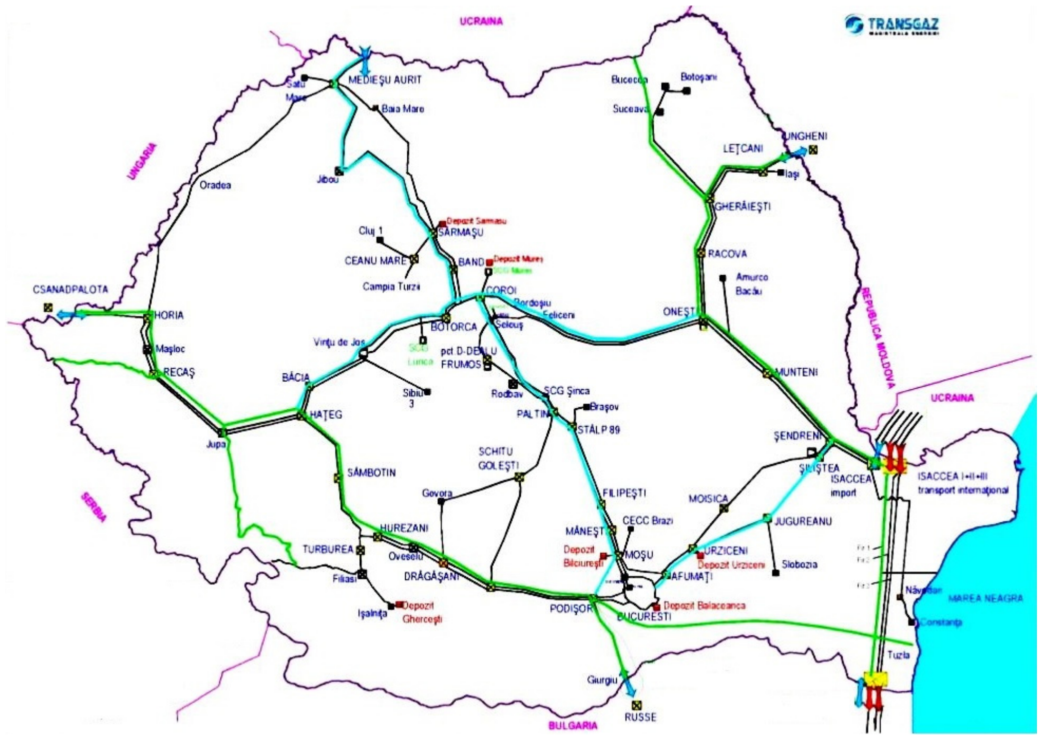


Figure 10. Eleven corridors in the Romanian NTS for hydrogen transport system (Source: https://financialintelligence.ro/transgaz-vrea-sa-integreze-hidrogenul-din-surse-regenerabile-si-cu-emisii-scazute-de-carbon-in-sistemul-de-transport/ accessed on 11 January 2023).

- HyFLEET: CUTE project in Europe aims to validate the viability of hydrogen fuel cell buses in urban transport systems.

FlixMobility, the leading tech-mobility company, Freudenberg Fuel Cell e-Power Systems, and ZF Friedrichshafen AG just received official confirmation from the German Federal Ministry of Transport and Digital Infrastructure to build the first green hydrogen long-distance buses. By 2024, the focus will be on developing a high-performance fuel cell system that can be used for buses over longer distances [109].

- Australian government's National Hydrogen Strategy includes plans for hydrogen production, transport, and storage. The Hydrogen Energy Supply Chain (HESC) project in Australia aims to produce hydrogen from brown coal and transport it to Japan via a pipeline.

The Australian government is funding a variety of demo projects and "hydrogen hubs" in order to prove the potential of this emerging technology. It aims to be a leading player in the global production and trade of hydrogen. The second largest capacity of zero-carbon hydrogen projects in development is located in Australia [110] and wants to take advantage of significant increases in demand for clean hydrogen in the area. As Australia is reliant on coal mining and liquified natural gas exports that drop over time, reducing its carbon emissions is one of its strategic goals, alongside the motivation to create jobs, attract investment, and open new export markets [110].

- Hydrogen Energy Supply Chain (HESC) Demo Project in Japan aims to produce, transport and store hydrogen using renewable energy.

Japan's Hydrogen Energy Supply Chain (HESC) project is developing a system to produce and transport hydrogen using natural gas as feedstock. The project targets validating the viability of transporting hydrogen by ship and injecting it into the natural gas network for power generation and other uses. The Hydrogen Energy Supply Chain (HESC) refers to the infrastructure and logistics involved in hydrogen fuel production, transportation, storage, and distribution. The HESC includes the various stages of hydrogen production, such as the extraction of hydrogen from natural gas or water and the transportation of hydrogen via pipelines or tankers. Additionally, the HESC includes storing and distributing hydrogen fuel, such as at refuelling stations for hydrogen fuel cell vehicles. The goal of the HESC is to make hydrogen fuel a viable and sustainable energy source for a variety of applications.

- H2@Scale Project in the United States aims to develop large-scale hydrogen production and storage technologies.

The initiative of the Department of Energy (DOE) brings together stakeholders to make reasonable hydrogen production, transport, storage, and utilisation in order to facilitate decarbonisation in many industry sectors [111].

- HyDeal Ambition project in Europe aims to validate the technical and economic feasibility of using hydrogen in heavy-duty vehicles and industrial processes.

In 2020, Soladvent launched HyDeal Ambition, an industry platform that brought together 30 companies covering the complete green hydrogen value chain with the objective of turning green hydrogen into a competitor to fossil fuels. The covered areas include electrolyser development, solar power generation, engineering, gas gathering, transmission and storage, steel chemicals, the power industry, and financing [112].

- The Hydrogen for Clean Transport project in Canada aims to improve hydrogen fuel cell vehicle infrastructure.

In order to be a leader in the manufacture, export, and use of pure hydrogen and related technology, Canada's Government is investing $1.5 billion. One obstacle that needs to be eliminated is the long distances across Canada [113].

These are just a few global examples, as there are many more hydrogen projects around the world in various stages of development and implementation.

- Yinchuan Project

The China National Petroleum Corporation has announced a major breakthrough in large-scale, low-cost, long-distance hydrogen transportation in Yinchuan, in the Ningxia Hui Autonomous Region of Northwest China. The hydrogen was successfully transported by mixing it in a natural gas pipeline, the company said. After 100 days of testing, the 397-kilometre pipeline operated safely and stably. Blending is seen as a means of increasing renewable energy production. Officials say the proportion of hydrogen in the company's natural gas pipeline network has reached 24%.

- Project Kawas

India's first green hydrogen blending project in the piped natural gas (PNG) network has been commissioned by NTPC Limited and Gujarat Gas Limited (GGL) at NTPC Kawas town in Surat. The project, which will supply households in Kawas town with H2NG gas as a result of electrolysis of water via energy from the 1 MW Floating Solar Project, has been implemented. The first green hydrogen molecule of the project was launched by P. Ram Prasad, Kawas Project Manager, in the presence of other senior officials from NTPC Kawas and GGL.

Unfortunately, there is no publicly available data for studies, projects, or initiatives from Russia, African countries, or Asian countries that will be discussed in this review.

