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A COMPREHENSIVE OVERVIEW OF THE EUROPEN AND BALTIC LANDSCAPE FOR HYDROGEN APPLICATIONS AND INNOVATIONS

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Hydrogen has been widely recognised as a versatile and environmentally-friendly energy carrier, with a broad range of potential applications across various sectors. The abundance of hydrogen in the universe and its high energy content makes it an attractive alternative to conventional fossil fuels. Moreover, the utilization of hydrogen does not produce greenhouse gases or other pollutants that contribute to air pollution and climate change. In recent years, there has been a growing interest in developing and deploying hydrogen technologies for a sustainable energy future. This paper provides an in-depth exploration of the potential of hydrogen as a clean energy source in different sectors, such as transportation, energy storage, power generation, industry, buildings, maritime transport, and aviation. The aim of the paper is to provide an overview of the current state of hydrogen applications in Europe and the Baltic States, including examples of ongoing projects and initiatives, and to assess the advantages and disadvantages of hydrogen technologies in different sectors. The main results of the paper highlight that hydrogen has the potential to significantly reduce greenhouse gas emissions and

achieve carbon neutrality targets. However, the deployment of hydrogen technologies also faces various challenges such as high production costs, lack of infrastructure, and safety concerns. The tasks of the paper are to provide an insight into the potential of hydrogen, identify the challenges and limitations, and highlight ongoing research and development efforts in this field. The paper concludes that the widespread adoption of hydrogen technologies is a long-term goal that requires the cooperation of various stakeholders and the development of innovative and cost-effective solutions. Despite the challenges, the current state of hydrogen applications and ongoing projects in Europe and the Baltic States demonstrate that hydrogen has the potential to play a significant role in the transition to a sustainable and low-carbon future.

Keywords: *Aviation, buildings, clean energy, energy storage, hydrogen, industry, marine, power generation, transportation.*

1. INTRODUCTION

Hydrogen, a colourless and odourless gas, is the most abundant element in the universe. It has a high energy content and can be produced from a variety of sources, including natural gas, coal, biomass, and renewable energy sources (hereinafter – RES). Hydrogen has been recognised as a promising alternative energy carrier that can contribute to a sustainable and low-carbon energy future. Its diverse range of applications across various sectors, including transportation, industry, and power generation, has garnered significant interest from governments, industry, and academia in recent years [1]–[5].

Hydrogen has emerged as a crucial element for the European market, as the region aims to transition, with the goal of achieving net-zero greenhouse gas emissions (hereinafter – GHG) by 2050. The European Union (EU) has recognised hydrogen as a key enabler of its energy and climate goals. One of the main reasons why hydrogen is so important for the European energy market is its potential to decarbonize sectors that are difficult to electrify, such as heavy industry, long-distance transport and aviation. The EU has set ambitious targets to reduce GHG by at least 55 % by 2030, and hydrogen can play a crucial role in achieving these targets. Moreover, hydrogen has the potential to reduce the EU's dependence on fossil fuels, improve energy security, and stimulate economic growth by creating new jobs and markets [2], [4]. The European Commission has identified hydrogen as a key priority and has proposed a strategy to support the development of a clean hydrogen economy in Europe. To achieve these goals, the EU has set a target of producing at least 40 gigawatts of renewable hydrogen by 2030, and has allocated significant funding to support research, development, and deployment of hydrogen technologies. The EU is also promoting the development of a hydrogen infrastructure network, including pipelines and refuelling stations, to support the widespread use of hydrogen in transportation and industry. In addition, the EU is collaborating with international partners, like Japan, South Korea, and the United States, to develop a blueprint of the global hydrogen market.

This collaboration aims at accelerating the development and deployment of hydrogen technologies, improving the cost-effectiveness of hydrogen production and storage, and establishing common standards

and regulations for safe handling and usage of hydrogen. The EU's commitment to the development of a clean hydrogen economy presents significant opportunities for the region, including reduced GHG, improved energy security, and enhanced economic growth [5]–[8].

