

Application of Hydrogen in Transport and Contribution to the Development of Green Logistics

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Abstract: *Hydrogen is considered by many experts to be the fuel of the future and the use of hydrogen is predicted in all branches of transport: road, rail, sea and air transport. The contribution of hydrogen in the fight against climate change is great because it has the ability to replace fossil fuels in traffic. The use of hydrogen in the transport sector enables a greater share of road electric vehicles, given that hydrogen as a fuel reduces the main disadvantages of today's electric vehicles with a built-in battery and plays a significant role in rail and ship transport. Day by day, hydrogen technology is advancing more and more, and there are fuel cells and hydrogen tanks used in airplanes. Thus, the paper provides a description of hydrogen as a fuel of the future, along with a description of its application and storage, and a critical view of the great expectations in the green logistic sector. Therefore, the aim of this work is to process and resolve the pre-set research hypotheses of the work that defines hydrogen as the fuel of the future. It also defines that by adhering to the European Green Plan and the Hydrogen Strategy, it is possible to achieve the desired results of sustainable logistics practice. This would render logistics operations ecologically sustainable in alignment with environmental protection regulations etc.*

Keywords: *hydrogen, transport, green logistics, climate change*

1. INTRODUCTION

The purpose of this paper is to highlight the importance of green logistics through the application of hydrogen in transportation. In order for hydrogen to be used as a fuel in the future, it is essential to thoroughly investigate and identify its primary advantages as well as its drawbacks. Additionally, the paper aims to outline the factors hindering the widespread use of hydrogen as a fuel, while also addressing its disadvantages and proposing effective solutions to overcome these challenges. The logistics sector is increasingly focusing its activities on reducing the negative impact on the environment, thereby actively contributing to the community. This approach is known as green logistics, and the achievement of environmental protection goals is realized through the use of renewable energy sources in logistics processes, while avoiding activities that harm the environment. The term "green logistics" emerged in the mid-1980s and is closely related to sustainable development. The impact of the transport sector on greenhouse gas emissions cannot be ignored, which is why the development of environmentally friendly alternative fuels has become crucial. Alternative fuels, which can

replace fossil fuels, even partially, are important for transportation energy and can help in the decarbonization of the transport system. One of these fuels is hydrogen, which is considered the fuel of the future. Research into fuel cell technology, which offers high efficiency and minimal environmental impact, is becoming increasingly important. Fuel cells convert the chemical energy of hydrogen into electrical energy, which can be used to power devices such as generators, batteries, laptops, mobile phones, and vehicles. The success of hydrogen vehicle technology depends on fuel costs, the development and expansion of hydrogen refueling stations, and the safety and characteristics of vehicles using hydrogen propulsion.

2. METHODOLOGY

The writing process involved the use of scientific methods. The primary method was definition, which clarified the key terms in the text. The content analysis technique was used to gather information about green logistics and hydrogen as a fuel. The description method refers to the application of hydrogen in transportation and hydrogen refueling stations. Deductive reasoning was used to process the data and draw conclusions about the importance of hydrogen as a fuel and the role of the European plan for the development of green logistics.

3. CONCEPTUAL DEFINITION OF GREEN LOGISTICS

Logistics derives from the French words *logistique* and *loger*, both meaning “storage.” Today, the term refers to a comprehensive system that enables the efficient movement of goods, materials, and information from the point of origin to the point of consumption or use. It includes a wide range of activities such as transportation, inventory management, packaging, and information flow. As an essential part of the supply chain, logistics aims to enhance the value of products through optimal use of time and space, ensuring timely delivery, cost efficiency, and greater customer satisfaction (Rodrig and co-authors, 2001).

Green logistics focuses on reducing the environmental impact of logistics operations. As customers increasingly value sustainability and prefer eco-conscious companies, logistics providers are expected to lower carbon emissions, improve waste management practices, and use recyclable materials. In densely populated urban centers, the environmental effects of logistics are especially noticeable. Despite rapid technological development, environmental considerations are often overlooked, and outdated practices continue to affect both ecosystems and public health. Traffic flow, as a fundamental part of daily life, has a profound influence on quality of life and overall social development.