European Hydrogen Industry

The European hydrogen industry is a rapidly growing sector focused on producing, distributing, and using hydrogen as an energy source. The European Union (EU) has set ambitious targets for the use of hydrogen in its energy mix, with the goal of producing at least 6 million tons of hydrogen by 2030 and at least 40 GW of hydrogen electrolysis capacity by that same year [114,115]. In Spain, using electrolysis to provide grid balancing services reveals a promising option for cost-competitive hydrogen [116,117]. Other studies have revealed that hydrogen is one of the best options for grid balancing [118,119]. This is expected to help the EU meet its climate goals and reduce its dependence on fossil fuels. The European hydrogen industry is diverse, with various countries and regions focusing on different aspects of the hydrogen value chain. For example, some countries focus on producing hydrogen from renewable energy sources, while others focus on developing hydrogen storage and distribution infrastructure and supply chains with countries outside the EU [120].

The EU started to research the impact of natural gas and hydrogen blends on their distribution to final consumers, focusing on the performance, emissions, and safety of the equipment used in both the domestic and commercial sectors [24,65,121]. The EU is also actively supporting the development of the hydrogen industry through funding and research programmes, such as the Fuel Cells and Hydrogen Joint Undertaking (FCH JU) and the Horizon 2020 research program. In addition, several European countries have established their own national hydrogen strategies, such as Germany's National Hydrogen Strategy and the French Hydrogen Plan. By 2050, the world's hydrogen consumption could reach 370 million tonnes per year [122].

It is worth mentioning that Europe has a big potential for hydrogen production due to the high availability of renewable energy sources, mainly wind, and solar power, which can be used to produce hydrogen through electrolysis [123]. Several ongoing projects and research studies worldwide or in the EU are investigating the mix of hydrogen and natural gas. Some examples include:

- H2NODE project in Germany, which aims to develop a hydrogen production and distribution network using renewable energy sources.

The project, which focuses on reducing pollution from public transportation and greenhouse gas emissions, has three main activities [124]:

1. Mapping the hydrogen production from renewable energy sources and establishing hydrogen delivery for real tests.
2. Increasing the hydrogen vehicle fleet.
3. Building and testing hydrogen refuelling stations in three cities and planning for continued expansion in other regions along the Trans-European Transport Network.

- The Power-to-Gas (P2G) project in Germany is investigating the use of hydrogen produced from renewable energy sources to blend with natural gas for use in power generation and other applications. The project aims to validate the technical and economic feasibility of using P2G to store excess renewable energy and balance the electric grid. The project is a technology that converts excess renewable energy, such as wind or solar power, into hydrogen gas. The hydrogen gas can then be stored and used as a clean fuel source for transportation or industrial processes. P2G technology is seen as a key solution for managing the variability of renewable energy sources and balancing supply and demand on the power grid. Germany has been a leader in developing and deploying P2G technology, with several pilot projects and demonstration plants currently in operation.
- The GRHYD demonstration project [125].

GHRYD is a collaborative effort between several companies and institutions to explore the potential of hydrogen as a clean energy source. The project scope is to build a hydrogen production facility in Dunkirk, France, that uses renewable energy sources like wind or solar power to produce hydrogen by electrolysis. The hydrogen produced will then be transported through a dedicated pipeline to a nearby industrial site, where it will be used to power various applications such as forklifts and heavy-duty vehicles. The project also includes the installation of hydrogen refuelling stations for vehicles in the region. The aim of the GRHYD project is to demonstrate the feasibility and viability of a hydrogen-based energy system in real-world conditions and to showcase the potential of hydrogen as a clean, renewable energy source for transport and industrial applications. The project is seen as an important step towards the French government's goal of becoming carbon neutral by 2050.

- The THyGA (Testing Hydrogen Admixtures for Gas Appliances) project is a research project that aims to investigate the use of hydrogen gas as a fuel for domestic gas appliances [126,127].

The project is funded by the European Union and involves collaboration between gas appliance manufacturers, gas network operators, and research institutions. The THyGA project aims to determine the safe and efficient use of hydrogen as a replacement for natural gas in domestic appliances such as boilers, ovens, and hobs. The project will investigate the effect of hydrogen gas on the performance and safety of these appliances as well as on the existing gas distribution infrastructure. The project will carry out a series of laboratory and field tests to assess the impact of different hydrogen gas mixtures on appliance performance and safety. The project will also assess the viability of using the existing gas distribution network to deliver hydrogen and the modifications that would be required to ensure safe and efficient delivery. The results are expected to provide valuable insights into the potential use of hydrogen as a sustainable and low-carbon fuel for domestic gas appliances and inform the development of policies and regulations governing the use of hydrogen in the energy sector.

- The Northern Lights project in Norway aims to establish a hydrogen supply chain by transporting hydrogen produced in Norway to European markets.

Yara and Northern Lights aim for a green transition of shipping, fertiliser production, and other energy-intensive industries to the hydrogen economy [128].

- H2Future project in Austria, which involves the construction of a green hydrogen production facility and a hydrogen storage and distribution system.

The project started in 2017 and, stretching over 4.5 years, brings together six partners from the steel industry, technology providers, energy suppliers, and research with the goal of producing green hydrogen from green electricity [129]. During the project, a 6 MW proton exchange membrane (PEM) electrolysis system will be installed and operated in Linz. Austrian Power Grid (APG), the transmission system operator, will further help in the prequalification of the electrolyser system in order to implement supplementary services in other areas. The replicability of the experiment on larger scales will be analysed for the steel industry [129].

- HyDeal projects in Germany and The Netherlands aim to demonstrate the feasibility of producing hydrogen from renewable energy sources and its use in various industrial applications.

This initiative has also been presented as an important point in relevant global projects and has been launched in 2020. HyDeal Ambition is an industry platform that brings together 30 companies covering the entire green hydrogen pathway, with the goal of turning green hydrogen into a competitor to fossil fuels [112].

- The Hydrogen Utilization in the Natural Gas Network (HyUNet) project in The Netherlands is studying the integration of hydrogen into the existing natural gas network to reduce greenhouse gas emissions and increase the use of renewable energy. The project aims to demonstrate the technical, economic, and safety aspects of hydrogen blending in the gas network.

Hydrogen Utilization in the Natural Gas Network (HyUNet) is a research project that aims to investigate the integration of hydrogen into existing natural gas networks as a means of decarbonising the energy system. The project is a collaboration between several universities, research institutes, and industry partners in The Netherlands and is funded by the Dutch government. The project will focus on the technical, economic, and regulatory aspects of integrating hydrogen into the natural gas network, as well as on developing new technologies and methods for the safe and efficient use of hydrogen in the natural gas network. The ultimate goal of the project is to demonstrate the feasibility of using hydrogen as a replacement for natural gas in the energy system and to support the transition to a low-carbon economy.

- HyBalance project in Denmark focuses on developing hydrogen storage solutions and integrating them into the existing natural gas grid.

The hydrogen in this project is produced from water electrolysis, facilitating the storage of cheap renewable electricity from wind turbines that can then be used to balance the grid. Air Liquide continues to produce hydrogen to supply clean transportation and the industrial sector long after the project was concluded in October 2020 [130].

- The HyNet project in the UK aims to create a hydrogen-based energy system that can decarbonise heavy industry and heat in the northwest of England.

