

Article

Enhancing Energy Supply Security Through Green Hydrogen Integration: The Role of Depleted Gas Reservoirs in Serbia

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Abstract

Serbia's energy sector is undergoing structural transformation driven by European climate policies, market volatility, and the need for long-term energy security. In this context, geological storage of energy carriers represents a strategically important option. Depleted gas reservoirs, particularly within the Pannonian Basin, constitute a technically validated subsurface infrastructure suitable for repurposing as multifunctional storage systems for natural gas, CO₂, and green hydrogen. This study analyzes trends in European and Serbian natural gas markets, EU decarbonization targets, and Serbia's energy balance to assess the feasibility of carbon capture and storage (CCS) and underground hydrogen storage. Key geological parameters governing long-term containment—lithology, effective porosity, permeability, caprock integrity, and structural stability—are evaluated, with emphasis on reservoirs combining favorable properties and proximity to existing infrastructure. Quantitative screening based on reservoir depth (approximately 1000–2500 m), effective porosity (15–25%), permeability (typically >50 mD), verified caprock integrity, and estimated geological storage capacities ranging from 0.17 to 1.25 billion m³ demonstrates that several depleted gas reservoirs in Serbia meet explicit fit-for-purpose criteria for underground storage applications. A comparative analysis of the physical and molecular behavior of H₂, CH₄, and CO₂ in porous media indicates that hydrogen storage is the most sensitive to reservoir integrity. The reported results provide quantitative and qualitative evidence that selected depleted gas reservoirs in Serbia satisfy essential requirements for project-level screening, including reservoir capacity, petrophysical suitability, caprock integrity, and infrastructure accessibility. These findings support the technical readiness of such reservoirs for staged deployment of natural gas storage, CO₂ sequestration, and underground hydrogen storage in the post-2035 energy system. Overall, combined subsurface storage of natural gas, CO₂, and hydrogen in Serbia is technically feasible, economically justified, and strategically relevant within the national energy transition framework.

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1. Introduction

The modern world is facing one of the most significant challenges in its history—ensuring a long-term and stable energy future while simultaneously preserving the

environment and mitigating the effects of climate change. The energy sector, as a key driver of technological, industrial, and economic development, is at the same time one of the main contributors to global pollution and greenhouse gas emissions. According to United Nations data, the combustion of fossil fuels such as coal, oil, and natural gas is responsible for more than 75% of global greenhouse gas emissions and nearly 90% of total carbon dioxide (CO₂) emissions [1,2]. Such data clearly indicate that a transition toward cleaner, more sustainable, and more efficient energy sources is essential in order to ensure stable development of humanity and protect the planet's ecological balance.

The daily mission of scientific and research institutions around the world, including those in Serbia, is to contribute—through science, innovation, and technological advances—to the development of solutions that will reduce dependence on fossil fuels and enable the introduction of sustainable energy systems. Energy is therefore an area of exceptional importance for every country: it is a driver of economic growth, the foundation of social stability, and a key factor in environmental protection [1]. Under contemporary conditions, the goal of national energy policies is no longer solely to ensure sufficient quantities of energy, but also to manage its production, transmission, and consumption in accordance with the principles of sustainability, energy efficiency, and environmental protection.

1.1. Energy Context of Serbia After 2035

In the context of Serbia, the energy system is at a turning point. By 2035, the completion of a series of reform and infrastructural processes is expected to significantly change the structure of the country's energy mix. Serbia's dependence on imports of natural gas and oil, as well as the large share of coal in electricity generation, represent challenges that require strategic planning and innovative approaches to the use of existing resources. Within this framework, an opportunity arises for depleted natural gas fields in Serbia—previously actively exploited—to gain a new functional value, namely as underground storage facilities for various energy carriers or media.

The use of depleted gas fields for the needs of the energy system offers multiple advantages. These include increased security of energy supply through the storage of imported natural gas, reduction in greenhouse gas emissions through the injection of carbon dioxide (CO₂) into porous formations, and the development of infrastructure for the storage of green hydrogen—a future energy carrier that can significantly contribute to energy independence and the decarbonization of industry. Such an approach also enables efficient use of existing natural resources, without the need to occupy new areas or disturb ecosystems.

Serbia currently emits approximately 48–52 MtCO₂ annually, with more than 70% of total emissions originating from the energy sector, primarily from lignite-fired thermal power plants. The Nikola Tesla and Kostolac power plants alone account for over 45% of national energy-sector CO₂ emissions. These large, concentrated point sources represent technically suitable candidates for carbon capture and storage (CCS) implementation. The magnitude of these emissions justifies the need for geological CO₂ storage solutions capable of accommodating several million tonnes of CO₂ per year, particularly within depleted gas reservoirs that already possess proven containment properties.

1.2. Potential of Depleted Gas Fields

Depleted gas fields in Serbia, formed through decades of natural gas exploitation, represent a significant infrastructural resource that can be transformed into underground reservoirs for various energy carriers.

Their geological structure has been extensively characterized through long-term production history, providing a valuable dataset for assessing reinjection and storage

behavior. Nevertheless, each type of gas—natural gas, carbon dioxide, and hydrogen—has specific physicochemical characteristics that affect its behavior during injection, storage, and potential withdrawal.

Molecular size represents one of the key parameters for analyzing injection feasibility (Table 1). The hydrogen molecule (H_2) is the smallest known molecule, composed of two hydrogen atoms, and is characterized by an extremely low molecular mass and diameter. The methane molecule (CH_4), the main component of natural gas, is larger and more stable, while the carbon dioxide molecule (CO_2), composed of one carbon atom and two oxygen atoms, has the greatest molecular mass and dimensions [3]. These differences in molecular size influence the ability to penetrate porous rocks and to be retained within the reservoir.

Table 1. Values of molecular masses and molecular diameters.

	H_2	CH_4	CO_2
Molecular mass	2.016 g/mol	16.04 g/mol	44.009 g/mol
Kinetic diameter	0.289 nm	0.380 nm	0.330 nm

These differences in molecular size and transport behavior are key factors in evaluating reservoir suitability for different gases.

The feasibility of subsurface gas storage is strongly influenced by the molecular and transport properties of the injected gases, including kinetic diameter, diffusivity, and mean free path. Smaller molecules, such as hydrogen (H_2), exhibit higher diffusivity and a greater tendency for migration through pore networks, microfractures, and caprock imperfections compared to methane (CH_4) and carbon dioxide (CO_2). As a result, hydrogen storage requires reservoirs with exceptionally low-permeability caprocks, high structural integrity, and minimal faulting. In addition to physical transport mechanisms, geochemical interactions must be considered. Hydrogen may react with iron-bearing minerals, sulfur compounds, and metallic components of well infrastructure, potentially leading to hydrogen embrittlement or microbial consumption. CO_2 , in contrast, can undergo mineral trapping through reactions with carbonate and silicate minerals, enhancing long-term storage security. These physicochemical differences should be considered when defining geological criteria for the storage of natural gas, CO_2 , and hydrogen [4].

1.3. The Role of Natural Gas in the Energy Transition

Although natural gas belongs to the group of fossil fuels, it plays an important transitional role in the shift toward cleaner energy sources. Storing natural gas in depleted reservoirs enables balancing of the energy system and ensures security of supply during periods of increased demand [5]. Serbia, as a country that covers a significant share of its gas needs through imports, can in this way improve its energy independence and increase system stability. The injection of natural gas into underground storage facilities also allows for more flexible market management of energy carriers, which is of exceptional importance under conditions of global energy instability and changing geopolitical circumstances.

1.4. Reduction in CO_2 Emissions and Contribution to Environmental Protection

In parallel with natural gas storage, there is also the possibility of using depleted gas reservoirs for the permanent disposal of carbon dioxide, a process known as carbon capture and storage (CCS). This technology represents one of the most important solutions in the fight against climate change, as it enables CO_2 —generated as a by-product in industrial plants, the energy sector, and the chemical industry—to be captured and permanently stored in geological formations deep below the Earth's surface [6]. In this way, the

amount of CO₂ in the atmosphere is directly reduced, mitigating the greenhouse effect and contributing to energy efficiency through more rational emissions management. The implementation of such projects in Serbia would contribute not only to environmental but also to economic progress [7]. The reduction in CO₂ emissions is linked to meeting international obligations under the Paris Agreement and the climate goals of the European Union, while at the same time opening opportunities to attract green investments and international support in the fields of renewable energy and environmental protection.

1.5. Green Hydrogen—The Energy Carrier of the Future

One of the key directions in energy development after 2035 will be the increased use of green hydrogen, produced through the process of water electrolysis using renewable energy sources—primarily solar and wind power [8]. Hydrogen is an extremely energy-rich gas that combusts without CO₂ emissions, making it an ideal energy carrier for a clean energy future. Its application can significantly contribute to the decarbonization of the transport, industrial, and energy sectors, while its storage in depleted gas reservoirs enables the creation of strategic reserves that can serve as a stable energy source over long periods of time.

By combining solar and wind energy with electrolysis, it is possible to create a closed energy cycle in which energy is produced, stored, and used without emissions of harmful gases. In this way, Serbia could develop a hydrogen-based economy, achieving significant technological progress, creating new jobs, and stimulating economic growth in line with the principles of sustainable development [9].

1.6. Technical and Technological Aspects and Challenges

The injection of different gases into underground reservoirs requires precise knowledge of the geological, chemical, and thermodynamic characteristics of the subsurface. Each gas has specific requirements in terms of pressure, temperature, and rock permeability. In the context of hydrogen, additional challenges include its low density and high diffusivity, which require advanced technical measures to preserve reservoir stability. In the future, the development of materials and methods for the safe storage of hydrogen will represent one of the key research fields in the energy sector [10]. Through adequate preparation and modification of existing gas reservoirs, Serbia could create multifunctional underground energy systems that would serve for natural gas storage, permanent CO₂ disposal, and green hydrogen storage alike. This would ensure a high level of flexibility and resilience of the energy system, as well as a significant reduction in the environmental footprint of domestic industry.

In line with the above, it is clear that the development of a sustainable energy system in Serbia after 2035 must be based on a combination of technical innovation, geological potential, and environmental responsibility. Depleted gas reservoirs represent an important resource that can play a key role in this transition—either as energy storage facilities or as sites for emissions reduction [9].

In the following research, the increase in energy potential through the use of injected natural gas in depleted gas reservoirs will be defined, with particular emphasis on its contribution to improving supply security and the stability of Serbia's energy system. This approach represents a strategic step toward enhancing the country's energy capacities, as it enables the creation of reliable energy reserves that can be utilized during periods of increased demand or supply disruptions. Injecting natural gas into existing depleted reservoirs also contributes to more rational use of existing infrastructure capacities, thereby reducing the need to construct new storage facilities and lowering the overall costs of the energy system. In this way, by optimizing storage capacities and increasing system flexibility, a higher level of energy security and supply stability is achieved [9,10].