Hydrogen can play a crucial role in helping countries to reach their neutrality targets by providing a versatile, low-carbon energy carrier that can be produced from a variety of sources, including renewable energy. Hydrogen has the potential to decarbonize various sectors that are difficult to electrify, such as heavy industry, long-distance transportation, and heating and cooling of buildings. One of the main ways how hydrogen can help reach neutrality targets is by replacing fossil fuels in transportation. Fuel cell electric vehicles powered by hydrogen fuel cells emit only water vapor as a by-product, making them a zero-emissions alternative to conventional gasoline and diesel vehicles. In addition, hydrogen can be used to power heavy-duty trucks, buses, and trains, which are difficult to electrify due to their energy demands. Hydrogen can also be used as a feedstock for the production of chemicals, such as ammonia and methanol, which are used in the production of fertilizers and other industrial products. By replacing fossil fuels with hydrogen in these sectors, significant reductions in GHG can be achieved. Furthermore, hydrogen can be used in power generation, either through combustion or in fuel cells. When combined with RES such as wind and solar power, hydrogen can help store excess energy and provide a reliable source of electricity during times of low RES availability.

In order to reach neutrality targets, significant investments are needed to develop and deploy hydrogen technologies. This includes investments in the production, storage, and distribution of hydrogen, as well as the development of supporting infrastructure such as refuelling stations, adapting existing natural gas pipelines to hydrogen transportation and building special hydrogen pipelines. Governments, industry, and other stakeholders will need to work together to establish common standards and regulations to ensure the safe handling and usage of hydrogen. Hydrogen can help countries reach their neutrality targets by providing a versatile, low-carbon energy carrier that can be used across various sectors. By replacing fossil fuels with hydrogen, significant reductions in GHG can be achieved, while also supporting the transition to a sustainable, low-carbon energy future [9]–[13].

The Baltic States, which include Estonia, Latvia, and Lithuania, have been exploring the potential of hydrogen to help achieve their climate and energy goals. The region has recognised hydrogen as a key enabler of this complex process. One of the main areas of focus for hydrogen in the Baltic States is transportation. The region has set ambitious targets to reduce GHG in transport, and hydrogen can play a crucial role in achieving these targets. For example, Estonia has developed a national hydrogen roadmap, which outlines the potential for hydrogen fuel cell vehicles and the necessary infrastructure to support them.

Moreover, the Baltic States have significant potential for RES such as wind and solar power, which can be used to produce renewable hydrogen through electrolysis. The region is already a leader in renewable energy, with Estonia and Latvia ranking in the top five in the EU in terms of the share of renewable energy in their total energy consumption.

In addition to transportation, the Baltic States are exploring the potential of hydrogen in other sectors such as industry and power

generation. For example, Lithuania is developing a green hydrogen production project, which aims at using renewable energy to produce hydrogen for industry. To support the development of a hydrogen economy in the Baltic States, significant investments are needed in research and development (hereinafter – R&D), as well as in the production, storage, and distribution of hydrogen. The region will also need to develop supporting infrastructure such as refuelling stations and pipelines [1], [2], [4], [8].

Latvia is exploring the potential of hydrogen to help achieve its climate and energy goals, and the main focus area for hydrogen in Latvia is transportation. The country has identified hydrogen fuel cell vehicles as a potential solution to vehicle triggered air pollution problem.

The Latvian government has developed a national hydrogen roadmap, which outlines the potential for hydrogen fuel cell vehicles and the necessary infrastructure to support them. In addition, the roadmap includes plans for the production of hydrogen from RES. Moreover, Latvia has significant potential of biomass. Biomass gasification is a mature technology that uses a controlled process involving heat, steam, and oxygen to convert biomass to hydrogen and other products, without combustion. Because growing biomass removes carbon dioxide (hereinafter – CO_2) from the atmosphere, the net carbon emissions of this method can be low, especially if coupled with carbon capture, utilization, and storage in the long term [14].

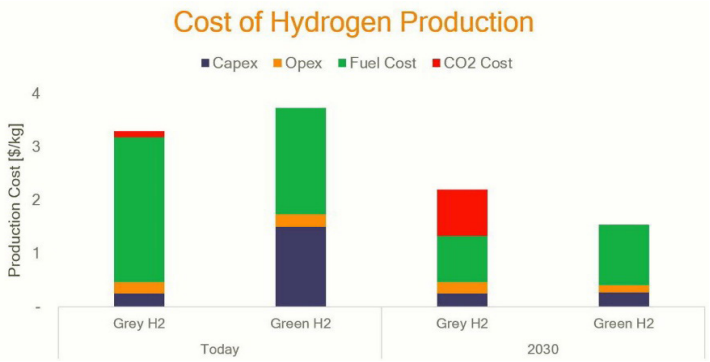
Latvia is already one of the leaders in the use of biomass for heat and electricity generation, and hydrogen produced from biomass could be yet another pathway in diversification of its use. In addition to transportation, Latvia is exploring the potential of hydrogen in other sectors such as industry and power generation. For example, the country's energy sector has already started to use hydrogen to balance the power grid during times of low renewable energy availability. The Latvian government is also promoting the use of hydrogen as a feedstock for the production of chemicals, such as ammonia, which are used in the production of fertilizers and other industrial products. To support the development of a hydrogen economy in Latvia, significant investments are needed in research and development, as well as in the production, storage, and distribution of hydrogen. The country will also need to develop supporting infrastructure such as refuelling stations and pipelines [3], [5]–[8].