The HyNet project in the UK looks at developing a low-carbon hydrogen and natural gas network for the northwest of England and north Wales. The project will involve the production of hydrogen from natural gas and the conversion of existing natural gas pipelines and storage facilities to handle hydrogen. HyNet is a proposed hydrogen production, storage, and distribution project in the UK. The project aims to use natural gas from the North West of England to produce hydrogen via steam methane reforming, with the excess carbon captured and stored underground. The hydrogen would then be distributed via a pipeline network for use in industry, transportation, and power generation. The project is being developed by a consortium of companies led by Cadent that includes Shell, National Grid, and Northern Gas Networks. The goal of the project is to reduce greenhouse gas emissions in the region and support the UK's transition to a low-carbon economy.

- The H2ME project in Europe focuses on developing hydrogen fuel cell electric vehicles and establishing a hydrogen refuelling infrastructure.

Like the HyDeal project, the description of the H2ME project was detailed as one of the most important global initiatives for the field under review [105].

- East Neuk Power is a proposed green hydrogen project in the East Neuk of Fife, Scotland [131].

The project aims to produce green hydrogen using renewable energy sources such as wind and solar power to power local transport and industry. Electrolysis, a technique in which electricity separates water into hydrogen and oxygen, produces hydrogen.

The project is still in the planning and development stages but has received funding and support from a number of organisations, including the Scottish Government, the European Union, and the University of St Andrews. It is expected to play a key role in Scotland's efforts to achieve net-zero carbon emissions by 2045.

- The HyDeploy project in the UK aims to demonstrate the feasibility of blending hydrogen with natural gas in the existing gas distribution network to heat homes and businesses [63,132].

One of the project's goals is to help the UK Government reach the net zero carbon emissions target by 2050 [132]. The project has three phases and tries to demonstrate how blended hydrogen can be used safely. The first phase (November 2019–March 2021) took place at Keele University using a private gas network. The second phase (August 2021–June 2022) occurred in a village in north–east England. In order to prove the safety of the process, the third phase focused on gathering evidence through industrial trials, as the proof of safety will allow the UK Government to make decisions about the future role of hydrogen blending within the gas networks [132].

- The Aberdeen Vision hydrogen project is a green energy initiative that aims to establish Aberdeen, Scotland, as a leading hub for producing and using hydrogen fuel [133,134].

The project is led by Aberdeen City Council in partnership with a range of stakeholders, including the Scottish Government, private sector companies, and academic institutions. This project involves the creation of a hydrogen production facility at Aberdeen Energy Park, which will use renewable energy sources such as wind and solar power to produce green hydrogen. The hydrogen produced will then be piped to various locations in Aberdeen, including the city's bus fleet, the Harbour Board's operations, and local heating systems. Aberdeen City Council also plans to develop a network of hydrogen refuelling stations across the city to facilitate the uptake of hydrogen fuel cell vehicles. In addition, the project will include research and development activities to explore the potential of hydrogen in various sectors, including transport, heating, and industry.

- The H21 programme is a major initiative to transform the way the UK's gas networks operate [135].

The programme is led by Northern Gas Networks, a gas distribution company serving the North of England, and involves collaboration between a range of stakeholders, including gas network operators, industry experts, and academics. The primary objective of the H21 programme is to demonstrate the feasibility of converting the UK's gas networks to run on 100% hydrogen rather than natural gas. This is seen as a key step in the transition to a low-carbon economy, as hydrogen is a clean-burning fuel that produces only water as a by-product when burned. In contrast, natural gas is a fossil fuel that produces carbon dioxide and other greenhouse gases when burned, contributing to climate change. The H21 programme has several key objectives, including developing and demonstrating the technical feasibility of hydrogen conversion, assessing the economic and environmental benefits, and engaging with stakeholders to build support for the transition. The programme also aims to create a regulatory framework that supports the development of a hydrogen economy in the UK. To achieve these aims, the H21 programme is carrying out a series of pilot projects and trials to test different aspects of the hydrogen conversion process. These include testing the safety and reliability of hydrogen gas networks, developing hydrogen production technologies, and investigating the impact of hydrogen on domestic appliances such as boilers and cookers.

Overall, the H21 programme is an ambitious and far-reaching initiative that has the potential to transform the UK's energy system and play a key role in the transition to a low-carbon future.

- The H2Grow project in Belgium focuses on developing a hydrogen production and distribution system for the horticultural industry.

The project's aims are: garden installations, social media presence, classes, workshops, and a fully immersive experience. The belief is that we can heal the planet by practising regenerative and sustainable agriculture methods by mimicking nature and farming in sync with the natural rhythm of the land [136].

- The HyChain project in The Netherlands aims to develop a hydrogen supply chain for industrial users, including the steel and chemical industries.

Several studies and projects around the world involve mixing hydrogen with natural gas. One example is the use of "power-to-gas" technology, where excess renewable energy is used to produce hydrogen through electrolysis. This hydrogen can then be blended with natural gas to be used in existing natural gas infrastructure, such as pipelines and power plants. This can help balance the grid and increase the use of renewable energy. In Belgium, a multi-energy model was used to simulate a 2050 energy system [137]. Another example is using hydrogen as a blending agent in natural gas engines, which can reduce emissions and improve the engine's overall efficiency.

These projects and studies are working to develop new technologies and infrastructure to enable the mixing of hydrogen and natural gas and to demonstrate the feasibility and benefits of using this approach to reduce emissions and increase the use of renewable energy.

At the moment, there are several hydrogen projects being developed in Romania. These include the development of hydrogen fuel cell buses, the construction of hydrogen production and refuelling infrastructure, and research into the use of hydrogen in various industrial applications. Additionally, the Romanian government has expressed interest in promoting the use of hydrogen as a means of decarbonising the country's energy mix. However, Romania has expressed interest in developing hydrogen as a potential source of clean energy. The country has significant potential for renewable energy production, particularly in wind and solar power, which could be used to generate hydrogen through electrolysis. Furthermore, as Romania has significant natural gas reserves, it can also produce hydrogen through processes such as steam methane reforming. The government has set a target to achieve a 30% share of renewable energy in the overall energy mix by 2030. There is not yet a specific hydrogen market in Romania. However, Romania has a growing renewable energy sector, and hydrogen can be produced from renewable sources such as wind and solar energy. The European Union has also set targets to increase the use of hydrogen as a clean energy source. As Romania is a member of the EU, national efforts to develop a hydrogen market are underway. Clean hydrogen, also known as green hydrogen, is produced using renewable energy sources such as wind or solar power. A strategy for implementing clean hydrogen in Romania could include the following elements:

- Developing renewable energy sources: Romania should invest in developing renewable energy sources, such as wind and solar power, to be used for hydrogen production.

Investing in the development of renewable energy sources, such as wind and solar power, creates particular opportunities for Romania, as it can help reduce dependence on fossil fuels and greenhouse gas emissions. Using these sources to produce hydrogen can also provide a clean and sustainable energy source for various industries, such as transportation and power generation. Additionally, developing a hydrogen economy in Romania could create new job opportunities and stimulate economic growth.

- Building hydrogen infrastructure: Romania should build the necessary infrastructure for hydrogen production, storage, and distribution.

Building a hydrogen production, storage, and distribution infrastructure in Romania can facilitate the use of hydrogen as a clean and renewable energy source. It can be used in a variety of applications, including transport, power generation, and industrial processes. However, it is important to note that hydrogen infrastructure development requires significant investment and cooperation between the government, the private sector, and research institutions. Additionally, it is important to consider the potential environmental and social impacts of hydrogen production and distribution and to ensure that the infrastructure is developed sustainably and responsibly.