Furthermore, a reduction in carbon dioxide (CO₂) emissions through its injection into depleted reservoirs will be defined, representing one of the most effective measures for reducing the greenhouse effect. This process enables the permanent underground storage of CO₂, preventing its release into the atmosphere and thereby directly contributing to climate change mitigation. The reduction in CO₂ emissions also contributes to improved energy efficiency, as it implies a transition to cleaner technologies and more sustainable energy sources. The link between emissions reduction and environmental protection is reflected in the long-term reduction in pollution, preservation of air quality, and the creation of a foundation for the development of an environmentally responsible energy sector. This measure not only contributes to fulfilling Serbia's international obligations under the European Green Deal and the Paris Agreement, but also strengthens the resilience of the national economy to future climate and energy challenges [11].

Finally, an increase in energy potential through the use of green hydrogen injected into depleted reservoirs will be defined, as hydrogen represents a key energy carrier of the future. Hydrogen, produced through electrolysis using energy from renewable sources (solar and wind power), forms the basis for creating a sustainable, decentralized, and climate-neutral economy [12]. Its storage in existing gas reservoirs provides an economical and technically safe solution for balancing energy production and consumption, particularly during periods when renewable energy generation exceeds current demand. The use of green hydrogen in industry, transport, and the power sector opens opportunities for significantly reducing dependence on fossil fuels and contributes to transforming the energy system toward a carbon-neutral future [11].

Overall, the approaches described—injecting natural gas, CO₂, and green hydrogen into depleted reservoirs—constitute interconnected segments of a unified energy strategy. This strategy aims to achieve greater energy independence, efficiency, and environmental sustainability for Serbia after 2035 through the integration of modern technologies and the application of the concept of circular energy. The objective of this paper is to analytically assess the possibility of using depleted gas reservoirs in Serbia as multifunctional energy spaces in order to increase energy stability, reduce greenhouse gas emissions, and improve energy efficiency. Particular focus will be placed on the injection of natural gas, carbon dioxide, and green hydrogen into existing reservoirs, along with an assessment of their potential and impact on the sustainable development of Serbia's energy system after 2035.

Unlike regional or descriptive reviews, this study provides a screening-level, decision-support framework for the repurposing of depleted gas reservoirs in Serbia. The proposed approach integrates geological suitability, storage capacity estimates, and post-2035 energy demand considerations to support reservoir prioritization for natural gas, CO₂, and hydrogen storage. By linking subsurface characteristics with system-level energy needs, the study offers a practical pre-feasibility assessment relevant for strategic planning and early-stage project development.

2. Use of Natural Gas in Europe and Serbia

Natural gas occupies a central position in the contemporary European energy system. As an energy carrier with lower carbon dioxide emissions compared to coal and oil, it has for decades been regarded as a transitional solution in the process of energy transition. Owing to its high energy efficiency, ease of transport, and wide range of applications, natural gas plays a significant role in the electricity sector, industry, heating, and transport. However, political, economic, and climatic circumstances in recent years have significantly influenced changes in Europe's energy landscape and have led to a reassessment of the long-term role of natural gas in European energy policy. Through the European Green Deal and the "Fit for 55" strategy, the European Union has set ambitious

targets to reduce greenhouse gas emissions by at least 55% by 2030 compared to 1990 levels, while the goal of climate neutrality has been set for 2050. In this context, natural gas is no longer perceived solely as a transitional energy carrier, but rather as a component of a broader system in which its use is expected to gradually decline and be replaced by renewable energy sources, biomethane, and green hydrogen [13,14].

The combined chart (Figure 1) shows natural gas consumption in European countries expressed in millions of cubic meters. It can be observed that Germany, Italy, and Turkey have the highest annual gas consumption, with values exceeding 700,000 million m^3 , while the United Kingdom, the Netherlands, and France follow closely with consumption between 300,000 and 500,000 million m^3 [15]. On the other hand, countries of Southeastern Europe, including Serbia, have significantly lower consumption; however, in relative terms—considering population size and industrial base—natural gas has a similar level of importance. The inset section of the chart presents Serbia's consumption in the period from 2017 to 2024, showing moderate fluctuations with an average value between 2.5 and 3.5 billion m^3 per year [15]. The largest increase in consumption was recorded in 2021, which can be linked to industrial recovery after the pandemic and increased use of gas in heat production and the power generation sector [15].

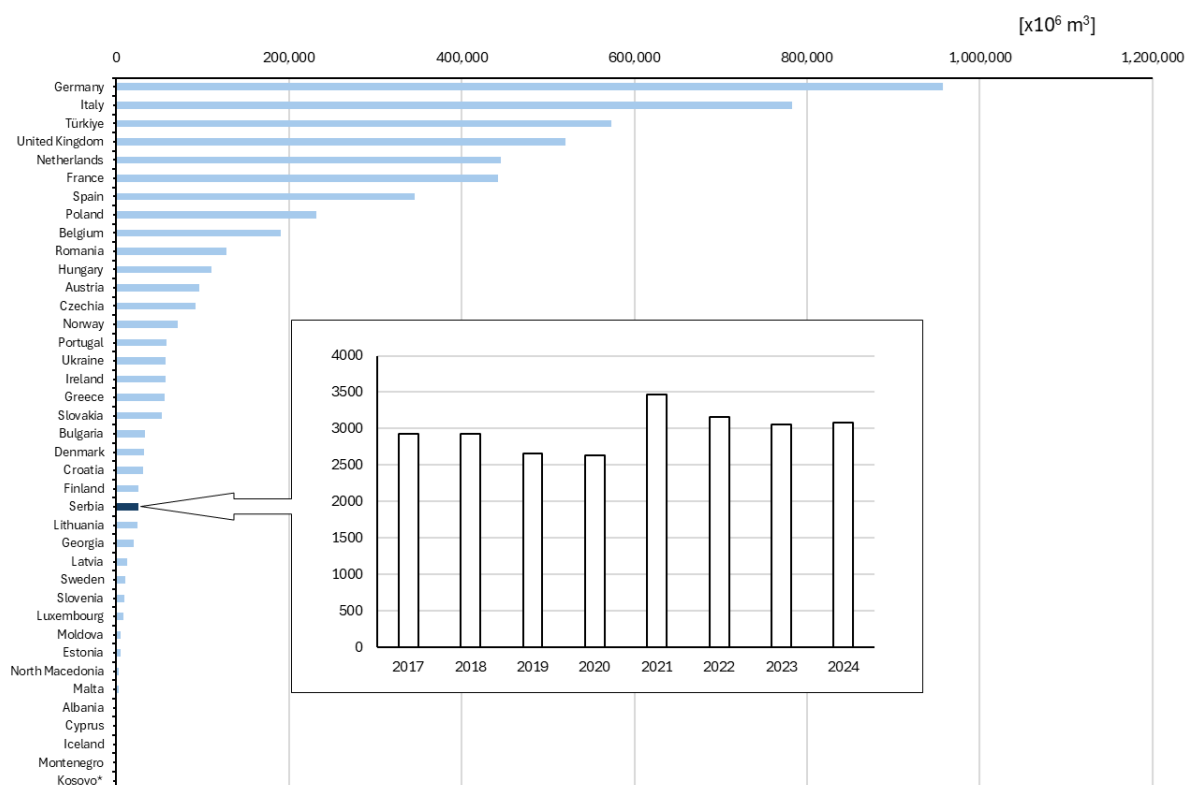


Figure 1. Diagram of natural gas consumption in Europe and Serbia for the period 2014–2024. (* This designation is without prejudice to positions on status, and is in line with United Nations Security Council Resolution 1244/1999 and the International Court of Justice Opinion on the Kosovo Declaration of Independence).

These data indicate two key facts:

- Europe's energy system is still significantly dependent on natural gas, particularly in the context of grid stabilization and balancing production from renewable energy sources.
- In countries such as Serbia, natural gas plays the role of a stable energy carrier that ensures security of supply and flexibility in the transition to clean technologies.

2.1. Consumption Structure and Sectoral Analysis

In Europe, natural gas is primarily used in the following sectors [15]:

- Industry (around 35%)—especially in the chemical, metallurgical, and food-processing industries.
- Electricity generation (around 30%)—gas turbines enable rapid response and system balancing.
- Households and heating (25%)—the dominant source of heat in urban areas.
- Transport and other uses (10%)—growing application in public and freight transport.

Table 2 presents natural gas consumption in European Union countries.

Table 2. Natural gas use in Europe, billion m³ (2017–2024).

Country	2017	2018	2019	2020	2021	2022	2023	2024	Difference 2017–2024 (%)
Germany	91.0	88.5	92.1	86.3	94.8	80.2	71.4	69.0	−24.2
Italy	74.0	70.6	71.5	68.2	76.3	65.1	62.5	61.0	−17.6
France	44.7	42.9	43.2	40.1	45.6	39.4	35.2	34.0	−23.9
Holland	36.5	35.8	33.4	31.6	30.9	25.5	23.7	22.0	−39.7
Spain	32.9	31.5	30.7	28.9	33.1	29.4	27.8	27.0	−17.9
Poland	17.5	18.0	18.3	17.0	19.4	16.1	15.3	15.0	−14.3
Czech Republic	9.2	9.3	9.0	8.6	9.8	8.4	7.9	7.7	−16.3
Hungary	10.4	10.1	10.3	9.8	10.9	9.1	8.7	8.4	−19.2
Austria	9.6	9.8	9.7	9.0	10.1	8.5	7.8	7.6	−20.8
Greece	5.0	5.2	5.3	5.1	5.6	4.8	4.5	4.4	−12.0
Romania	12.3	12.1	11.8	10.9	12.6	11.2	10.7	10.5	−14.6
Croatia	2.8	2.9	3.0	2.7	3.2	2.7	2.5	2.4	−14.3
Bulgaria	3.1	3.0	3.2	3.0	3.3	2.7	2.6	2.5	−19.4
EU total (EU27)	435.0	425.0	440.0	404.0	455.0	385.0	360.0	348.0	−20.0

Observing the period from 2017 to 2024, the European Union recorded a decrease in total natural gas consumption of approximately 20%, representing the fastest rate of reduction since the 1990s. The main reasons include:

- Accelerated energy transition toward renewable energy sources;
- The 2022 energy crisis caused by disruptions in supplies from Russia;
- Increased efficiency and electrification of heating and industry;
- Growing LNG imports and diversification of suppliers.

The most pronounced decline was recorded in the Netherlands (−39.7%), partly due to the closure of the Groningen field, and in Germany (−24.2%), where dependence on Russian gas was gradually reduced. On the other hand, countries of Central and South-eastern Europe (Poland, Romania, Hungary, Bulgaria) have maintained moderate fluctuations thanks to a combination of domestic production and new LNG terminals (e.g., Krk, Poland, Lithuania). Overall, the trend indicates that the EU is systematically transitioning toward a low-carbon energy model, in line with the objectives of the “Fit for 55” package and climate neutrality by 2050. Figure 2 illustrates the decline in natural gas consumption in the EU [15,16].

In Serbia, the structure of consumption is somewhat different: more than 50% of natural gas is used in industry and district heating plants, while households account for about 35%, and the remainder relates to the power generation sector. The importance of natural gas is also reflected in its role as a stabilizer—an energy carrier that can replace lignite and fuel oil during the transitional period, until a fully developed network of renewable energy sources is established. As part of the analysis of natural gas use in Serbia, annual consumption values were monitored over the period from 2017 to 2024 [17,18]. The presented data (Table 3) and the corresponding chart (Figure 3) highlight the main trends in

the consumption of this energy carrier, including fluctuations caused by economic, climatic, and geopolitical factors.