While hydrogen offers significant potential for decarbonizing various sectors and achieving climate and energy goals, there are several challenges and issues that need to be addressed to realise its full potential. One of the main challenges with hydrogen applications is cost. The production, storage, and distribution of hydrogen can be expensive, particularly when produced from renewable sources. However, as shown in Fig. 1, and according to some researchers, the situation in green hydrogen production could also change for the best even by 2030.

Another challenge with hydrogen applications is infrastructure. The development of supporting infrastructure, such as refuelling stations and pipelines, is necessary for widespread adoption of hydrogen in transportation and other sectors. Building the infrastructure can be costly and time-consuming, particularly in areas where demand is low. Furthermore, there are concerns about the safety of hydrogen due to its flammability and potential for leaks. While hydrogen is safe when handled properly, there are risks associated with its production, storage, and transport that need to be managed carefully.

Another issue with hydrogen applications is the current lack of regulations and

standards for its production, storage, and use. Establishing common standards and regulations will be necessary to ensure the safe handling and use of hydrogen and to support the development of a hydrogen economy. Finally, the current supply of hydrogen is largely dependent on natural gas, which produces greenhouse gas emissions during production. To realise the full potential of hydrogen as a low-carbon energy carrier, the production of hydrogen needs to shift towards RES [15]–[17].



Source: Rethink Energy

Fig. 1. Comparison of costs in green and grey hydrogen production (2022, 2030, in $/kg).

There are several strategies and solutions that can be implemented to address the challenges associated with hydrogen applications and support the development of a sustainable hydrogen economy. Some of them include:

- technological advancements: continued research and development can lead to new and more efficient technologies for producing, storing, and distributing hydrogen, which can help reduce costs and increase the competitiveness;
- scale-up of production: by scaling up the production of hydrogen, economies of scale can be achieved, which can help drive down the cost of hydrogen production;
- supporting infrastructure: developing the necessary infrastructure, such as refuelling stations and pipelines, can help promote the adoption of hydrogen in transportation and other sectors. Governments and private enterprises can invest in building this infrastructure to create a national, transnational or regional hydrogen network;
- safety regulations: establishing common safety regulations and standards for the production, storage, and transport of hydrogen at the EU level can help ensure the safe handling and use of hydrogen and promote public confidence in the technology;
- policy support: governments can provide policy support, such as tax incentives, grants, and subsidies, to promote the development and adoption of hydrogen technologies. This support can help reduce the cost of hydrogen and encourage investment in hydrogen-related infrastructure;
- collaboration: collaboration between stakeholders, including governments, industry, and academia, can help accelerate the development and adoption of hydrogen technologies. Collaboration can lead to knowledge sharing and transfer, increased investment, and the development of common standards and regulations;

- shift towards renewable energy: the production of hydrogen should enhance shift towards RES such as wind and solar power, which, hence, can help reduce GHG associated with hydrogen production and support the transition to a low-carbon economy.

Addressing the challenges associated with hydrogen applications will require a multifaceted approach that includes technological advancements, supporting infrastructure, safety regulations, policy support, collaboration, and a shift towards renewable energy. Implementing these strategies can help overcome these challenges and support the development of a sustainable hydrogen economy. Continued research and development can help overcome many of the technological challenges associated with hydrogen applications.