- Research and development: Romania should invest in research and development to improve the efficiency and cost-effectiveness of hydrogen production and storage technologies.

Investing in R&D for hydrogen production and storage technologies is an appropriate ambition for Romania, as innovation can help the country improve the efficiency and cost-effectiveness of hydrogen production. This can lead to a reduction in the cost of hydrogen and increase its competitiveness as an energy source. Additionally, investing in R&D can help Romania develop a domestic hydrogen industry, which could create jobs and stimulate economic growth.

- Government incentives: The Romanian government should provide incentives for the development of clean hydrogen projects and the adoption of hydrogen-powered vehicles.

It is generally agreed that investing in clean energy technologies such as hydrogen can help reduce greenhouse gas emissions and combat climate change. Government incentives, such as grants, tax breaks, and subsidies, can be effective in encouraging the development and adoption of these technologies. By providing incentives for the development of clean hydrogen projects and the adoption of hydrogen-powered vehicles, the Romanian government could help promote the use of a clean and renewable energy source, which could have a positive impact on the environment and the economy.

- Partnerships and collaborations: Romania should establish partnerships and collaborations with other countries, companies, and organisations to share knowledge and resources to help accelerate the development of a clean hydrogen economy.

Establishing partnerships and collaborations is a good strategy for Romania to accelerate the development of a clean hydrogen economy. By working with other countries, companies, and organisations, Romania can access a wider range of knowledge and resources and also benefit from the expertise and experience of others. This can help speed up the development of new technologies, lower costs, and increase the deployment of clean hydrogen solutions. Additionally, partnerships and collaborations can help create new markets for clean hydrogen and open up new opportunities for business and investment.

- Education and awareness: Romania should create educational programmes and awareness campaigns to educate the public about the benefits of clean hydrogen and how to use it safely.

Creating educational programmes and awareness campaigns is one way Romania could increase understanding and use of clean hydrogen. This could include information on the benefits of clean hydrogen, such as its potential to reduce greenhouse gas emissions and improve energy security, as well as guidance on how to safely handle and use hydrogen fuel. Additionally, Romania could also invest in the research and development of clean hydrogen production and distribution infrastructure to make it more accessible and practical for the general public to use.

- Regulation: Romania should put in place regulations to promote safety and environmental protection in the production and use of clean hydrogen.

It is important for Romania to establish regulations to promote safety and environmental protection in the production and use of clean hydrogen. This can include guidelines for the safe handling and storage of hydrogen, regulations for the emissions of pollutants during hydrogen production, and standards for the use of hydrogen in vehicles and other applications. By implementing these regulations, Romania can help ensure a safe and sustainable transition to clean hydrogen [138].

Romania's large and small energy companies, as well as researchers in the field, have already initiated projects targeting hydrogen as an energy resource and storage medium. However, the demand for green hydrogen is too low without a government strategy. The government promises to have a finalised strategy by 2023. Hidroelectrica, Romgaz (stock symbol SNG), OMV Petrom (SNP), Liberty Galati, several wind power producers, and even Lukoil, through its Petrotel subsidiary in Ploiești, are putting together plans for green hydrogen production. That is, hydrogen is produced by water electrolysis using only renewable energy. The latest development is also among the most important because, without a transport infrastructure, hydrogen production projects cannot be developed, and financing them is no easier.

National gas system operator Transgaz SA is to team up with the Three Seas Initiative (TSI) Investment Fund in a €626 million hydrogen pipeline project. For the first time in Romania, Transgaz has started a national project in the field of hydrogen transport by tendering the purchase of materials suitable for introducing up to 20% hydrogen in a mixture with methane gas necessary for constructing two pipelines essential for the SNT. These are the Prunișor—Orșova—Băile Herculane—Jupa and Ghercești—Jitaru gas pipelines, which are included in the 2022–2030 SNT Development Plan and in the Modernisation Fund for financing. Moreover, research development on the possibility of accepting the hydrogen mix in the Romanian National Transmission System (NTS) alongside the modernisation and adaptation of the existing infrastructure for the use of hydrogen for decarbonisation is a future objective of Transgaz. In this respect, Transgaz is running a pilot project to use natural gas hydrogen mix and studying the influences on materials, metering systems, and combustion equipment—ROHYD. The design and execution of the concept were carried out by Transgaz specialists advised by academics from the University of Petroleum and Gas in Ploiești. At the same time, the pilot plant can determine the impact of the natural gas–hydrogen mixture on gas distribution networks. The main directions of analysis are:

- The behaviour of equipment used in NTS in the presence of methane and hydrogen mixtures. The plant incorporates a wide range of equipment found in the NTS (turbine metre, piston metre, volumetric metre, pressure regulators, ball valves, gate valves, directional valves, gas chromatograph, and pressure sensors). Also, it includes the usual types of pipes and welded joints, respectively, and flanges, with different types of seals [139]. The use of the mixture did not affect the functioning of the equipment.
- The hydrogen impact on the materials used in SNT. For this purpose, the facility was provided with a test chamber into which pieces of various pipes, including samples from polyethylene pipes, were placed. At the end of the test period, both the results of the metallographic analysis of the samples and the analysis of the behaviour of the polyethylene pipes will be reported.
- Analysis of the dynamics of the hydrogen mixing process in natural gas and the possibility of hydrogen “pockets” in the upper parts of the plants.
- Analysis of the variation of the gross calorific value for the methane/hydrogen mixture.
- Research on carbon footprint reduction due to the addition of hydrogen in the natural gas mix. Preliminary carbon dioxide stack determinations of commonly used equipment showed improved carbon emissions correlated with increased hydrogen concentrations.

Petroleum-Gas University from Ploiesti is commencing a new project that will analyse the combination between hydrogen and natural gas starting from the point of injection, going through T&Dsys to the final customers, and the implication of this blending in existing burners. The project, starting from the existing research [140], applies the current findings to the Romanian gas networks and current burners used in the distribution systems. The goal of the project is to gain a clear picture of the rules needed to obtain the best mix between hydrogen and natural gas for T&Dsys, accounting for the burning process in the current burners, the limitation of hydrogen percentage, and the problems generated from the injection of hydrogen in the gas systems as constraints in the process, which are issues intensively investigated all around the world [39,141]. We will design, test, and patent a new burner that can be used for a higher percentage of hydrogen. The aim is to define the limits for hydrogen injection that can be used in the Romanian T&Dsys without damaging the pipes and the equipment in place. A second test stand is already being built at INSPET SA and will help investigate the corrosion effects of the hydrogen–natural gas blend. Crystallographic texture analysis is required for an in-depth assessment of corrosion effects [37].

COMOTI Bucharest (The National Institute for Research and Development of Turbomachines) has been developing, for some years, applied research regarding the use of hydrogen in gas turbine burning chambers through a PN-II-PT-PCCA-2013 contract. The objective of the research is to replace natural gas with a maximum of 50% hydrogen, and at present, this research continues to have as its main object the enrichment of hydrogen up to 60%. COMOTI Bucharest has also carried out many studies and implemented several projects in the field of transmission of natural gas from the fields to the distribution networks [142–144], research that can be extended to natural gas blended with hydrogen.