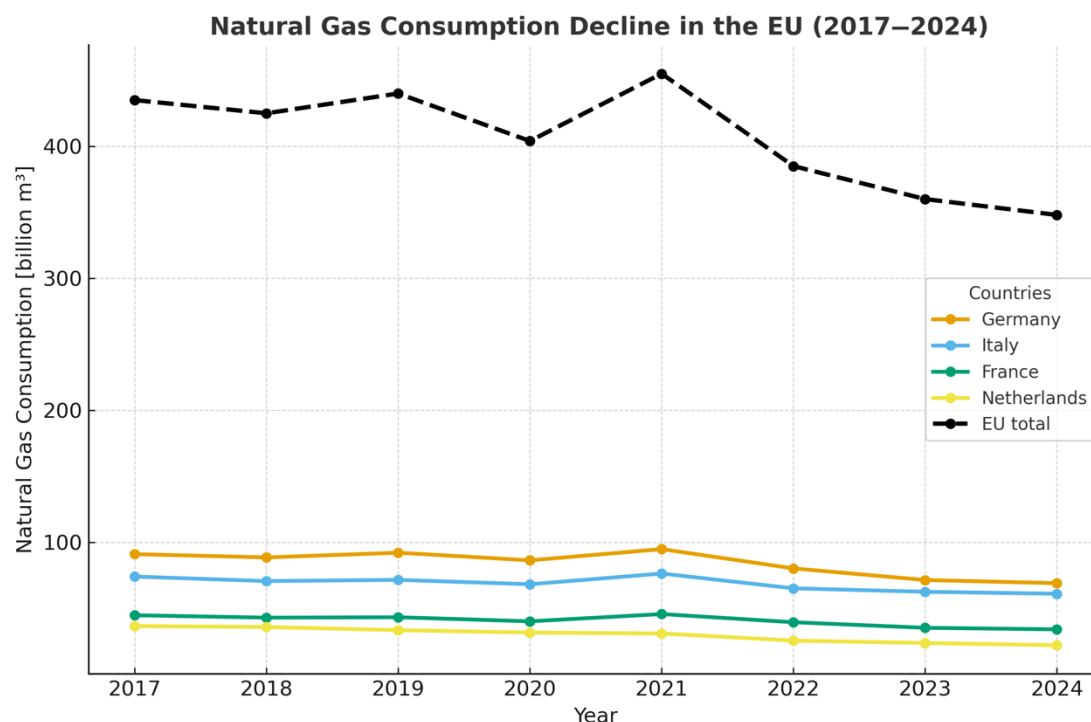


Figure 2. Natural gas consumption decline in the EU (2017–2024).

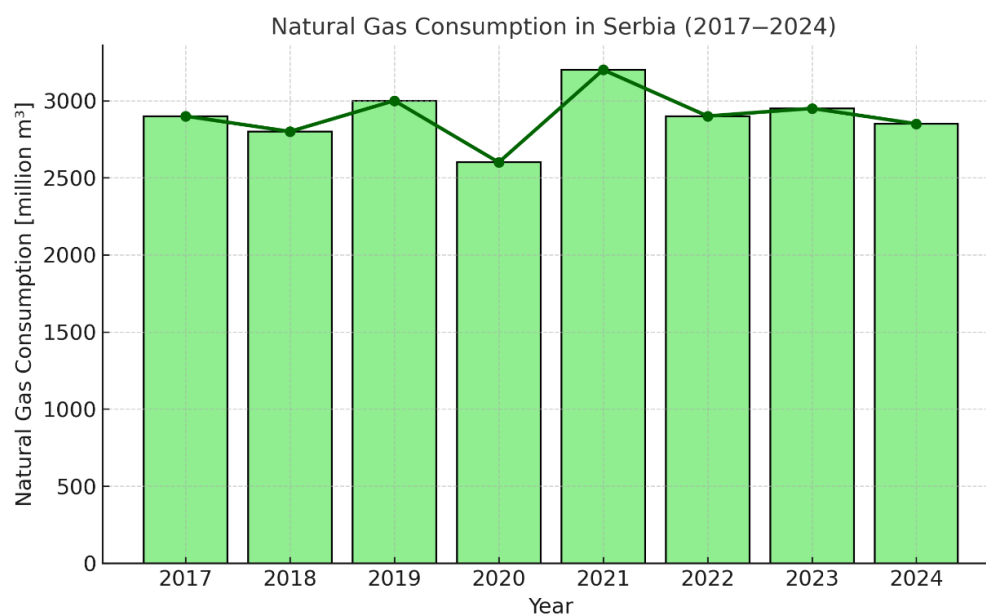


Figure 3. Natural gas consumption in Serbia (2017–2024) [17,18].

The observed time interval covers a period of eight years, during which an unstable but slightly declining trend in natural gas consumption in Serbia can be clearly identified. This trend is the result of the combined influence of three key factors:

- Changes in the structure of the energy mix;
- Economic fluctuations and changes in industrial activity;

- The introduction of energy efficiency measures and the transition to renewable energy sources.

Table 3. Natural gas use in Serbia (2017–2024) [17,18].

Years	Natural Gas Use (mil. m ³)	Difference (%)
2017	2900	—
2018	2800	−3.4
2019	3000	+7.1
2020	2600	−13.3
2021	3200	+23.1
2022	2900	−9.4
2023	2950	+1.7
2024	2850	−3.4

The highest level of natural gas consumption in Serbia was recorded in 2021 (approximately 3200 million m³), while the lowest consumption occurred in 2020 (about 2600 million m³), primarily due to reduced industrial activity during the COVID–19 pandemic and a relatively mild winter [19]. The consumption peak in 2021 can be attributed to a combination of factors, including post-pandemic economic recovery, increased industrial energy demand, higher utilization of gas-fired district heating and power generation, and colder winter conditions compared to the previous year. In addition, temporary fuel substitution and favorable supply conditions further contributed to increased natural gas use during this period.

This peak was followed by a phase of relative stabilization, with annual fluctuations within a range of $\pm 5\%$. In 2022, a renewed decline in consumption was observed, coinciding with global energy market disruptions caused by the energy crisis and reduced gas supplies from the Russian Federation. This decrease was further driven by rising natural gas prices, which prompted optimization of industrial processes and a partial shift toward alternative energy sources. During 2023 and 2024, natural gas consumption stabilized at approximately 2900 million m³, indicating the onset of structural adaptation of Serbia's energy system toward reduced gas dependence and an increasing share of renewable energy sources, particularly wind, solar, and biomass.

When the structure of natural gas consumption by sector is considered, the following categories dominate [19]:

- Industrial sector (around 40–45%);
- Electricity and heat generation (35–40%);
- Households and commercial sector (15–20%).

This distribution confirms that natural gas plays a key role in Serbia's energy chain, particularly in sectors requiring high process temperatures (chemical, food-processing, and metalworking industries). However, the high share in energy production also indicates significant potential for improving efficiency and diversifying energy sources.

2.2. Trends in Europe and Serbia's Position

Compared to the European average, natural gas consumption in Serbia shows moderate stability and lower sensitivity to seasonal fluctuations. While Western European countries such as Germany and Italy recorded consumption reductions of 15–25% during the observed period, Serbia experienced fluctuations within a narrower range [15,17]. This difference stems from the fact that Serbia's energy system still has limited options for substituting natural gas with other sources in the district heating and thermal power sectors. On the other hand, European trends indicate a gradual reduction in natural gas

consumption due to accelerated electrification and investments in renewable energy sources, while Serbia is only beginning to intensify investments in infrastructure for the storage of gas, CO₂, and hydrogen, which will in the long term contribute to increased energy resilience and system flexibility. Projections up to 2035 suggest that Serbia will need to balance energy security and environmental sustainability. In this context, the key components of the energy transition will be:

- Reconstruction of existing gas storage facilities (Banatski Dvor and potential conversion of depleted reservoirs);
- Introduction of CO₂ injection technologies to reduce emissions and improve energy efficiency;
- Development of capacities for green hydrogen storage, which can significantly increase the country's overall energy potential.

It is expected that the combined use of these technologies could contribute to:

- Increasing energy potential through the use of injected gas from reservoirs;
- Reducing CO₂ emissions through its injection;
- Increasing energy capacity through the storage and use of green hydrogen.

The analysis of the presented data confirms that Serbia maintained stable but limitably flexible natural gas consumption in the period 2017–2024, with a tendency toward a slight decline. Although natural gas remains a key energy carrier, trends clearly indicate the need to transform the energy system toward:

- Diversification of supply sources;
- Increased consumption efficiency;
- Development of storage capacities for alternative energy carriers (hydrogen, CO₂).

This period can be viewed as a preparatory phase for Serbia's energy transition, which by 2035 should ensure greater system resilience and reduced greenhouse gas emissions.

2.3. Market, Transport, and Storage

The European gas pipeline network (ENTSO-G) connects more than 200,000 km of transmission pipelines, with most of the infrastructure designed for gas inflows from Russia and Norway. The 2022 supply crisis demonstrated the vulnerability of such a model, leading to intensive development of LNG terminals and diversification of supply sources. Countries such as Germany, Italy, and the Netherlands responded rapidly by constructing floating LNG terminals and increasing storage capacities, thereby mitigating market shocks.

In Serbia, the key role in storage is played by the Banatski Dvor underground gas storage facility, with a capacity of approximately 450 million m³ [17]. Although modest relative to demand, this capacity has strategic importance, as it enables balancing between seasonal consumption and imports. Plans include expanding the storage facility, as well as considering the use of depleted gas fields in Vojvodina for additional capacity. These projects are directly linked to future concepts of CO₂ and green hydrogen injection, enabling multifunctional use of the same geological structures [18,19].

2.4. Energy Efficiency and Environmental Aspects

Natural gas, although cleaner than coal, still emits CO₂ during combustion. On average, emissions per unit of energy amount to around 202 g CO₂/kWh, which is about 40% lower than coal, but far from climate-neutral technologies. To reduce emissions, many countries are introducing combined heat and power (CHP) systems that enable more efficient use of gas, as well as carbon capture and storage (CCS) technologies.

In Serbia, the decarbonization process in the gas sector is still at an early stage, but projects have been launched aimed at reducing transport losses, modernizing the gas network, and optimizing district heating systems in cities. In addition, it is planned that natural gas will gradually be blended with biomethane and green hydrogen, further reducing emissions.

2.5. Projection of Natural Gas Use After 2035

It is expected that natural gas consumption in Europe will decrease by about 25% by 2035, while the share of renewable energy sources will rise to over 50%. Nevertheless, natural gas will continue to play a significant role in stabilizing the power system and ensuring security of supply. For Serbia, projections indicate that consumption may remain stable or slightly decline (2.5–3 billion m³ annually), accompanied by increased efficiency and reduced emissions [18,19]. Key development directions include:

- Use of depleted reservoirs for the storage of natural gas and green hydrogen;
- CO₂ injection to reduce emissions;
- Integration with solar and wind power plants through electrolysis technology;
- Development of a hydrogen-based economy as the foundation of energy independence.