Transportation is a major source of pollution in logistics. High traffic volumes contribute significantly to environmental problems, particularly through noise pollution and carbon dioxide emissions, two of the most pressing challenges. Because time is crucial in logistics, the use of faster but more polluting transport modes such as air and road freight has increased, despite their low energy efficiency (Rodrig and co-authors, 2001).

Environmental pollution from logistics takes many forms: greenhouse gas emissions, water contamination, noise, and habitat degradation. The transport of goods poses risks to oceans, rivers, and underground waters, with oil spills from tankers being a well-known and visibly harmful example.

Energy use is also a central issue. It is indispensable for industrial activity and essential to the production of goods and services, but its responsible and efficient use is key to achieving both economic and environmental sustainability. When considering the use of resources, it is crucial to take into account the natural environment and energy systems. Sustainable development requires responsible utilization of available natural sources with minimal impact on ecosystems. This includes a strong focus on alternative energy sources, such as solar and wind power to reduce dependence on limited, non-renewable resources. Our ability to manage the environment and energy sustainably will determine society's resilience and the planet's long-term health.

The development of transport infrastructure has led to significant loss of natural habitats, especially in densely populated urban areas. Transport systems, including road, air, maritime, and rail, shape urban environments but are also major contributors to climate change. Due to heavy reliance on fossil fuels, the transport sector is responsible for a substantial share of global greenhouse gas emissions. Vehicles emit large amounts of carbon dioxide (CO₂), methane (CH₄), which intensify the greenhouse effect and accelerate global warming.

Moreover, transport contributes to ozone layer depletion and air pollution, further exacerbating ecological and health challenges. From infrastructure construction to fuel combustion, every phase leaves a measurable impact on the climate system.

In this context, the concept of green logistics encompasses practices and strategies aimed at reducing the environmental footprint of transportation activities. This includes route optimization, switching to low-emission vehicles, increasing energy efficiency, and integrating renewable energy sources wherever possible. Sustainability is no longer a choice, it is a necessity that must be embedded in every aspect of future-oriented transport planning.

Transportation has numerous advantages, but like any other means of transport, there are also disadvantages that need to be considered. The most prominent and significant drawback is undoubtedly the considerable amount of environmental pollution that occurs. The introduction of eco-friendly transportation methods has become an essential necessity (Duić, 2004).

4. PRODUCTION AND APPLICATION OF HYDROGEN IN TRANSPORT

At standard temperature and pressure, hydrogen gas is non-toxic, colorless, odorless, and highly flammable, making it the lightest of all gases. Due to its low density, hydrogen typically rises to the top of the atmosphere and is rarely found in its pure molecular form. However, when used as a fuel in combination with oxygen, the combustion of hydrogen produces no toxic by-

products.

The energy released from the combustion of hydrogen and oxygen makes it possible to use hydrogen as a fuel source that can power fuel cells and internal combustion engines. Recently, hydrogen has been utilized in commercial electric vehicles powered by fuel cells, such as buses and cars. Hydrogen is often seen as an energy carrier because it must be produced from primary energy sources such as coal, natural gas, or renewable energy sources (Jukić, 2009).

Hydrogen color coding is a system used to indicate how hydrogen is produced. According to current nomenclature, there are:

- green
- blue
- grey
- turquoise hydrogen.

Green hydrogen is produced from renewable energy sources, such as wind or solar power.

Grey hydrogen is derived from fossil fuels, primarily natural gas, without carbon capture, making it cost-effective but environmentally harmful.

Blue hydrogen is similar to grey hydrogen but incorporates carbon capture and storage, reducing CO₂ emissions during production.

Turquoise hydrogen is an emerging alternative produced through methane pyrolysis, generating solid carbon instead of CO₂, offering a lower-emission transitional pathway between grey and green hydrogen.

Hydrogen from black or brown coal is classified as black or brown hydrogen, while white hydrogen occurs naturally in underground reservoirs. Each type differs in environmental impact, cost, and production feasibility (Rodrig and co-authors, 2001).