Some potential areas for technological advancements include:

- electrolysis: electrolysis is the process of splitting water molecules into hydrogen and oxygen using an electric current. Advances in electrolysis technology can lead to more efficient and cost-effective production of hydrogen from renewable energy sources;
- fuel cells: fuel cells convert hydrogen into electricity with high efficiency, producing only water as a by-product. Advances in fuel cell technology can improve their performance and reduce their cost, making them more competitive with conventional technologies;
- hydrogen storage: storing hydrogen can be challenging due to its low energy density, which means that large volumes of hydrogen are needed to store a significant amount of energy. Advances in hydrogen storage technology, such as improved materials for hydrogen storage, can help increase the energy density of hydrogen storage and reduce the cost;
- distribution infrastructure: the development of a hydrogen distribution infrastructure, including pipelines and refuelling stations, is crucial for the widespread adoption of hydrogen in transportation and other sectors. Advances in distribution infrastructure technology can help make hydrogen more widely available and accessible;
- safety: addressing safety concerns associated with hydrogen, such as its flammability and potential for leaks, is crucial for public acceptance of the technology. Advances in safety technology, such as better sensors and leak detection systems, can help improve the safety of hydrogen applications [17]–[20].

Continued R&D can help overcome many of the technological challenges associated with hydrogen applications. Advances in electrolysis, fuel cells, hydrogen storage, distribution infrastructure, and safety technology can help reduce costs and increase the competitiveness of hydrogen, making it a more viable solution for decarbonizing various sectors and achieving climate and energy goals. At the same time, hydrogen has a wide range of potential applications, particularly in the context of transitioning to a low-carbon economy.

The key applications of hydrogen include, but are not limited to:

- transportation: hydrogen fuel cell vehicles are a promising alternative to gasoline-powered vehicles, producing only water as a by-product. Hydrogen can also be used as a fuel for buses, trucks, and trains, particularly in long-haul applications;
- energy storage: hydrogen has the potential to be used as a form of energy storage, particularly in combination with

RES such as wind and solar power. Hydrogen can be produced during times of excess renewable energy production and stored for later use;
- power generation: hydrogen can be used in fuel cells to generate electricity. This can be particularly useful in remote areas or for backup power generation;
- industry: hydrogen is used in a variety of industrial applications, particularly in the production of ammonia for fertilizer and other chemical processes;
- buildings: hydrogen can be used in buildings for heating and cooking, particularly in areas where natural gas is not available;
- Maritime transport: hydrogen fuel cells can also be used in maritime transport applications, particularly in shipping.
- aviation: hydrogen has a potential to be used as a fuel for aviation, particularly for short-distance flights [20]–[22], [24], [25].

This paper will assess various applications of hydrogen as a sustainable and low-carbon energy source. We will focus on its use in transportation, energy storage, power generation, industry, buildings, maritime transport, and aviation [15], [18], [24]. The assessment will consider the technological, economic, and environmental aspects of hydrogen applications in each of these sectors.

2. ASSESSING THE POTENTIAL OF HYDROGEN IN DIFFERENT SECTORS

Hydrogen has emerged as a promising energy carrier for a low-carbon future, offering a range of potential applications in different sectors. The use of hydrogen has been identified as a key strategy for reducing GHG, particularly in sectors that are difficult to decarbonize.

2.1. Transportation

Transportation is one of the critical sectors where hydrogen has the potential to make a significant impact as a low-carbon energy source. Hydrogen fuel cell vehicles are a promising alternative to traditional gasoline-powered vehicles, as they produce only water as a by-product and do not emit harmful pollutants that contribute to air pollution and climate change. In addition to personal vehicles, hydrogen can also be used as fuel for larger modes of transportation such as buses, trucks, and trains. One of the advantages of using hydrogen in these applications is the long-range capability of fuel cell vehicles, making them suitable for long-haul transportation needs.

The use of hydrogen in transportation faces some challenges, including the limited availability of refuelling infrastructure and the high cost of fuel cell technology. However, there has been increasing interest in the development and deployment of hydrogen refuelling infrastructure, particularly in regions where there are ambitious climate goals and a strong commitment to decarbonizing transportation. Furthermore, there have been significant technological advancements in hydrogen fuel cell technology, making it more efficient and cost-effective.

As a result, hydrogen has the potential to play a major role in the future of clean transportation. In addition to reducing GHG emissions, the use of hydrogen in

transportation can also improve air quality by reducing harmful pollutants that contribute to respiratory diseases. Furthermore, the use of hydrogen as a fuel in transportation can enhance energy security, as it reduces dependence on imported oil and provides an alternative to traditional fossil fuels. Hydrogen-powered buses, trucks, and trains are already in use in various parts of the world, and several major automakers have announced plans to release hydrogen-powered vehicles for the consumer market.