Such an approach would enable Serbia, after 2035, to become part of the European energy community with a stable, modern, and environmentally responsible system. The use of natural gas in Europe shows significant regional differences, but also a common tendency toward reducing dependence on fossil fuels and transitioning to renewable energy carriers. Serbia, although a relatively small consumer in European terms, has the opportunity—through smart resource management and infrastructure development—to significantly enhance its energy security. Depleted gas reservoirs represent a bridge between the current energy model and future technologies—storage facilities that can serve for natural gas, CO₂, and green hydrogen alike. It is precisely this multifunctional role that holds the potential for creating a sustainable, flexible, and economically viable energy system in Serbia after 2035.

3. CO₂ Emissions in Europe and Serbia—Relationship Between Production and Consumption

Carbon dioxide (CO₂) emissions represent one of the key indicators of the sustainability of the energy system, as well as the main driver of global climate change. Within both the European and national contexts, analyzing the sources, scale, and structure of emissions enables an assessment of the relationship between energy production and consumption, as well as the identification of opportunities for their reduction. CO₂ emissions are directly linked to the types of energy carriers used, the level of energy efficiency, and the industrial structure of the economy. In this sense, understanding emission trends in Europe and Serbia is crucial for planning future steps in the energy transition and achieving climate neutrality goals.

3.1. CO₂ Emissions in the European Union—Trends and Structure

The European Union (EU) is one of the global leaders in combating climate change and decarbonizing the energy sector. According to data from Eurostat and the European Environment Agency (EEA), CO₂ emissions from the combustion of fossil fuels in the EU decreased by approximately 32% between 1990 and 2023, while gross domestic product (GDP) increased by more than 60% over the same period [20]. These data confirm that “sustainable decoupling” is possible—economic growth accompanied by a simultaneous

reduction in emissions—which represents the foundation of the European Green Deal [20].

The main sources of CO₂ emissions in the EU are:

- The energy sector (coal-, oil-, and gas-fired power plants);
- Industry (metallurgy, cement, and chemical production);
- Transport;
- Households and the municipal sector.

The largest reduction in emissions has been recorded in the energy sector, primarily due to the closure of coal-fired power plants and the increased share of renewable energy sources (RES)—wind, solar, and biomass (Figure 4). Carbon dioxide (CO₂) emissions represent a key indicator of the sustainability of the energy system and its impact on the environment. In the context of the energy transition, the European Union (EU) and Serbia face similar challenges—reducing dependence on fossil fuels, increasing energy efficiency, and integrating renewable energy sources into national energy balances. An analysis of CO₂ emission trends in the period from 2014 to 2024 provides insight into the degree of implementation of decarbonization policies, the effectiveness of applied measures, and the ability of energy systems to maintain supply stability while reducing negative environmental impacts.

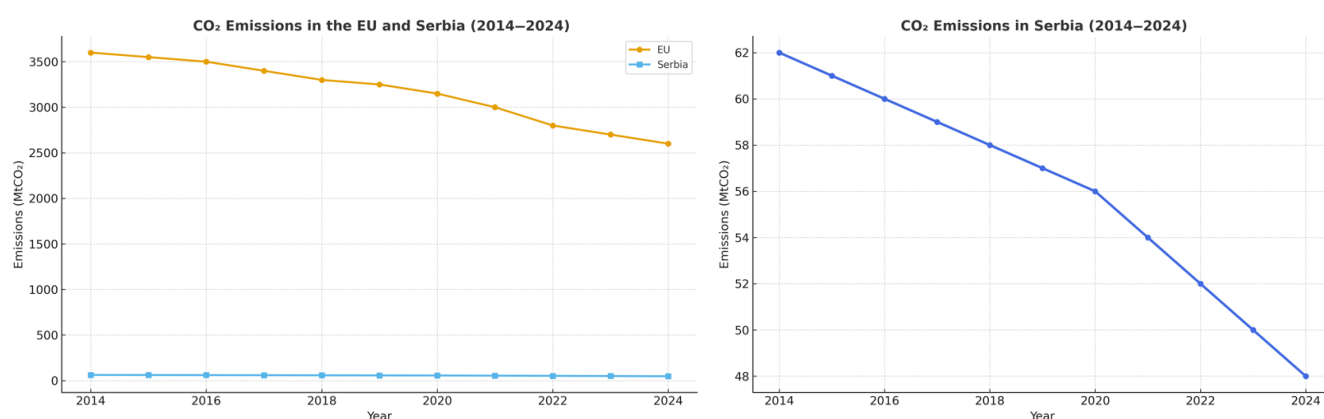


Figure 4. CO₂ Emissions EU vs. Serbia (2014–2024) [21,22].

For example, Germany, which was once the largest CO₂ emitter in Europe, has been continuously reducing its emissions since 2010 and plans to completely phase out coal-fired power plants by 2038. France, thanks to the dominant use of nuclear energy, has for many years recorded one of the lowest per capita emissions in the EU (around 4.5 t CO₂ per person). In 2023, the average CO₂ emission in the EU was about 6.1 tonnes per capita, while the highest emissions were recorded in Poland, the Czech Republic, and Germany—countries that still rely heavily on coal. At the same time, Scandinavian countries, due to their high shares of hydropower and wind energy, have average emissions of only about 3 tonnes per capita, confirming that the transition to clean energy is the most effective path toward emission reduction [22,23].

Over the observed period, total CO₂ emissions in the European Union show a continuous decline—from around 3600 MtCO₂ in 2014 to approximately 2600 MtCO₂ in 2024, representing a reduction of about 28%. This trend is the result of the coordinated implementation of European climate policies and strategic frameworks such as the European Green Deal and the Fit for 55 initiative, which aim to reduce net greenhouse gas emissions by at least 55% by 2030 compared to 1990 levels [20].

The most significant reduction in emissions has been recorded in the energy sector, particularly in electricity generation, where the gradual closure of coal-fired power plants

and the increased share of wind, solar, and hydropower have contributed to substantial emission reductions [20]. In parallel, the implementation of energy efficiency measures in industry and transport has further reduced emissions, while the development of emissions markets (EU ETS) has created economic incentives for the transition to clean technologies. The transport sector remains a challenge, as emission reductions in this area are slower than in energy and industry. Nevertheless, progress in road transport electrification and subsidies for electric vehicles indicate a positive long-term trend.

During the same period, CO₂ emissions in Serbia decreased from about 62 MtCO₂ in 2014 to 48 MtCO₂ in 2024, representing a reduction of approximately 22.6% [21]. Although Serbia's absolute emissions constitute a negligible share of total European emissions, this trend reflects progress in the implementation of domestic energy and climate policies. According to reports by the Ministry of Mining and Energy of the Republic of Serbia [21], the key factors behind emission reductions include the modernization of thermal power plants, the introduction of natural gas as a transitional energy source, and an increased share of renewable energy sources in total production. In addition, the adoption of the Climate Change Law and the establishment of a monitoring, reporting, and verification (MRV) system have created institutional conditions for more accurate emission tracking and mitigation planning. The reduction in emissions in Serbia is particularly pronounced in the industry and electricity generation sectors, while emissions from transport and the municipal sector have remained almost unchanged. However, the transition to lower-carbon energy sources, along with plans to develop capacities for carbon capture and storage (CCS technologies) in depleted gas fields, indicates Serbia's readiness to actively participate in the decarbonization process in the coming decades.

A comparative analysis of CO₂ emissions between the European Union and Serbia indicates different decarbonization dynamics. While the EU records a uniform and stable decline supported by clear institutional and financial frameworks, Serbia is in a transitional phase of energy development. The main difference lies in the level of integration of renewable energy sources and the development of market-based emission mechanisms. In the EU, instruments such as the EU Emissions Trading System (ETS) and the Innovation Fund enable investments in clean technologies and energy efficiency. In Serbia, the process of alignment with these mechanisms is ongoing, with the major challenge being the modernization of outdated thermal power plants and insufficient diversification of energy sources. Nevertheless, it is important to note that Serbia has significant potential to mitigate emissions through the injection of CO₂ into depleted gas reservoirs, which would simultaneously contribute to reducing the greenhouse effect and increasing energy stability. Such technologies are already delivering results in Europe, particularly in Scandinavian countries and the Netherlands [23].

Figure 5 presents CO₂ emissions in Europe [24] and in Serbia [18]. The graphical representation of trends clearly illustrates the difference in the scale and pace of emission reductions. The curve representing EU emissions shows a steeper decline, while Serbia's curve is milder but steady. This dynamic indicates Serbia's gradual transition toward a more sustainable energy model while maintaining energy stability and security of supply.

The diagram presents carbon dioxide (CO₂) emissions in European countries based on data from Eurostat and the Statistical Office of the Republic of Serbia for the period from 2010 to 2022. At the level of the European Union, a clear trend of gradual reduction in CO₂ emissions can be observed, resulting from intensive decarbonization policies, the transition to renewable energy sources, and increased energy efficiency in industry and transport. The largest emitters are traditionally the most economically developed countries—Germany, France, and Italy—which reflects the scale of their industrial production and energy consumption.