The E.ON Romania Group, through its natural gas distribution company Delgaz Grid, started, in November 2022, a pilot project to test the compatibility and operation of current distribution system components and utilisation installations with a 20% natural gas–hydrogen mixture. The project will last 2 years and first test network components and natural gas utilisation devices in its own training range in Mediaș. The second phase has two subsequent subphases and will be carried out on selected steel and polyethylene network sections to which customers are connected [145]. In the first phase, tests on tightness, combustion, etc., will be carried out on existing installations and appliances of customers connected to these networks. No hydrogen shall be injected into the chosen distribution network at this stage. To analyse the behaviour of selected network elements and consumers' installations and appliances in the second phase, tests will be carried out with a mixture of NG + 20% vol. H_2. Delgaz Grid will benefit from the support of E.ON experts from Germany, where many such projects have been carried out, and from the expertise and know-how of the technical faculty of the Petroleum-Gas University in Ploiesti.

The issue of storage of natural gas hydrogen mix is also one of the main concerns of current researchers. This particular part is analysed by Depogaz, a company with a lot of experience in underground storage of natural gas and the main storage operator in Romania, with a share of approximately 90.54% of the total active storage capacity of Romania.

Progress is being made, but it is still modest compared to its potential. Even though the National Research and Development Institute for Cryogenic and Isotope Technologies Ramnicu Valcea (ICSI) has been operating since 2009, the National Centre for Hydrogen and Fuel Cells (CNHPC) has been tasked "with the mission to implement, develop, and disseminate hydrogen-based energy technologies in Romania."

The National Center for Hydrogen and Fuel Cells is a research and development organisation that focuses on the development and application of hydrogen and fuel cell technology. Their work may include research on the production, storage, and use of hydrogen as an energy source, along with the development of fuel cell systems for transport and power generation. The centre may also work on related areas such as energy storage, renewable energy, and sustainable transportation. Not coincidentally, researchers at ICSI Rm. Vâlcea are developing two prototype electric cars using hydrogen fuel cells as a means of propulsion, with a maximum range of about 320 km.

The government and the investment allocated for hydrogen research

Twelve years after the creation of the CNHPC, it took pressure from European Commission criteria for Romania to include hydrogen more firmly in its Romanian National Recovery and Resilience Plan (NRRP). The other Romanian emergencies, however, reduced the funding dedicated exclusively to 100 MW of hydrogen production and/or hydrogen energy storage capacity to €115 million (out of a total NRRP of €29 billion). Other hundreds of millions of euros are dedicated to constructing 1870 km of new distribution infrastructure ready for the natural gas–hydrogen mix, in line with Romania's orientation to rely on natural gas in the green transition. And, of course, the Ministry of Energy will spend €1 million from the NRRP on consulting to develop the Hydrogen Strategy by 2023. At the same time, part of the 15–16 billion euros available through the Modernisation Fund (through its 10d Mechanism based on emission allowances allocated by the European Commission to countries with green transition problems) is earmarked for the purchase of electrolysers for hydrogen production. This allocation is hoped to benefit Romania, where a call for renewable energy projects was launched in March 2023.

Offshore green energy and hydrogen are worth €600 bn to the European Commission.

Infrastructure is also part of the energy transition in Romania, which means investing in integrated production chains for hydrogen, batteries, and graphite, according to energy expert Răzvan Nicolescu. "We talk a lot about hydrogen (. . .), but we have not even asked ourselves how we could convince Cummins, one of the biggest manufacturers of hydrogen equipment, which is already in Craiova, to produce electrolysers in Romania," Răzvan Nicolescu told a CursDeGuvernare conference in autumn 2021.

Romania's big hydrogen companies

Also new is that Russian giant Lukoil intends to develop green hydrogen production capacity at its Petrotel refinery in Ploiesti. According to a memorandum of intent between the two parties, Lukoil would partner with another Russian giant, Rosatom. The memorandum promises, for now, only that it will "assess the prospects of transitioning the refinery to one of the most environmentally friendly hydrogen production technologies" to reduce the carbon footprint resulting from processing crude oil in the refinery. The task is part of a series of intentions by industrial hydrogen consumers who, like Petrotel-Lukoil, want to replace H_2 production by steam conversion of methane with electrolysis using renewable energy sources.

Romania has 13 industrial hydrogen producers (all from fossil fuels). Chimcomplex (CHOB) and Liberty Galați also have renewable energy production projects. To this end, the Liberty Galați steel combine (formerly Sidex) has signed a memorandum of cooperation with the Romanian Energy Centre, the international engineering group MTAG Switzerland, ICSI Rm. Vâlcea and the company Adrem. Liberty Galați wants to produce "green steel" and is looking for solutions to introduce "new energy and fuel production technologies, in particular hydrogen-based."

Dobrogea—stake for the big names in Energy

Romania's major natural gas producers, Romgaz (NGS) and OMV Petrom (SNP), announced more than a year ago that they wanted to invest in a joint hydrogen production project at a wind farm in Dobrogea, a first for the Romanian market (see Figure 11).

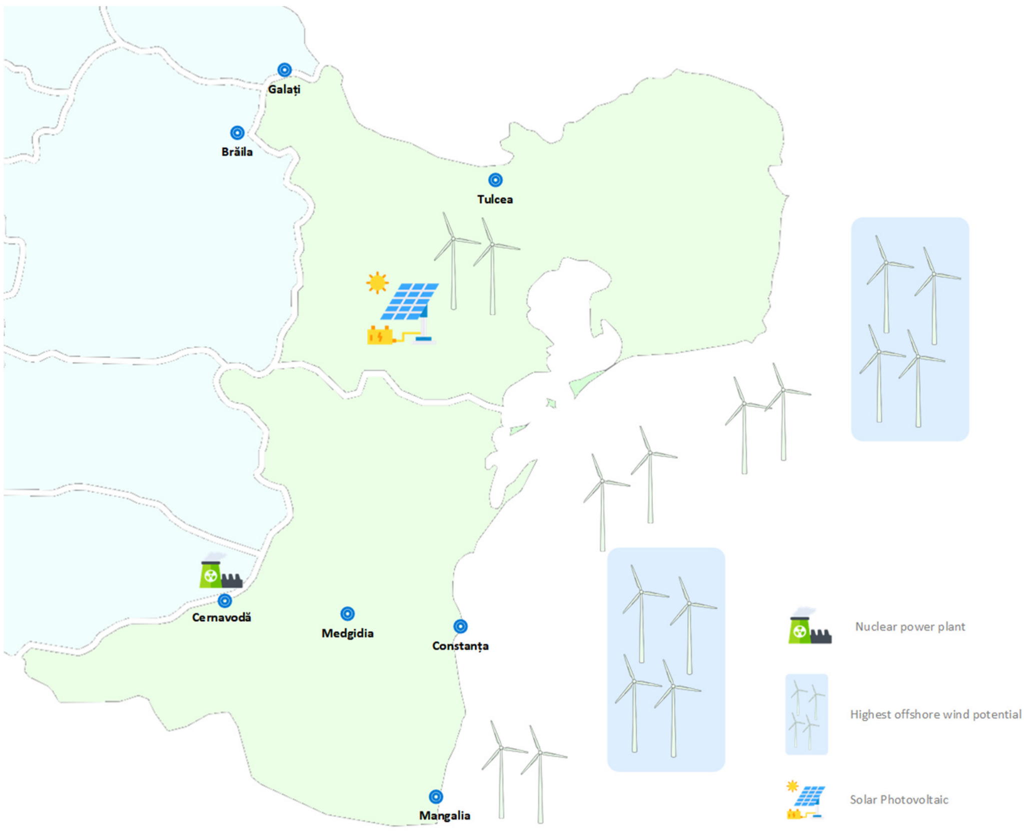


Figure 11. Dobrogea—Clean Hydrogen Valley (Source: authors based on Energy Policy Group Report [138]).