Currently, grey hydrogen remains the most common due to its low cost (~€1.5/kg), whereas green hydrogen produced via electrolysis using renewable energy ranges from €2.5–5.5/kg, depending on electricity prices. Technological advances and scaling of electrolyzers are expected to reduce costs, with renewable hydrogen projected to become more competitive by 2030.

In Croatia and the EU, renewable hydrogen production is closely linked to industrial and transport applications, leveraging existing infrastructure. Continuous development of grey, blue, and turquoise hydrogen can provide transitional solutions while green hydrogen capacity

expands, enabling a gradual shift toward sustainable energy systems. There are also cases where the generated hydrogen does not fit into the colors mentioned above, leading to the appearance of yellow, white, and even purple hydrogen.

Many experts suggest that instead of directly transitioning to green hydrogen, a more feasible approach would be to use blue hydrogen as a transitional fuel. This approach involves capturing the carbon emissions produced during the hydrogen production process and storing them, thereby reducing overall emissions. The primary method for producing blue hydrogen involves using natural gas in a process commonly referred to as blue hydrogen production. When carbon dioxide turns into vapor, it is not climate-neutral and behaves in a special way.

When discussing the storage of carbon dioxide as a by-product, it is often referred to as a greenhouse gas. The hydrogen production process must first be considered, followed by the storage and capture of carbon in this form. One of the main advantages of blue hydrogen is that it does not emit significant amounts of carbon dioxide, unlike other hydrogen production methods. It is well-known that producing grey hydrogen is a cost-effective production method, making it a desirable option.

The production process can be enhanced by installing a more powerful electrolyzer. This upgrade will be particularly simple in cases where only the electrolyzer needs to be replaced with a higher-capacity model. Some facilities already have the necessary infrastructure for this purpose. Demand is expected to rise significantly after 2030, with an even greater increase anticipated by 2040 and beyond. To meet the demand for sustainable hydrogen, it is imperative that renewable hydrogen production is sufficient to fulfill all needs.

When considering the needs of Croatia, it is also important to recognize the potential for exporting renewable hydrogen to other countries. Expanding the scope of the environment requires a focus on developing and promoting complementary capabilities. This is essential for ensuring a broader and more comprehensive environmental impact. The development of electricity generated from renewable sources and advancements in renewable hydrogen production technology offer promising prospects for establishing sustainable energy solutions.

Effective cooperation between sectors such as agriculture, waste management, energy, and transportation confirms the quality of inter-sectoral collaboration. Implementing various measures, such as utilizing advanced technologies and forming strategic partnerships, can help achieve competitive input costs for renewable hydrogen production.

4.1. ADVANTAGES AND DISADVANTAGES OF USING HYDROGEN

As previously mentioned, hydrogen is an important energy carrier in the alternative and renewable energy sector. However, it has its advantages and disadvantages.

The advantages of using hydrogen as an energy source include:

- It is renewable and abundant, so there is no risk of depletion.
- A clean fuel that does not leave impurities when burned, and the byproduct is clean drinking water.
- More environmentally friendly and reduces greenhouse gas emissions.
- It is non-toxic, making it unique compared to many other fuels.
- It has a high energy value per unit of mass (around 120 MJ/kg) but a low energy value per unit of volume, which explains why it requires compression, liquefaction, or advanced storage methods for effective use. These technical requirements present practical challenges in transport and energy systems.
- More efficient than other types of fuels (a vehicle using hydrogen can travel further than a vehicle using the same amount of conventional gasoline).

The disadvantages that prevent its wider use are:

- Fuels are currently expensive and obtaining pure hydrogen from chemical compounds is often unprofitable.
- Acquiring hydrogen is not straightforward as there are currently very few hydrogen fuel stations in the world, i.e., there are few hydrogen refueling stations.
- As mentioned, transporting hydrogen is inconvenient and difficult to implement. Storage methods have been proposed, but none are simple, which further complicates transport and the feasibility of widespread use.
- It is highly flammable, hence safety in its use is one of the issues, although it is not any more dangerous than other fuels.
- Given that hydrogen molecules are very small, very large amounts of hydrogen leak through tanks and pipelines. Unlike natural gas, hydrogen is odorless, which is why sensors must be used to detect hydrogen leaks (Gomes and co-authors, 2008).