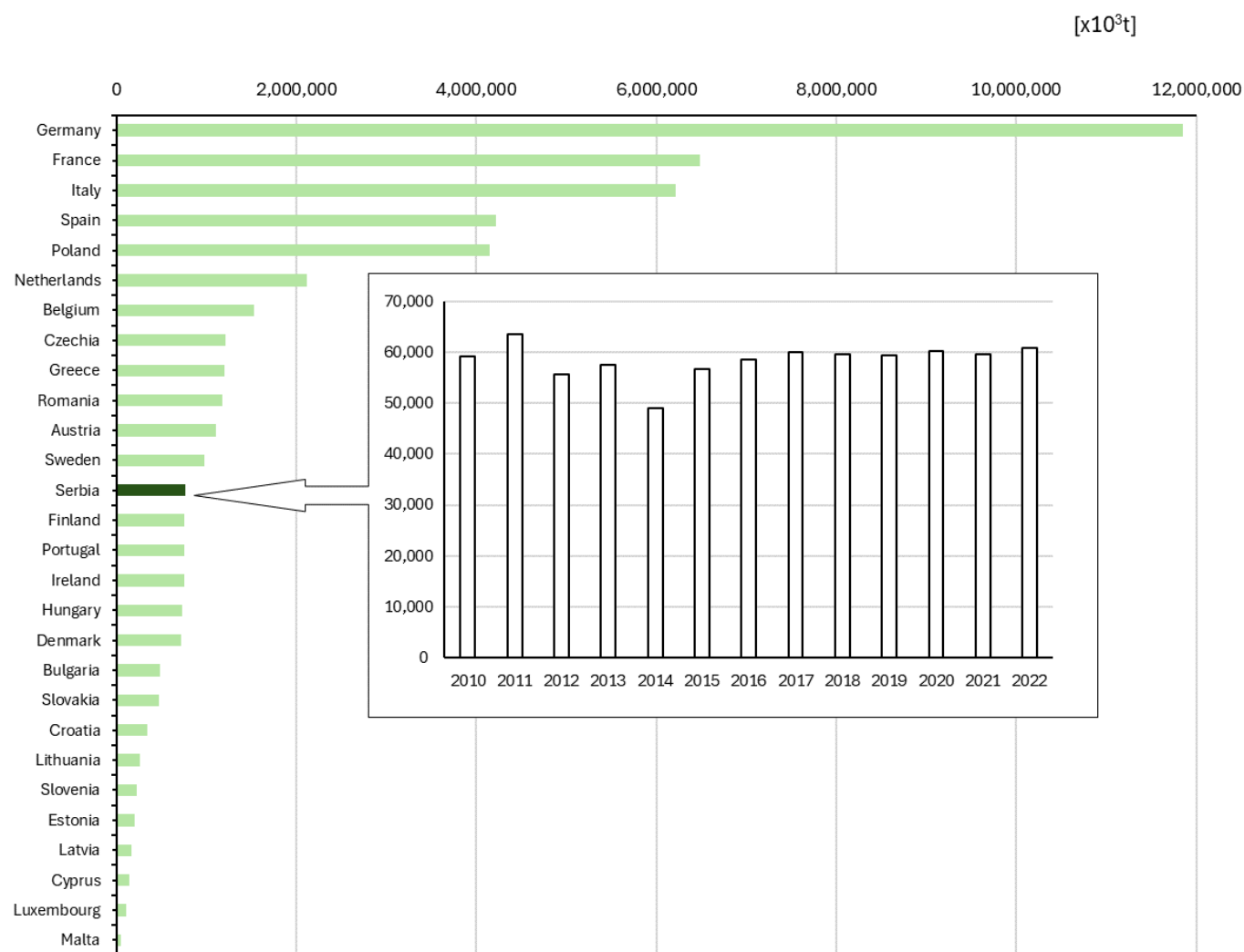


Figure 5. CO₂ emission diagram in Europe [Eurostat] and in Serbia [Statistical Office of the Republic of Serbia].

In the case of Serbia, which is positioned in the middle of the scale on the graph, a slight decline in emissions after 2014 is noticeable, but not to an extent that would indicate a systemic transition toward a low-carbon energy mix. CO₂ emissions remain relatively stable at around 45–50 million tonnes per year, which is a direct consequence of dependence on lignite as the primary fuel in electricity generation [18,22]. Although progress has been made in the development of renewable energy sources (wind, solar, biomass), their share in total energy production is still insufficient to significantly reduce CO₂ emissions. Serbia is therefore in a phase of energy transition that involves balancing the need for secure energy supply with the requirement to reduce greenhouse gas emissions. The data point to the need to accelerate the decarbonization process, primarily through the gradual phase-out of coal-fired power plants, increased energy efficiency, and the application of technologies such as carbon capture and storage (CCS) and the use of green hydrogen [21].

Compared to the EU average, where emissions have been reduced by about 25% over the past decade, Serbia has recorded a significantly smaller reduction, indicating the need for a more systematic approach and a clear strategy for reducing its carbon footprint. These results should serve as a basis for further research into emission reduction potential through optimization of the energy mix and the use of depleted gas fields for CO₂ storage.

3.2. CO₂ Emissions in Serbia—Current State and Trends

Serbia, as a country in transition and a candidate for EU membership, faces significant challenges in reducing CO₂ emissions. According to data from the Ministry of Mining and Energy and the Environmental Protection Agency, total CO₂ emissions in Serbia in 2023 amounted to approximately 51 million tonnes, more than 70% of which originated from the energy sector, primarily from lignite-fired thermal power plants. The “Nikola Tesla” and “Kostolac” power plants together account for over 45% of total emissions from the energy sector. Unlike the European trend, CO₂ emissions in Serbia have not been decreasing at a steady pace. In the period from 2015 to 2021, mild fluctuations were recorded—a reduction in 2020 due to the COVID-19 pandemic and the temporary decline in consumption, followed by renewed growth in 2021–2022 driven by increased electricity demand and limited imports [21]. The structure of energy consumption in Serbia still shows a high dependence on fossil fuels: around 65% of total electricity generation comes from coal, while renewable energy sources account for less than 30%. A particular challenge is low energy efficiency in households and industry, which further increases emissions. According to estimates, average CO₂ emissions per capita in Serbia amount to about 7.4 tonnes, which is higher than the EU average, despite significantly lower economic output per capita. This imbalance highlights the need for accelerated modernization of the energy sector, improved energy efficiency, and systematic investment in renewable energy sources [18,22].

3.3. Relationship Between Production and Consumption—Energy Balance and Carbon Footprint

Analyzing the relationship between energy production and consumption is essential for understanding the sources of CO₂ emissions. In the EU, emissions are increasingly being “imported,” meaning that part of emissions occurs in countries producing goods and energy carriers for the European market. For example, a large share of emissions is associated with the production of steel, aluminum, and cement in Asia, which implies that the actual carbon footprint of European consumption exceeds locally recorded emissions. This has led the EU to introduce the Carbon Border Adjustment Mechanism (CBAM), which imposes charges on products with high CO₂ emissions imported from countries with weaker climate standards.

In Serbia, the situation is reversed—most emissions are generated domestically through electricity production, while energy imports (mainly natural gas and oil derivatives) represent a secondary source of emissions. This means that Serbia is directly responsible for its carbon footprint, but it also has significant potential to reduce it by changing the structure of production. The introduction of modern carbon capture and storage (CCS) technologies, as well as a transition to low-carbon energy carriers such as natural gas and green hydrogen, could significantly reduce emissions from the production sector. At the same time, improving energy efficiency in households and industry contributes to lower consumption and, consequently, reduced emissions.

3.4. Perspectives for Emission Reduction and Development Pathways

The European Union has set the goal of achieving climate neutrality by 2050, with an interim target of reducing emissions by at least 55% by 2030 (compared to 1990 levels). Achieving these goals requires key measures in energy efficiency, transport decarbonization, investment in renewable energy sources, and the development of infrastructure for green hydrogen.

In line with its international commitments (NDC—Nationally Determined Contributions), Serbia has adopted a target of reducing greenhouse gas emissions by 33.3% by 2030 [22]. However, achieving this goal requires faster implementation of systemic measures. Priority areas include:

- Modernization of thermal power plants and their replacement with cleaner technologies;
- Increasing the share of renewable energy sources in final energy consumption;
- Development of infrastructure for CO₂ and hydrogen storage in depleted reservoirs;
- Introduction of economic instruments such as emission taxes and carbon credit trading.

In addition, transitioning from a production model based on fossil fuels to a consumption model based on renewable sources requires not only technological change but also a broader socio-economic transition—changes in mindset, consumer behavior, and energy policies. CO₂ emissions in Europe show a clear downward trend, while in Serbia this process is slower, with fluctuations depending on seasonal and market conditions. The difference between the EU and Serbia lies not only in technological capacity but also in institutional readiness and access to financial mechanisms for decarbonization. Nevertheless, Serbia has considerable potential—in renewable energy sources, in the use of depleted gas fields for CO₂ storage, and in the development of the green hydrogen sector. Balancing energy production and consumption, reducing the carbon footprint, and improving energy efficiency represent the three pillars of Serbia's future energy strategy. The adoption of European standards and innovative technologies, combined with strengthening the research and development sector, can enable Serbia to achieve a stable and sustainable energy system in the coming decades—one that does not harm the environment, but instead protects and develops it in line with global climate neutrality goals.

4. Use of Green Hydrogen in Europe and Serbia

Green hydrogen is becoming a key element of the energy transition in Europe, acting as a bridge between traditional energy sources and a future based on renewable resources. Its production is based on the process of water electrolysis, in which electricity from renewable sources—primarily solar and wind—is used to split water molecules into hydrogen (H₂) and oxygen (O₂). Unlike so-called grey hydrogen, which is produced from natural gas and releases carbon dioxide in the process, green hydrogen does not emit CO₂ during production and is therefore considered a climate-neutral energy carrier [25].

4.1. European Framework and Trends

The European Union (EU) has recognized green hydrogen as one of the pillars of its strategy to achieve climate neutrality by 2050, as defined within the European Green Deal package. The Hydrogen Strategy adopted in 2020 set ambitious targets—production of up to 10 million tonnes of green hydrogen per year by 2030, as well as the development of a trans-European infrastructure for hydrogen transport and storage [25,26].

Countries such as Germany, the Netherlands, Denmark, and Spain are leading the development of the green hydrogen market, thanks to investments in solar and wind parks, as well as in electrolysis infrastructure. For example, Germany plans to build the European Hydrogen Backbone, a pipeline network connecting the entire continent, while the Netherlands is developing storage systems in depleted gas fields in the North Sea (IEA, 2023) [23]. The European Investment Bank (EIB) and mechanisms such as the Innovation Fund provide financial support for green hydrogen production and storage projects [26].

According to data from [27,28], hydrogen consumption in the EU amounted to approximately 8.2 million tonnes (Mt) in 2022 and about 7.3 Mt in 2023. The main users of hydrogen are refineries and the ammonia industry, which together account for more than 80% of total hydrogen consumption in the EU. As much as 96% of the existing hydrogen in the EU is produced from natural gas (i.e., fossil sources) without carbon capture,

resulting in a significant environmental footprint. Hydrogen consumption in the EU accounts for less than 2% of total energy consumption, indicating that hydrogen is still a marginal component of the energy mix, although its role is expected to grow. Figure 6 illustrates the distribution of hydrogen consumption across selected EU countries. In countries such as Germany, the Netherlands, Poland, and Spain, hydrogen consumption is the most significant, and together these countries account for a large share of total hydrogen use in the EU [29].