According to the company's strategy, part of the €11 billion that OMV Petrom aims to invest by 2030 will be dedicated to the hydrogen market. Romgaz (NGS) wishes to produce green electricity in photovoltaic parks and use the hydrogen produced in its own cars, as it intends to convert 20% of its fleet to this type of propulsion. Hidroelectrica has also announced that it "is interested in investing in onshore and offshore wind farms, photovoltaic farms, biomass electricity production, hydrogen production through hydrolysis, and the development of e-mobility networks," according to the company's investment strategy. More specifically, Hidroelectrica intends to develop, in partnership with Verbund (Austria), a large-scale green hydrogen project through water electrolysis in Romania. It will use a mix of green energy (off-grid wind and on-grid hydro).

The problem is that the hydrogen produced will then be exported. It will be embedded in mineral oil and transported down the Danube to countries in the Danube Interreg Transnational Programme ("Green Hydrogen on the Blue Danube"), such as Austria, Bulgaria, the Czech Republic, Germany, Hungary, Slovakia, Montenegro, and Serbia, according to the Austrian Economic Chamber.

Hidroelectrica also bought the wind farm at Crucea in 2021, with an installed capacity of 108 MW, as it intends to diversify into hydro-generation.

NERA (ANRE) has received several applications from investors seeking approval to build hydrogen production and storage facilities. Things are still in their infancy because there is not yet a market or enough demand for green hydrogen. Some producers of renewable energy, such as wind power, want to balance their electricity production when there is surplus and use it to produce hydrogen. However, the quantities are not large (less than 10% of energy production is used).

Instead, however, Dobrogea could become a veritable "Hydrogen Valley," according to a study conducted by the Energy Policy Group. The Hydrogen Valley project is a research and development project in the field of hydrogen energy, specifically focused on creating a hydrogen hub in the region of Dobrogea, Romania. The project aims to demonstrate and develop hydrogen technologies and infrastructure, such as hydrogen production, storage, and distribution, in order to promote the use of hydrogen as a clean energy source. The overall goal of the project is to create a sustainable, integrated hydrogen economy in the region and to help establish hydrogen as a key element in the transition to a low-carbon energy system. Dobrogea is suitable for the application of the "Hydrogen Valley" concept, as it ticks three key factors to become a hub for clean hydrogen development:

- exceptional potential for hydrogen production from on-shore and offshore renewable energy;
- regional demand for hydrogen from refineries, steel mills, and various transport sectors;
- the strategic role that the Port of Constanta can play.

According to the study, Dobrogea could host a large part of Romania's electrolysers, which would produce green hydrogen and should reach a capacity of 1400 MW to reach the "Fit for 55" targets in industry and transport. There is also an initiative to set up the Romanian Hydrogen and New Energy Technologies HUB ROHYDROHUB. Regardless of the existence of a million-euro strategy, it seems a long way off without decisive government action.

From the analysis carried out on projects at international, European, and Romanian levels, it is clear that one of the main challenges in the use of the natural gas and hydrogen mix as an energy source is the production of hydrogen. As mentioned above, hydrogen production often requires the use of fossil fuels such as natural gas, which can contribute to greenhouse gas emissions. In addition, hydrogen production can consume a significant amount of energy, especially if produced by electrolysis. Another challenge is the cost of modifying the existing natural gas infrastructure to allow hydrogen to be used [146].

3. Results of Analysis

From the literature review, initiatives, studies, and projects presented, it can be appreciated that the use of hydrogen (H_2) mixed with natural gas as an energy source is a current topic of great interest, especially regarding the potential of this mix as a viable alternative to fossil fuels [147]. Combining the two gases to use as fuel has the potential to provide a reliable, low-carbon energy source that can help reduce GHG and diminish the impact of climate change. This review set out to explore the potential of a combination of H_2 and natural gas and its viability as an energy source from both an environmental and societal perspective.

Hydrogen is a clean-burning fuel that does not produce greenhouse gas emissions or harmful pollutants when burned. In addition to a range of uses, including transport, heating, and electricity generation, it is an adaptable fuel. However, hydrogen production can be expensive and energy-intensive, and the infrastructure needed to transport and store hydrogen is still under development.

On the other hand, natural gas is a fossil fuel that is now widely used worldwide. It is a reliable and cheap energy source and is used in various applications, including electricity generation, heating, and cooking. However, burning natural gas produces carbon dioxide and other pollutants, contributing to global warming and other environmental problems.

For these reasons, using the combination of hydrogen and natural gas as a fuel source has the potential to reduce GHG emissions and mitigate the environmental impact of natural gas use. Blending can be achieved in two main ways:

Mixing natural gas with hydrogen: By adding hydrogen to natural gas, the resulting mixture can be used as a fuel source [148]. This is known as hydrogen-enriched natural gas (HENG) and can be consumed in the same applications as natural gas, such as heating and power generation.

By using hydrogen to produce synthetic natural gas in combination with carbon dioxide, hydrogen may be used to synthesise natural gas. Synthetic natural gas can be used in the same applications as natural gas but has lower greenhouse gas emissions because carbon dioxide is captured and stored.

The use of H_2 mixed in various concentrations with natural gas as an energy source has the potential to reduce greenhouse gas emissions and relieve the environmental impact of using natural gas. By using hydrogen to produce synthetic natural gas or by blending hydrogen with natural gas, the resulting mixture has lower greenhouse gas emissions than natural gas alone [149–152]. This may contribute to reducing the impacts of climate change and air pollution, improving environmental quality, and protecting people's health.

In addition, hydrogen production can rely on sustainable renewable energy sources such as wind, solar, or hydropower [119,153]. This can further reduce the carbon footprint of the H_2-natural gas mix, making it a truly low-carbon energy source.

From a societal perspective, H_2 blending with natural gas can provide a reliable, low-cost energy source, contributing to energy security and economic growth. Using existing natural gas infrastructure, the mix can be integrated into the existing energy system, reducing the need for additional investment in new infrastructure.

In addition, the mix can support the development of new industries and job creation in the renewable energy sector, contributing to economic growth and social welfare. Increased use of renewable energy can also diminish dependence on imported fossil fuels, increasing energy independence and security.

In the context of this review, a mix between H_2 and natural gas is a viable prospect for the environment and society. Combined with these sources, energy can be produced at a low-carbon, reliable, and cost-effective level, which may help reduce greenhouse gas emissions and mitigate the effects of climate change. Using hydrogen to produce SNG or blending hydrogen with natural gas has the capability to reduce carbon emissions.

4. Discussions

Recently, there has been a growing concern about the impact of fossil fuels on the environment and society. As a result, there's been a growing interest in developing alternative energy sources that can reduce the carbon footprint and improve sustainability. One of the most promising alternatives is using a mix of hydrogen (H_2) and natural gas [154].

Hydrogen is an abundant element that can be extracted from various sources, including natural gas, biomass, and water. It is a clean-burning fuel that produces water as its only byproduct. On the other hand, natural gas is a fossil fuel commonly used in power generation, heating, and transportation. While natural gas is less polluting than coal and oil, it still contributes to greenhouse gas emissions.