4. 2. THE APPLICATION OF HYDROGEN IN TRANSPORTATION AND HYDROGEN REFUELING STATIONS

The production of hydrogen from renewable energy sources is a key prerequisite for its use in transportation. Equally important is the development of compatible vehicles and the establishment of hydrogen transport and supply infrastructure. These tasks must be carried out simultaneously, requiring significant resource investment. The transition from fossil fuels to hydrogen as a primary energy source must be practical and feasible, ensuring that existing infrastructure is not disrupted. Expanding renewable energy production capacities demands coordinated efforts.

Hydrogen's potential as a fuel for vehicles has been researched in recent years. It has been proven that hydrogen-powered vehicles benefit the environment, as they only produce water

vapor as a by-product. Furthermore, hydrogen use can reduce our dependence on non-renewable energy sources. As technology continues to evolve, hydrogen remains a promising option for a sustainable future.

Emissions are a key factor, and alternative fuels like hydrogen play an important role in their reduction. Hydrogen technology has advanced impressively in transportation, from roadways to railways and even to maritime transport. Additionally, fuel cells and hydrogen tanks, particularly for aircraft, have become incredibly lightweight.

To maximize hydrogen's efficiency in the transport sector, the simultaneous delivery of all necessary components is essential.

The hydrogen value chain includes all stages from production, transport, to usage. Coordinating the development of hydrogen-powered vehicles and building an effective infrastructure is crucial for successful deployment. The establishment of such infrastructure strongly impacts the speed of market growth and fosters trust between stakeholders, ultimately leading to successful outcomes.

Its use across air, maritime, and road transport offers significant advantages not only in terms of reducing harmful emissions like carbon dioxide but also in terms of energy efficiency and sustainability. In the aviation sector, although commercial hydrogen-powered aircraft are still in development, prototypes using hydrogen as fuel promise a radical shift in reducing emissions from the aviation industry. The maritime sector also shows significant progress, with projects exploring hydrogen use in ships, thereby reducing harmful emissions in oceans—an area often overlooked in the global emissions debate. In road transport, hydrogen-powered vehicles, ranging from cars to buses and trucks, already operate commercially, helping to reduce emissions in urban environments and increase energy efficiency over long distances.

However, a successful transition to hydrogen as a primary energy source in transport requires coordinated efforts in technology development, infrastructure construction, and market adaptation. Additionally, a key component for the success of this transition will be the production of hydrogen from renewable energy sources, which will further reduce overall emissions and enable a more sustainable energy system. Given all the challenges, including investment in infrastructure and vehicle development, it is essential that international efforts are coordinated to achieve global emission reductions and ensure a sustainable future for the transport industry.

Hydrogen not only offers solutions for reducing carbon dioxide emissions but also plays a key role in mitigating climate change, as reducing emissions from transport is a significant step in the global fight against global warming.

Hydrogen fueling stations are becoming a crucial part of the infrastructure enabling the wider adoption of hydrogen-powered vehicles. While the number of fueling stations is still growing,

many countries in Europe and Asia are seriously considering hydrogen as a viable alternative to fossil fuels and have created ambitious plans for building a hydrogen station network.