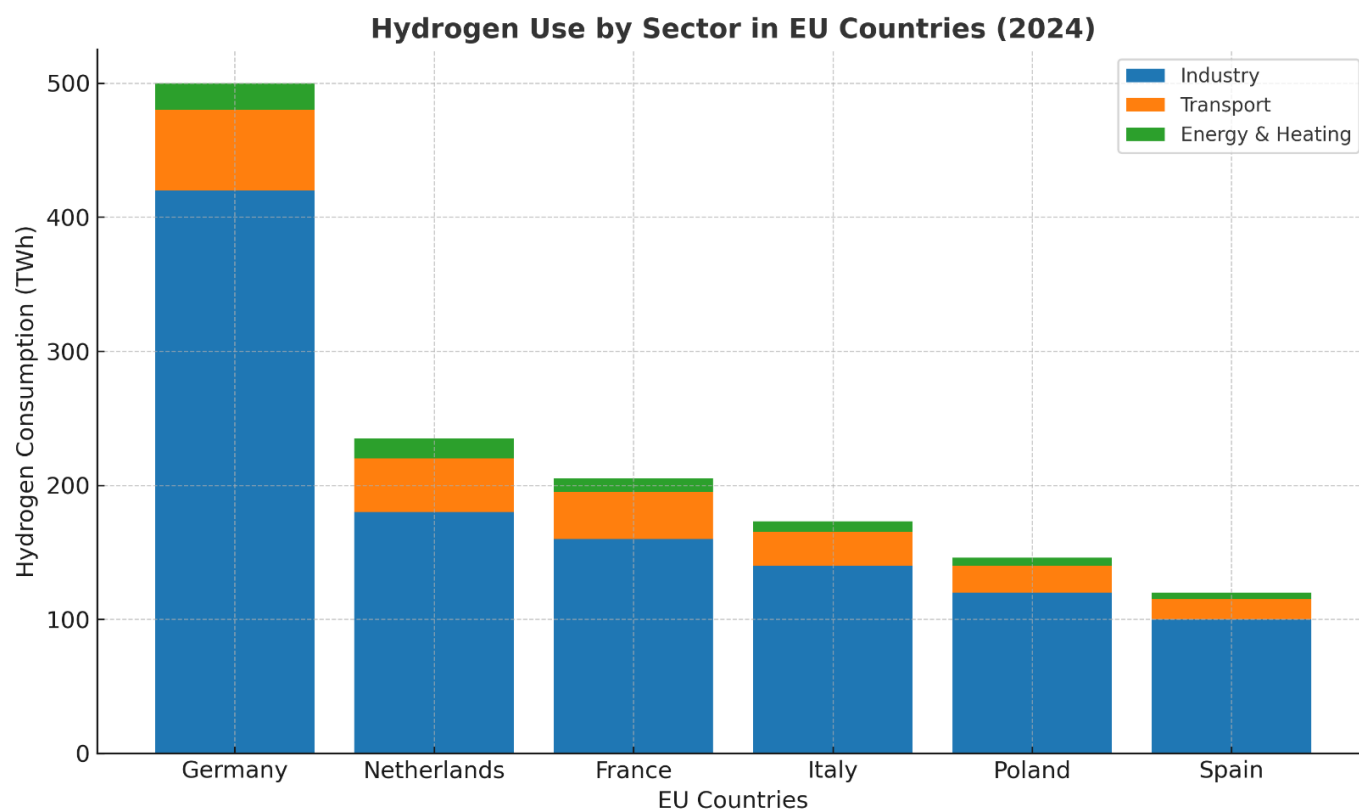


Figure 6. Hydrogen use in the EU by main sectors, 2022–2024 [26,27].

The use of green hydrogen in industry and transport is increasing, particularly in sectors that are difficult to decarbonize, such as the steel industry, chemical production, and heavy transport. In this way, hydrogen represents not only an energy source, but also a key feedstock in sustainable industrial policy [4,30].

4.2. Serbia and the Potential for the Development of a Hydrogen Economy

Serbia is at an early stage of hydrogen economy development, but it possesses significant potential for green hydrogen production due to the availability of renewable resources, existing gas infrastructure, and geological formations suitable for storage. According to data from the Ministry of Mining and Energy [31], installed wind power capacity exceeds 500 MW, while solar projects under development surpass 1 GW. These resources can serve as a basis for powering electrolyzers and producing green hydrogen.

Depleted gas fields in Serbia, such as those in Banatski Dvor and surrounding areas, represent substantial infrastructural potential for the safe storage of hydrogen. Given hydrogen's low molecular mass and high diffusivity, additional research is required on the compatibility of geological layers and the possibilities for long-term storage [30,32]. This would ensure a stable and decentralized energy supply system, contributing to increased national energy security.

In national strategic documents, such as the Integrated National Energy and Climate Plan (INECP) [10], hydrogen is recognized as part of the energy mix after 2030. It is expected that Serbia will develop its own Hydrogen Strategy in line with European standards, with support from EU programs for the Western Balkans [33]. Figure 7 presents a projection of hydrogen use in Serbia across different sectors.

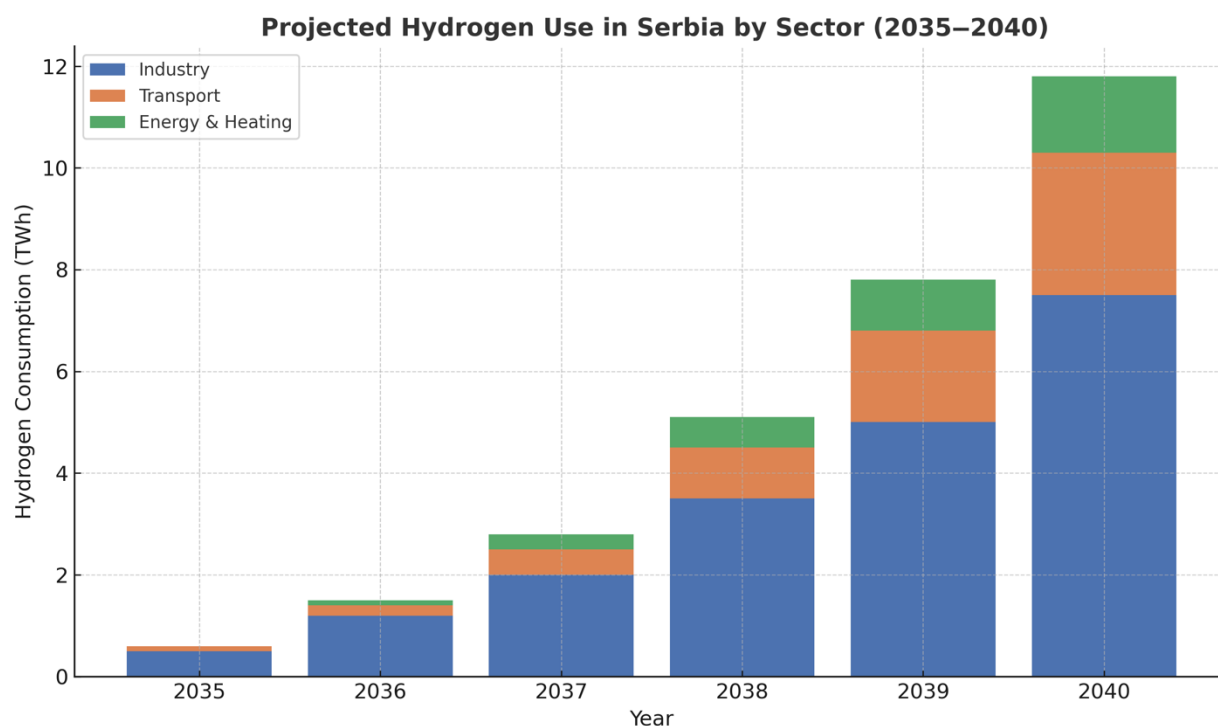


Figure 7. Projection of green hydrogen consumption in the Republic of Serbia, 2035–2040.

The chart presents a projection of green hydrogen consumption in the Republic of Serbia by sector—industry, transport, energy, and heating—for the period 2035–2040, expressed in TWh. The presented values are simulated, illustrative projections, based on publicly available national and European strategic documents, as well as relevant analytical sources related to the development of hydrogen technologies in the region.

4.3. Challenges and Perspectives

The main challenges in the development of the green hydrogen market in Serbia relate to the high costs of electrolysis, the need for an appropriate regulatory framework, and integration with the existing gas network. However, the experience of EU Member States shows that hydrogen production costs decrease significantly with the expansion of renewable energy capacities and technological progress [4]. In the long term, investments in hydrogen can contribute to the development of new economic sectors, job creation, and the establishment of a sustainable economic model based on low-carbon technologies [30].

Green hydrogen can play a dual role—as a means of reducing CO₂ emissions and as an energy carrier for storing surplus energy from renewable sources [34]. In this way, it enables balancing of the power system and contributes to security of supply during periods of unstable production from wind and solar energy. Its integration into the existing natural gas infrastructure and the use of depleted gas fields as storage facilities represent a strategic development direction for Serbia after 2035.

5. Geological Suitability of Serbian Subsurface Reservoirs for the Injection of Natural Gas, CO₂, and Green Hydrogen

Gas reservoirs in Serbia, primarily within the Pannonian Basin and in areas south of the Sava and Danube rivers near the Kostolac coal basin, are analyzed in this study as potential subsurface reservoirs for the injection of imported natural gas, CO₂ from domestic industrial sources (for greenhouse gas mitigation), and green hydrogen produced via electrolysis. These reservoirs include fields that are currently under production, depleted, or partially exploited. The potential of green hydrogen is particularly significant, as its energy content is approximately three times higher than that of natural gas on a mass basis.

The fundamental geological characteristics that determine the suitability of a gas reservoir for the injection and storage of natural gas, CO₂, and green hydrogen are closely related to the lithological, structural, and reservoir properties of the sedimentary formations. Of particular importance are the continuity and effectiveness of existing cap rocks, with low fault density being a favorable condition [28]. In addition, reservoirs must be well explored from a geological perspective, with special emphasis on reservoir rock characteristics, including storage capacity, lithological composition (sandstones and carbonates), effective porosity (>10%, optimally 15–30%), and permeability (>10 mD, preferably >100 mD to allow efficient injection). Reservoir depth is also a critical factor, with optimal depths ranging between 800 and 3000 m to ensure CO₂ remains in a supercritical state. The availability of wells, seismic data, and well logs significantly enhances reservoir characterization and enables the potential conversion of existing wells for injection purposes.

One of the potential gas reservoirs for gas and CO₂ injection is the Itebej field, located in northern Banat. From a lithostratigraphic perspective, the field consists of Upper Cretaceous, Miocene, Pliocene, and Quaternary sediments [29,35]. A key advantage for CO₂ storage is the presence of effective cap rocks composed of marls, siltstones, and clay-rich shales with extremely low permeability ($\leq 10^{-6}$ m/s) and reservoir pressures ranging from 100 to 150 bar, which are considered efficient barriers for CO₂ containment [29]. Additional verification of cap rock integrity at the Itebej field could be achieved through detailed 3D seismic analysis and advanced interpretation of well log data. The total thickness of reservoir rocks at Itebej, an important parameter for assessing CO₂ storage capacity, was determined based on well log interpretation, core analysis, and well testing results. Reservoir thickness varies between wells, with a maximum effective thickness of 19 m and a minimum of 1.5 m [29].

The Tilva gas field is located in southern Banat and was put into production in 1969. After the cessation of production, the wells were not permanently abandoned but preserved in anticipation of potential interest in developing an underground gas storage facility, given the relative proximity of Belgrade as a major consumption and industrial center. Since production at this site has ended, the reservoir is also considered suitable for potential CO₂ storage. From a geological perspective, the main advantages of the Tilva field include thick cap rocks composed of clayey to clay–marl sediments and compact Miocene shales, as well as favorable reservoir rocks represented by sandstones, marls, and marly sandstones. A key geological limitation of the Tilva field is the presence of fault zones [29]. Furthermore, planned development of a storage facility at this location has been challenged by the designation (or anticipated designation) of the area as a national park, which would restrict geological exploration and subsurface operations.

The Ostrovo gas field, located near Kostolac in eastern Serbia, represents a significant energy resource that has been under production since 2017. The field covers an area of approximately 5.9 km² and includes four wells with a daily production of about 17,000 m³

of natural gas. In 2017, the Oil Industry of Serbia (NIS) invested approximately EUR 3.2 million in the construction of a compressed natural gas (CNG) production facility at this site, with an annual capacity of 9000 tons (NIS source). Lithologically, the field is composed predominantly of Badenian, Pontian, and Pliocene sediments. Reservoir rocks consist mainly of sands and sandstones with very favorable effective porosity ranging from approximately 12% to 25% and permeability values typical of many Pannonian sandy reservoirs, commonly around 10 mD and locally reaching up to 200 mD. These properties are particularly favorable for storage applications, especially for green hydrogen. Cap rocks are composed of clays, marly clays, and marls, which are well suited for the containment of injected gases.