A mix of hydrogen and natural gas can offer several benefits over traditional fossil fuels. The combination of hydrogen and natural gas reduces carbon emissions by 20–30% compared to natural gas alone. Additionally, using hydrogen can help reduce the dependency on fossil fuels, increase energy security, and improve air quality [155].

Using hydrogen–natural gas mix can offer several environmental benefits. Firstly, hydrogen is a clean-burning fuel that produces water as its only byproduct. When hydrogen is mixed with natural gas, it reduces the amount of carbon emissions by up to 30%. This reduction in emissions can help to reduce the carbon footprint and diminish the impact of climate change.

Secondly, the use of hydrogen can help reduce the dependency on fossil fuels. Renewable energy sources like wind, sunshine, and biomass could be used to produce hydrogen. This can help diversify the energy mix and reduce the reliance on fossil fuels.

Thirdly, using a hydrogen–natural gas mix can improve air quality. Natural gas is a cleaner-burning fuel compared to coal and oil, and when mixed with hydrogen, it produces even fewer emissions. This can lead to a reduction in air pollutants such as sulphur dioxide, nitrogen oxide, and particulate matter.

The use of a hydrogen–natural gas mix can also offer several social benefits. Firstly, it can create new job opportunities in the renewable energy sector. The production, storage, and transportation of hydrogen require specialised skills and knowledge, which can create new job opportunities in the industry.

Secondly, the use of hydrogen can improve energy security. Locally produced hydrogen from renewable sources can reduce dependence on foreign oil and gas. This can help improve energy security and reduce vulnerability to geopolitical risks.

Thirdly, the use of a hydrogen–natural gas mix can help reduce energy costs for consumers. Hydrogen from renewable sources has become increasingly cost-competitive with fossil fuels. This can help reduce the cost of energy for consumers, particularly in regions where renewable energy is abundant.

Mixing hydrogen (H_2) and natural gas is a viable perspective for the environment and society, as it can offer certain advantages and disadvantages. The potential advantages and disadvantages of using the H_2 energy mix with natural gas are summarised below.

Advantages

- Lower carbon emissions compared to using natural gas alone since hydrogen does not emit carbon when burned.
- Reduced dependence on fossil fuels, as hydrogen can be produced from renewable sources such as wind, solar, and hydropower.
- Improved air quality is possible because hydrogen combustion produces only water vapour and no harmful pollutants.
- Flexibility in terms of blending ratios, which can allow for gradual adoption and testing of the mix before full-scale implementation.
- Potential to support the development of a hydrogen economy, which can create new jobs and economic opportunities.

Disadvantages

- The high cost of producing and distributing hydrogen can make the mix more expensive than using natural gas alone.
- Limited availability of infrastructure for transporting and distributing hydrogen can make it difficult to scale up its use.
- Lower energy density of hydrogen compared to natural gas can reduce the overall energy efficiency of the mix.
- Safety concerns related to handling and storing hydrogen, which is highly flammable and requires special safety measures.
- Potential for methane slip, which can occur when natural gas engines are not optimised for hydrogen blends and can lead to higher emissions of methane, a potent greenhouse gas.

The cost of using the hydrogen–methane mixture for different industrial or domestic applications may vary depending on several factors, such as the scale of the application, location, infrastructure requirements, and current market conditions. However, based on the authors' experience, some general considerations can be made regarding the cost comparison between piped natural gas (PNG) and hydrogen–methane blends.

a. Infrastructure costs:
   - The implementation of a storage, transport, and distribution system for a hydrogen/methane gas mixture usually requires the installation of specialised equipment, such as reformers or hydrogen blenders, to produce the gas. Additionally, highly sophisticated pipeline systems are required to efficiently distribute the mixed gas. These infrastructure costs can vary depending on the size and complexity of the system.
   - Pipeline gas infrastructure generally involves the installation of pipelines and associated equipment for gas extraction, processing, and distribution. The cost of constructing the necessary pipeline infrastructure can be significant, particularly for long-distance distribution.

b. Fuel costs:
   - The cost of hydrogen can vary significantly depending on the production method (e.g., steam reforming of methane, electrolysis, etc.) and the availability of hydrogen sources. On the other hand, methane is a fossil fuel, and the price of natural gas influences its cost. The ratio of hydrogen to methane in the mixed gas also affects the total cost of the fuel.
   - Prevailing market prices mainly determine the cost of natural gas for NGP systems. Natural gas prices can be influenced by factors such as supply and demand dynamics, transportation costs, and government regulations.

c. Operational efficiency:
   - The efficiency of a mixed hydrogen and methane system depends on several factors, including the combustion process, energy losses during hydrogen production, and overall energy conversion efficiency. Higher concentrations of hydrogen in the mixed gas can lead to higher efficiency but may also lead to higher costs due to the more expensive nature of hydrogen.
   - Piped natural gas is generally considered an efficient fuel due to its high energy content and efficient combustion characteristics. The operational efficiency of piped natural gas systems is well-established and widely used.

It is important to note that the cost dynamics of energy sources can change over time due to technological advances, changing energy markets, and government policies. Therefore, for an accurate cost comparison between hydrogen and methane blending and natural gas pipeline applications, it is recommended to consult updated information from emerging markets and conduct a detailed cost analysis specific to the location and project requirements.

The mixture between H_2 and natural gas is known as "hydrogen-enriched natural gas" (HENG). The exact blend of hydrogen and natural gas can vary but typically ranges from 5% to 20% hydrogen.

One of the main benefits of using a mix of natural gas and hydrogen as an energy source is its potential to lower greenhouse gas emissions. HENG produces fewer emissions than natural gas alone, as hydrogen burns more cleanly. Additionally, blending hydrogen with natural gas can help reduce the carbon footprint of existing natural gas infrastructure, as the modifications needed to accommodate hydrogen are minimal. Using a mix of natural gas and hydrogen can also improve energy security by reducing dependence on a single energy source.

Future directions in research on hydrogen and methane mixtures

As shown throughout this review, the use of mixtures of hydrogen and methane in various proportions for industrial or domestic applications has great potential for various applications, including energy storage, fuel synthesis, and emission reduction. Although significant progress has been made in understanding the behaviour and use of these gases individually, further research is needed to fully understand their interactions in the mixed state and optimise their use. This section aims to highlight future directions that should be explored in independent research on hydrogen–methane mixtures.

- Fundamental studies

To improve the understanding of hydrogen–methane blends, future research should focus on fundamental studies to investigate their thermodynamic properties, phase behaviour, and reaction kinetics. This will include comprehensive experimental studies, computational modelling, and theoretical analysis to elucidate the mechanisms governing the interaction and conversion processes between hydrogen and methane under different conditions. Such studies will provide valuable insights into the potential applications and limitations of mixed hydrogen–methane systems.

- Catalyst development

Catalysts play a crucial role in facilitating the conversion of hydrogen and methane into desired products such as syngas, higher hydrocarbons, or hydrogen-rich fuels. Future research efforts should aim to develop efficient and selective catalysts specifically designed for mixed hydrogen–methane reactions. This will involve exploring new catalyst materials, optimising their composition and structure, and understanding their catalytic mechanisms. In addition, studying catalyst regeneration and stability in mixed hydrogen–methane environments will be essential for developing practical applications.