1. **Fast Refueling:** Hydrogen fueling stations allow for very fast refueling, it typically takes only 3-5 minutes to fill a vehicle's hydrogen tank. This is a significant advantage over electric vehicles, which require much longer charging times for their batteries.
2. **“Smart” Location Strategy:** Fueling stations are often located at high-traffic areas such as gas stations, making it easier to integrate into the existing infrastructure. Additionally, some cities are developing “green zones” where hydrogen fueling stations will be the only option, encouraging the reduction of CO₂ emissions.
3. **New Approaches to Hydrogen Distribution:** In addition to traditional fueling stations, mobile hydrogen fueling stations are being explored as temporary solutions for short distances or in areas where large infrastructure investments might not be economical. There are also innovations like “decentralized fueling stations” that use renewable energy sources (such as solar power) to produce hydrogen on-site.
4. **The Future of Hydrogen Stations:** With the rapid development of hydrogen technology and the growing demand for sustainable transport, the number of hydrogen fueling stations is expected to grow rapidly, creating a global network that will further facilitate the growth of the hydrogen vehicle market. By 2030, the number of fueling stations could increase to more than 10,000 worldwide, according to various industry predictions. (Verhelst and Sierens, 2006).

5. THE EUROPEAN GREEN DEAL AND THE ROLE OF HYDROGEN IN MITIGATING CLIMATE CHANGE

The European Union has set an ambitious goal of achieving carbon neutrality by 2050 through its European Green Deal. Hydrogen plays a central role in this plan as a clean fuel capable of significantly reducing greenhouse gas emissions in transport, industry, and energy systems. In the context of climate change, hydrogen offers concrete solutions to mitigate the impacts of global warming.

Hydrogen can help mitigate climate change:

1. **Reducing emissions and temperatures:** Hydrogen helps lower CO₂ emissions, directly reducing average temperatures and the frequency of tropical nights.
2. **Addressing droughts:** Hydrogen reduces water consumption in industries, particularly in energy generation, helping alleviate drought pressures in water-scarce regions.
3. **Mitigating sea-level rise:** By reducing CO₂ emissions, hydrogen helps slow down the melting of glaciers, indirectly mitigating sea-level rise.
4. **Flood prevention and extreme weather:** Hydrogen can reduce urban heat islands by replacing fossil fuels in transportation, thus decreasing urban flooding and extreme weather events.

5. **Green transport and decentralized energy:** The adoption of hydrogen vehicles and fueling stations, alongside decentralized energy solutions, promotes energy stability and reduces emissions (Verhelst and Sierens, 2006).

6. CONCLUSION

The paper proposed two hypotheses, with the first being confirmed. It states that hydrogen is the fuel of the future due to the growing demand for renewable and sustainable energy. Hydrogen is not only the fuel of the future with the potential to replace fossil fuels, but it also offers dual benefits: it reduces greenhouse gas emissions and contributes to sustainable waste management. When combined with green technologies such as solar panels, green roofs, and rain gardens, hydrogen can significantly help in mitigating climate change, reducing the risks of flooding and urban heat islands.

The key to achieving carbon neutrality and sustainable development lies in integrating hydrogen into energy systems and urban technologies, thereby contributing to the preservation of the environment and human health.

Hydrogen vehicles, powered by fuel cells, reduce greenhouse gas emissions and offer an efficient, clean solution. Investment in infrastructure will lower costs and increase hydrogen vehicle availability, with Croatia's hydrogen bus project in Zagreb being a key example.

The second hypothesis, still under investigation, suggests that alignment with the European Green Deal and hydrogen strategies will drive green logistics development, depending on significant investments. Change will take time, but once individuals recognize the importance of green logistics, we can collectively make a meaningful impact. This paper offers recommendations for achieving ecological sustainability and social responsibility.

In conclusion, although hydrogen plays an important role in the long-term decarbonization of the energy and transport sectors, its application in transportation is currently constrained by significant technical, economic, and infrastructural challenges. High costs of green hydrogen production, low overall efficiency of the hydrogen value chain, and the complexity and expense of the required infrastructure considerably limit its large-scale commercial adoption. In addition, storage and safety requirements further complicate the deployment of hydrogen technologies, particularly in road and urban transport.

Therefore, hydrogen cannot presently be regarded as a universal solution for all transport modes. Its use is most justified in sectors where direct electrification is technically or economically unfeasible, while battery-electric vehicles remain a more efficient and mature option for most road transport applications. Future development of hydrogen mobility will depend on technological progress, cost reductions, and the expansion of renewable energy sources, highlighting the need for a gradual, selective, and pragmatic approach to its integration into transport systems.

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