The Ada gas field is located in eastern Bačka, near the town of Ada, and represents one of the important natural gas production sites in Serbia. Gas production at this field is approaching its final phase, making it a potential candidate for CO₂ storage. The Ada field is a relatively small massive-type reservoir with a morphological trap within the Serbian sector of the Pannonian Basin. It is composed of Pontian and Upper Pliocene sediments, underlain by crystalline schists. Cap rocks, which are critical for CO₂ containment, are also of Pontian and Pliocene age and consist predominantly of clays and clayey marls. The reservoir exhibits an average porosity of approximately 22%, a pressure of about 88 bar, and a temperature of 66 °C [36].

The Čestereg gas field, located in the Banat depression in Vojvodina, has been identified as a potentially suitable site for geological CO₂ storage. The field is in the final stage of natural gas production, which makes it a strong candidate for repurposing. An important advantage is the existing gas production infrastructure, which can be adapted for CO₂ storage, thereby reducing both costs and implementation time.

The Mokrin oil and gas field comprises a massive oil reservoir with a gas cap hosted in fractured Paleozoic schists and Miocene sands/sandstones, five stratified oil reservoirs with gas caps in Lower Pontian sands and sandstones, and five gas reservoirs of Lower and Upper Pontian age. These reservoirs are of particular interest for natural gas and CO₂ injection and storage. The field covers an area of approximately 55 km², with reservoir depths reaching up to 1950 m, pressures of around 250 bar, and temperatures of approximately 114 °C. The average effective porosity is about 20%, with permeability values around 80 mD [35].

The Mramorak field is located in the South Banat District in northern Serbia, within the Pannonian Basin. It represents a relatively small oil and gas field that has been exploited by NIS Naftagas since 1970. According to NIS reports from 2023, the formal process of production cessation and site remediation has begun. The reservoir is hosted predominantly in Pontian and Pannonian sandstones, with reservoir rocks consisting of sandstones interbedded with marl layers. These reservoirs occur at depths of 1500–2500 m, with porosity values ranging from 15% to 22% and permeability between 50 and 350 mD. Both exploration and production wells are present, and the field is connected to the gas transmission network via the Mramorak gas metering and regulation station. Based on analogies with similar fields, the Mramorak reservoir is characterized by low to medium estimated reserves (~50–100 million m³). In synergy with the nearby Čibuk 1 wind farm, which generates electricity from renewable sources, infrastructure for the production and underground storage of green hydrogen could be developed, enabling an integrated energy system model in southern Banat [37–39].

The key geological and reservoir parameters of the analyzed depleted gas fields, used as input data for the suitability assessment, are summarized in Table 4.

Table 4. Geological and reservoir parameters of analyzed gas fields in Serbia.

Field	Geographic Location/Basin	Reservoir Lithology	Stratigraphic Age	Depth (m)	Effective Porosity (%)	Permeability (mD)	Pressure (bar)	Caprock Lithology	Key Geological Remarks	References
Itebej	Northern Banat, Pannonian Basin	Sandstones	Upper Cretaceous–Miocene–Pliocene	~1000–1200	~18–25	Tens to hundreds	100–150	Marls, siltstones, clayey shales	Highly effective caprock; very low permeability ($\leq 10^{-6}$ m/s); effective thickness 1.5–19 m	[29]
Tilva	Southern Banat	Sandstones with interbedded marls	Miocene	~1200	15–20	50–300	~110	Clayey and clay–marl sediments, compact shales	Presence of fault zones; limitations for H ₂ storage; protected natural area	Analogy, [29], (NIS source)
Ostrovo	Eastern Serbia, vicinity of Kostolac	Sands and sandstones	Badenian–Pontian–Pliocene	~1300	12–25	10–200	220–250	Clays, marly clays, marls	Very favorable reservoir properties; currently in production; high potential for H ₂ storage	[40,41]
Ada	Eastern Bačka	Sandstones	Pontian–Upper Pliocene	~1100	~22	5–100	~88	Clays and clay–marl sediments	Small, compact reservoir; suitable for pilot-scale CO ₂ projects	[36]
Čestereg	Banat Depression, Vojvodina	Sandstones	Pontian	~1200	~20	~40–300	~127	Clayey sediments	Final stage of production; existing surface and subsurface infrastructure	Analogy with Banatski Dvor [42]
Mokrin	Northern Banat	Sandstones and shales	Paleozoic–Miocene–Pontian	up to ~1950	~20	~80	~250	Compact clays and shales	Large areal extent (~55 km ²); multiple gas and oil reservoirs	[35]
Mramorak	Southern Banat, Pannonian Basin	Sandstones with interbedded marls	Pontian–Pannonian	1500–2500	15–22	50–350	~200	Marls and clays	Connected to gas transmission network; proximity to Čibuk 1 wind farm; potential for H ₂ storage	[37–39]

The dataset summarized in Table 4 integrates information from various publicly available sources and technical documentation, complemented by analogical assessments where direct reservoir data are restricted by commercial confidentiality and regulatory constraints.

5.1. Criteria for the Selection of Reservoirs for Natural Gas, CO₂, and H₂ Injection

In geological storage of natural gas CO₂ and H₂ in depleted reservoirs, the maximum allowable injection pressure is constrained by fracture pressure and in situ stress to preserve reservoir and caprock integrity. Injection pressures are often limited to ~80–90% of the fracture pressure, with typical fracture pressure ranges in target reservoirs between approximately 25–35 MPa; pore pressure increases exceeding ~25–30% above initial stress are considered high—risk for inducing fracturing or fault reactivation [43,44]. Exceeding these pressures can alter key geophysical properties of the reservoir, including porosity, permeability, caprock sealing capacity, stress redistribution, and fault stability, thereby compromising long-term storage safety [45].

The assessment of depleted gas reservoirs for the storage of CO₂, natural gas, and hydrogen (H₂) should be based on an integrated, phased approach that combines structural, petrophysical, geomechanical, and reservoir analyses [46]. In the initial phase, a detailed structural interpretation of the reservoir is carried out based on the reinterpretation of available 2D/3D seismic data, aiming to identify fault zones, their geometry and continuity, as well as to evaluate their role in maintaining caprock integrity.

In the next phase, the characterization of fracture systems and reservoir petrophysical properties relies on existing well data collected during exploration and production. These data include conventional and advanced well logs (gamma ray, density, neutron, sonic, resistivity) and laboratory analyses of core and sidewall samples. Integration of these data allows determination of key reservoir parameters, such as effective porosity, permeability, fluid saturation, and heterogeneity, which control the distribution and movement of fluids within the reservoir [47,48].

Assessment of the integrity of existing (legacy) wells constitutes a separate methodological step and includes the analysis of cement quality, wellbore conditions, and abandoned intervals using available technical documentation and integrity test results. This analysis enables the identification of potential vertical leakage pathways and the evaluation of risks associated with the long-term containment of CO₂, natural gas, or H₂.

In the final phase, all results are integrated into a three-dimensional reservoir and geomechanical model, which is used to simulate injection and withdrawal cycles, assess pressure and stress changes, and evaluate the stability of the reservoir, fault zones, and caprock during and after injection. This approach provides a preliminary yet technically grounded assessment of the safety and long-term stability of CO₂, natural gas, and H₂ storage in depleted gas reservoirs [49].

5.1.1. Criteria for the Selection of Reservoirs for Natural Gas Injection

From a geological perspective, reservoirs suitable for underground natural gas storage must be located at sufficient depths to ensure adequate compressibility and stable pressure performance. Regarding the petrophysical properties of reservoir rocks, sufficiently high porosity (>15%) and permeability (>50 mD) are required to allow efficient gas injection and flow. One of the most critical geological factors is the effectiveness of cap rocks, which must prevent fluid leakage and upward migration toward the surface [50].

From a technical standpoint, it is essential to ensure reliable injectivity and deliverability, enabling rapid filling and withdrawal cycles without excessive pressure drops within the reservoir [51]. Continuous monitoring of pressure, temperature, and gas

composition within the reservoir is also a key requirement, directly related to operational safety and system control. Economically, proximity to the existing gas transmission network represents a major advantage, as it reduces transportation costs and allows the reuse of depleted gas reservoirs that already meet the necessary geological and technical criteria for underground gas storage [50].

5.1.2. Criteria for the Selection of Reservoirs for CO₂ Injection

With respect to geological criteria, reservoirs intended for CO₂ injection must be located at depths exceeding 800 m to ensure that CO₂ remains in a supercritical state. Reservoir rocks must exhibit sufficient permeability to allow injection while maintaining long-term storage integrity. Cap rocks play a crucial role in preventing gas diffusion and migration; clay-rich formations, shales, and evaporites are considered the most effective sealing lithologies for CO₂ containment. From a geomechanical perspective, reservoir and cap rock formations must demonstrate sufficient stability to maintain structural integrity under elevated injection pressures [4].

In the context of geological storage, reservoir permeability should be quantitatively defined. Screening studies for CO₂ storage have proposed average permeability thresholds of approximately ≥ 10 mD, with operational practical thresholds ranging between ~ 5 –20 mD depending on reservoir type and desired injection rate [47,48]. Similar reservoir quality criteria for natural gas and hydrogen storage suggest that permeability on the order of ≥ 10 –50 mD generally supports effective injectivity and fluid mobility, though exact thresholds vary with reservoir geology and fluid properties [52–54].

To minimize the risk of leakage and ensure injection safety, a comprehensive assessment of the reservoir is required, including the evaluation of fracture systems, fault zones, and legacy wells. From an economic perspective, the availability of existing infrastructure and the use of depleted reservoirs significantly reduce investment costs and operational risks associated with CO₂ storage projects [51].

5.1.3. Criteria for the Selection of Reservoirs for Green Hydrogen (H₂) Injection

From a geological standpoint, reservoirs suitable for green hydrogen storage should exhibit moderate to high porosity (10–20%) and permeability greater than 10 mD, as these petrophysical properties strongly influence both hydrogen injection and withdrawal performance. Cap rocks must be characterized by extremely low diffusivity to prevent hydrogen leakage.

In geomechanical and geochemical terms, it is necessary to assess hydrogen interactions with materials used in well construction and infrastructure (e.g., cement, steel, and other metals), as well as potential reactions between H₂ and reservoir rocks or in situ fluids. These interactions may involve iron-bearing minerals, sulfur compounds, and microbial activity, all of which can affect hydrogen losses and reservoir integrity [30].

Literature data indicate that hydrogen losses due to diffusion, microbial consumption, and material interactions are typically limited to a few percent per year under conservative operational conditions, provided that appropriate reservoir selection, material compatibility, and monitoring strategies are applied. These effects are therefore considered manageable at the screening stage but require detailed site-specific assessment during project development.