- Process Optimisation

The efficient use of hydrogen–methane blends requires the development of optimised processes that maximise product yield and minimise energy consumption. Future research should focus on process engineering and optimisation to increase the efficiency of hydrogen–methane conversion technologies. This includes investigating reactor design, operating conditions, process integration, and control strategies to achieve improved performance, cost-effectiveness, and environmental sustainability.

- Energy Storage and Grid Integration

Hydrogen–methane blends can serve as an important component of energy storage and grid integration solutions, enabling the integration of intermittent renewable energy sources into the electricity grid. Future research should explore the development of advanced storage technologies and the synergistic use of hydrogen and methane for energy storage and grid-balancing applications. This includes the investigation of optimal storage capacities, system dynamics, and techno-economic analyses to assess the viability and scalability of hydrogen–methane blend energy storage systems.

- Environmental impact and sustainability

As with all energy research, the environmental impact and sustainability aspects of hydrogen and methane mixtures need to be carefully considered. Future studies should assess the life cycle assessment, greenhouse gas emissions, and environmental impacts associated with the production, use, and disposal of hydrogen and methane mixtures. This will help to identify potential environmental challenges and guide the development of sustainable practices and policies for the widespread adoption of hydrogen–methane blending technologies.

By addressing these research directions, researchers can contribute to a better understanding of the phenomenon and its efficient use in various practical applications using hydrogen and methane mixtures, leading to a more sustainable and energy-diverse future.

Overall, a mix of hydrogen and natural gas can offer several environmental and economic benefits. Still, it also poses some technical and economic challenges that need to be addressed to become a widespread solution for reducing carbon emissions.

5. Conclusions

The use of a hydrogen–NG mix as an energy source is becoming increasingly popular in today's society, as this mix is seen as a cleaner solution to traditional fossil fuels. This review is an analysis of the possibility of using hydrogen–natural gas mixtures as an energy source and the viability of pipeline transport from the perspective of environmental protection and a reduction in technical risks for society.

The transition to a more sustainable energy mix is critical to mitigating climate change and achieving global carbon neutrality goals. Hydrogen is one of the most promising alternative fuels that can potentially replace fossil fuels and has the potential to play a significant role in the decarbonisation of various sectors, such as transport, industry, and power generation. In this report, we discuss the potential of using a mix of hydrogen and NG as an energy source as well as its environmental and societal impacts.

Following extensive research and analysis in various projects, it is clear that H_2 blending with natural gas can bring significant environmental and societal benefits. Some of the main findings from this review are presented below.

In terms of environmental impact, hydrogen is a clean and renewable energy source that can be produced by various methods, including water electrolysis, biomass conversion, and thermal cracking of natural gas. Using hydrogen as an energy source can significantly reduce greenhouse gas emissions and air pollution.

On the other hand, NG is a fossil fuel that still works in combination with other energy sources. However, it also emits toxic gases such as carbon dioxide, nitrogen oxides, and sulphur dioxide, contributing to global warming and air pollution.

By using a mix of hydrogen and natural gas, our dependence on fossil fuels can be reduced, and society can gradually move towards an energy mix with one component from sustainable sources. This would benefit the environment, improve energy security, and reduce countries' dependence on oil and gas imports. While natural gas and hydrogen mixtures can be a transition solution to transport energy, long-term net-zero targets can only be achieved with pure, dedicated hydrogen solutions.

In terms of societal impact, using the hydrogen–natural gas mix can also have significant consequences because hydrogen can be used in fuel cells to power vehicles and buildings, creating new jobs and stimulating economic growth. In addition, hydrogen can be produced and transported locally, reducing the cost of accessing energy sources.

On the other hand, NG is already widely used in the energy sector, and the infrastructure for its production, T&Dsys is already in place. By using a combination of hydrogen and natural gas, existing infrastructure can gradually move towards a more sustainable energy mix without significant disruption.

In conclusion, a mix of hydrogen and natural gas is a viable prospect in terms of both environmental and social impacts. We can substantially reduce greenhouse gas emissions and air pollution through the application of hydrogen as a cleaner, more renewable energy source, which will also create new jobs and stimulate growth. In addition, by using the existing natural gas infrastructure, we can transition to a more sustainable energy mix without significant disruption. It is very important to maintain investments in research, development, and innovation to increase the efficiency and cost-effectiveness of hydrogen production and storage and accelerate the transition to a more sustainable energy future. Moreover, to completely realise the capacity of this energy mix, industry stakeholders must adopt best practices for the production, T&Dsys of the mix between hydrogen and NG. In addition, regulations must be implemented to mitigate the negative social and environmental impacts associated with the use of natural gas.

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Nomenclature

EU	European Union
REPowerEU Plan	A plan to rapidly reduce dependence on Russian fossil fuels and fast forward the green transition
MWh	Megawatt-hour
GWh	Gigawatt-hour
€	Euro: European Union Currency
OPCOM	Romanian Electricity and Natural Gas Market Operator
NERA (ANRE)	Romanian National Energy Regulatory Authority
SICBPVLI	State Inspection for the Control of Boilers, Pressure Vessels, and Lifting Installations
CNG	Compressed Natural Gas
CO_2	Carbon Dioxide
H_2	Molecular Hydrogen
HRS	Hydrogen Refuelling Stations
SMR	Small Modular Reactor
NCV	Net Calorific Value
GCV	Gross Calorific Value
CEO	Chief Executive Officer
NTS	Romanian National Transmission System
H2ME	Hydrogen Mobility Europe Project
HyFLEET-CUTE	Fuel Cell Electric Buses
HESC	Hydrogen Energy Supply Chain
H2@Scale	Project Launched in US (Texas)
PNG	Piped Natural Gas
DOE	Department of Energy
FCH JU	Fuel Cells and Hydrogen Joint Undertaking
H2Nodes	European Hydrogen Refuelling Station Network
P2G	Power-to-Gas Project in Germany
PEM	Polymer Electrolyte Membrane
APG	Austrian Power Grid
HyUNet	Hydrogen Utilization in the Natural Gas Network Project
R&D	Research and Development
SNG	Bucharest Stock Exchange details for S.N.G.N. ROMGAZ S.A.
SNP	Bucharest Stock Exchange details for OMV Petrom
TSI	Three Seas Initiative Investment Fund
TRANSGAZ	Romanian Technical Operator of the National Gas Transmission System
ROHYD	Pilot Project at Transgaz for the use of natural gas mixture with hydrogen and study of influences on materials, metering systems, and combustion equipment
INSPET SA	Romanian company in oil and gas domain with private capital
COMOTI	Romanian National Institute for Research and Development of Turbomachines
ICSI	Romanian National Research and Development Institute for Cryogenic and Isotope Technologies Ramnicu Valcea
CNHPC	Romanian National Centre for Hydrogen and Fuel Cells
NRRP	Romanian National Recovery and Resilience Plan
CHOB	Chimcomplex Company the Main Producer and Supplier of Vital Chemicals in Romania
NGS	ROMGAZ is Romanian Largest Producer and Main Supplier of Natural Gas
HUB ROHYDROHUB	Romanian Hydrogen and New Energy Technologies

HENG	Hydrogen-Enriched Natural Gas
GRHYD	The GRHYD project—Grid Management by Hydrogen Injection for Reducing Carbonaceous Energies
THyGA	Testing Hydrogen Admixtures for Gas Appliances
T&Dsys	Transmission and distribution systems

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