From an operational perspective, reservoirs must support high-capacity and cyclic operation, allowing multiple injection–withdrawal cycles without degradation of storage performance. Safety considerations include continuous monitoring for potential micro-leakage using acoustic and chemical sensors. Economic criteria focus on the assessment of hydrogen losses over repeated cycles and the long-term maintenance costs of storage infrastructure [30].

The applied evaluation represents a screening-level assessment rather than a formal multi-criteria optimization. The criteria are not treated as equally weighted; reservoir integrity, injectivity, and storage capacity represent dominant constraints, while secondary parameters are evaluated qualitatively due to data availability limitations. Within this framework, variations in secondary criteria do not alter the identification of the most suitable reservoirs, supporting the robustness of the preliminary classification.

5.2. Classification of Serbian Reservoirs for Fluid Storage

Table 5 presents an overview and preliminary classification of seven significant reservoirs in Serbia according to their suitability for the storage of three types of fluids: natural gas (NG), carbon dioxide (CO₂), and green hydrogen (H₂). The classification is based on geological, technical–operational, safety, and infrastructural criteria. A score of 0 indicates a completely unsuitable reservoir, while a score of 5 denotes exceptionally high suitability.

Methodology and Criteria

For each reservoir, quantitative scores (0–5) were assigned across the following categories:

- Geological criteria—lithological composition, porosity, permeability, cap rock integrity, and depth.
- Operational criteria—injectivity, cyclic performance, and well infrastructure.
- Integrity and safety—tectonic setting, leakage risk, rock stability, and well integrity.
- Economic and infrastructural criteria—proximity to demand centers, costs, and access to existing pipeline networks.

Table 5. Classification of Serbian Reservoirs.

Reservoir	Score	NG Rating	Score	CO ₂ Rating	Score	H ₂ Rating	Remarks
Mokrin	3.5	Moderate	4.0	Moderate–High	2.5	Moderate–Low	Good reservoir properties; cap rock integrity requires further verification.
Itebej	3.8	Moderate	4.8	High	2.7	Moderate–Low	Excellent sealing formations; highly suitable for CO ₂ storage.
Čestereg	4.7	High	4.9	High	3.2	Moderate	Existing infrastructure; high suitability for CO ₂ and NG storage.
Ada	3.2	Moderate–Low	3.7	Moderate	2.6	Moderate–Low	Limited capacity; suitable for pilot-scale projects.
Tilva	3.5	Moderate	3.8	Moderate	2.0	Low	Fault zones limit suitability for H ₂ storage.
Ostrovo	4.0	High	3.8	Moderate	4.0	High	Currently under production; potential for future conversion; favorable reservoir properties.
Mramorak	4.0	High	3.9	Moderate	4.1	High	Production suspended; favorable reservoir properties.

Based on the analysis of the evaluated indicators, it can be concluded that the Ostrovo and Mramorak reservoirs exhibit the highest potential for the development of underground fluid storage projects and represent particularly promising candidates for green hydrogen injection. In addition to their favorable geological characteristics and estimated storage capacities of approximately 0.17 billion m³ and 0.34 billion m³, respectively, these reservoirs are located in close proximity to existing and planned green hydrogen production sites, which significantly reduces the need for investments in dedicated hydrogen transportation infrastructure [55].

The Čestereg and Itebej reservoirs meet the key geological and infrastructural criteria required for CO₂ injection, with estimated total storage capacities of approximately 0.40 billion m³ and 1.17 billion m³, respectively [29].

Reservoirs such as Ada and Tilva, with comparatively lower estimated capacities of approximately 0.64 billion m³ and 0.30 billion m³, may be suitable for research-oriented and pilot-scale activities, while the Mokrin field, despite exhibiting the largest estimated geological capacity (approximately 1.25 billion m³), requires additional assessment of cap rock integrity, although a generally balanced performance across the evaluated criteria is observed [55].

6. Discussion

Maintaining energy stability represents one of the key challenges and strategic priorities of Serbia's national energy policy in the coming decades. Under conditions of global energy market volatility, increasing climate pressures, and the ongoing transition toward a low-carbon economy, security of supply has become a critical factor for societal resilience and economic development. As a country with limited domestic fossil fuel resources, Serbia faces the need to ensure a stable, reliable, and economically sustainable energy supply while simultaneously reducing negative environmental impacts. In this context, the rational utilization of depleted gas reservoirs plays a central role, as these structures can form the foundation of a new energy infrastructure. Their repurposing for the storage of natural gas, carbon dioxide, and green hydrogen offers multiple benefits, including increased storage capacity, enhanced system flexibility, reduced greenhouse gas emissions, and the creation of favorable conditions for the deployment of clean energy technologies. This approach supports a closed energy cycle in which resources are not merely consumed but transformed and reused in accordance with the principles of sustainable development.

The injection of natural gas into depleted reservoirs contributes directly to energy supply security by enabling the establishment of strategic reserves that can be utilized during crisis situations or periods of seasonal demand fluctuation. In parallel, CO₂ storage in the same reservoirs supports emission reduction and the achievement of climate targets, thereby helping to balance energy needs with environmental protection objectives. As a result, the energy system becomes not only more reliable but also more environmentally sustainable. A particularly important aspect of the future energy system is the development of infrastructure for the storage and utilization of green hydrogen. Hydrogen, as a clean and renewable energy carrier, has the potential to become a central pillar of Serbia's energy transition. Its safe storage in depleted gas reservoirs and subsequent use in industry, transport, and power generation enable the gradual decarbonization of the economy and an increase in energy independence. When combined with the expansion of solar and wind power generation, hydrogen serves as an effective bridge between variable renewable energy production and a stable energy system.

Despite the expected increase in the share of renewable energy sources, projections indicate that natural gas will continue to play a significant role in Serbia's energy mix beyond 2035, particularly as a balancing fuel for district heating systems, electricity generation, and industrial consumption. Stabilized demand levels on the order of approximately 2.7–3.0 billion m³ per year suggest a sustained need for seasonal and strategic storage capacities to mitigate demand variability and external supply disruptions. From an energy security perspective, international practice indicates that underground gas storage capacities corresponding to approximately 20–30% of annual consumption are required to ensure system resilience. For Serbia, this implies a target storage volume of approximately 0.6–0.9 billion m³, a substantial share of which could be provided through the phased repurposing of existing depleted gas reservoirs.

From an economic standpoint, the conversion of depleted gas fields into storage sites offers clear advantages over the development of new greenfield facilities. Capital expenditures are significantly reduced through the reuse of existing wells, surface installations, and pipeline infrastructure, while operational experience from decades of gas production further lowers implementation risk. Although hydrogen storage requires additional investments related to material compatibility, monitoring systems, and operational control, current technologies demonstrate sufficient maturity for pilot-scale and early commercial deployment. Consequently, a phased implementation strategy—beginning with natural gas and CO₂ storage and progressively integrating hydrogen—represents a technically feasible and economically robust pathway for Serbia's energy transition.

Potential challenges associated with underground storage include pressure-induced geomechanical effects, fault reactivation, legacy well integrity issues, and geochemical interactions between injected fluids and reservoir rocks, all of which may alter reservoir characteristics if not properly managed. However, these risks can be mitigated through conservative pressure management, rigorous well integrity assessment, and continuous monitoring, supported by integrated reservoir and geomechanical modeling. Addressing these uncertainties at an early stage is essential for ensuring long-term storage safety and maintaining public and regulatory confidence in subsurface energy storage projects.

Ensuring energy stability beyond 2035 therefore requires an integrated approach that combines technological innovation, strategic planning, and environmental responsibility. In this process, research institutions play a crucial role in advancing knowledge, methodologies, and technologies that enable the effective implementation of emerging solutions. Sustainable energy development is not limited to securing sufficient energy supply but also encompasses responsible resource management, emission reduction, improvements in energy efficiency, and the protection of natural ecosystems. In conclusion, the preservation of Serbia's energy stability relies on the rational use of existing resources, the integration of renewable energy sources, and the development of infrastructure for energy storage and management. The implementation of innovative solutions, such as the injection of natural gas, CO₂, and green hydrogen into depleted reservoirs, represents a concrete step toward the establishment of a modern, resilient, and sustainable energy system. Such a system would not only ensure security of supply but also contribute to the long-term objectives of climate neutrality, economic resilience, and environmental protection in the Republic of Serbia.

7. Conclusions

The analysis presented in this study demonstrates that depleted gas reservoirs in the territory of Serbia have a significantly broader potential application beyond their original production role. Quantitative assessment of geological and reservoir parameters indicates that the analyzed fields exhibit total geological storage capacities ranging from approximately 0.17 to 1.25 billion m³, with petrophysical properties and caprock characteristics that satisfy key technical criteria for underground storage. Within these constraints, the injection of natural gas into existing reservoirs enables the formation of stable and reliable seasonal and strategic reserves, thereby increasing the country's overall energy potential and enhancing system resilience during periods of peak demand or supply disruption. This form of storage represents a rational utilization of existing geological structures and constitutes an important pillar of future energy planning.

In parallel, the permanent storage of CO₂ in the same reservoirs provides a dual benefit by contributing to greenhouse gas emission reduction while supporting compliance with European climate and decarbonization policies. The feasibility of CO₂ sequestration is supported by defined pressure limits, caprock integrity, and reservoir containment conditions identified in this study. Over the long term, such storage solutions may facilitate

the deployment of carbon capture and storage technologies, reduce the environmental footprint of the energy sector, and create additional opportunities for Serbia to access international funding mechanisms related to climate mitigation and environmental protection.

The third component—green hydrogen storage—represents the segment with the greatest long-term potential. Although the current role of hydrogen in the Serbian energy system remains limited, its importance is expected to increase with the expansion of renewable energy sources and the development of advanced electrolyzer technologies. The results indicate that selected depleted gas reservoirs, particularly those characterized by favorable permeability, integrity, and proximity to existing infrastructure, can support pilot-scale to early commercial hydrogen storage under conservative operational conditions. Geological hydrogen storage enables surplus electricity from wind and solar generation to be converted into a long-term, high-energy-density reserve, thereby enhancing system flexibility and supporting the integration of variable renewable energy sources.

Taken together, the combined injection of natural gas, CO₂, and green hydrogen represents a set of mutually complementary processes that can contribute to a more stable, economically efficient, and environmentally sustainable energy system in Serbia. By integrating quantified storage capacities, defined technical feasibility criteria, and demand-oriented considerations, this study provides a technically grounded basis for the phased implementation of underground energy storage beyond 2035. Based on the available data and relevant literature in gas technologies, geology, and energy systems, there are realistic grounds for depleted reservoirs—such as Ostrvo and Mramorak—to become an important component of Serbia's modern energy infrastructure and, in a broader context, the evolving European energy system in the coming decades.

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Abbreviations

The following abbreviations are used in this manuscript:

CCS	Carbon Capture and Storage
CH ₄	Methane
CO ₂	Carbon Dioxide
GHG	Greenhouse Gas
H ₂	Hydrogen
INECP	Integrated National Energy and Climate Plan
LNG	Liquefied Natural Gas
MtCO ₂	Million Tonnes of Carbon Dioxide

NDC	Nationally Determined Contribution
NG	Natural Gas
RES	Renewable Energy Sources

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