It is also significant to note that using hydrogen fuel cells also work well in trolleybuses as range extenders, which enables the system to increase reachable distance beyond the current network and provides resilience and flexibility against electricity grid blackouts. Replacing the diesel range extenders currently in use will greatly reduce GHG emissions, whilst providing the same level of operational flexibility. Ten hydrogen powered trolleybuses are currently in daily operation in Riga and they also are the first vehicles of this type worldwide [23].

However, the cost of hydrogen fuel cell technology and the limited availability of hydrogen refuelling infrastructure remain significant barriers to wider adoption of hydrogen in transportation. Despite these challenges, the potential benefits of hydrogen in transportation are significant, particularly for long-haul transportation needs where other low-carbon options such as battery-electric vehicles may not be practical. As such, continued investment in the development of hydrogen fuel cell technology and the deployment of hydrogen refuelling infrastructure is critical to unlocking the potential of hydrogen in transportation.

There are several examples of hydrogen-powered transportation initiatives and projects in Europe:

- The H2ME project: The Hydrogen Mobility Europe (H2ME) project is a European public-private partnership aimed at expanding the deployment of hydrogen fuel cell vehicles and infrastructure in Europe. The project has supported the deployment of over 1,000 fuel cell vehicles and over 40 refuelling stations across Europe [26];
- The JIVE project: The Joint Initiative for Hydrogen Vehicles across Europe (JIVE) is a European initiative aimed at deploying fuel cell buses in several cities across Europe. The project has supported the deployment of over 150 fuel cell buses across 14 cities in Europe [27];
- The H2Ports project: The H2Ports project is a European initiative aimed at demonstrating the feasibility of using hydrogen in ports and shipping. The project will deploy a range of hydrogen-powered equipment, including forklifts and cargo handling equipment, as well as a hydrogen refuelling station, at the Port of Valencia in Spain [28];
- The H2-Share project: The H2-Share project is a European initiative aimed at deploying a fleet of hydrogen-powered trucks for logistics operations. The project will deploy a range of fuel cell trucks for logistics operations in four European countries [29];
- The H2GO project: The H2GO project is a European initiative aimed at developing a network of hydrogen refuelling stations for heavy-duty vehicles in Europe. It will deploy 1000 hydrogen refuelling stations across Europe, with a focus on heavy-duty vehicle applications [30].

Here are some real examples of hydrogen initiatives and projects in the transportation sector in the Baltic States as well:

- The Latvian company “Riga Hydrogen City” is developing a fleet of hydrogen fuel cell buses for public transportation in Riga. The project is supported by the

European Union and aims at reducing emissions and improving air quality in the city [31];
- The Lithuanian company "Elinta Motors" is developing a hydrogen fuel cell truck for long-haul transportation. The company has already built a prototype and planned to start production in 2022 [32];
- The Estonian company "H2Pro" is developing a hydrogen production technology that can be used to power hydrogen fuel cell cars. The company is working with several partners to develop a complete hydrogen-based transportation system [33].

The advantages of using hydrogen in the transportation sector include:
- zero GHG emissions: hydrogen fuel cell vehicles produce zero emissions, which makes them a cleaner alternative to gasoline and diesel-powered vehicles. This can help reduce air pollution and improve air quality in urban areas;
- long driving range: hydrogen fuel cell vehicles have a similar driving range to gasoline vehicles and can be refuelled in a matter of minutes, making them suitable for long-distance travel;
- versatility: hydrogen can be used as a fuel for a variety of transportation modes, including cars, buses, trucks, trolleybuses and trains, which makes it a versatile solution for reducing emissions in the transportation sector;
- energy security: hydrogen can be produced from a variety of sources, including renewable sources such as wind and solar power, which can help increase energy security and reduce dependence on fossil fuels [10], [12], [19].

However, there are also several disadvantages associated with using hydrogen in the transport sector:
- infrastructure challenges: one of the main challenges of using hydrogen as a fuel for transportation is the lack of infrastructure, such as hydrogen refuelling stations, which makes it difficult for consumers to adopt hydrogen fuel cell vehicles;
- cost: hydrogen fuel cell vehicles are currently more expensive than gasoline and diesel-powered vehicles, and the cost of producing and distributing hydrogen is also relatively high compared to other fuels;
- safety concerns: hydrogen is a highly flammable gas and requires special handling and storage procedures to ensure safety. This can make it more challenging to establish a widespread hydrogen infrastructure for transportation;
- technology development: while hydrogen fuel cell technology has made significant advances in recent years, further research and development are needed to improve the efficiency and durability of fuel cells and reduce costs [15], [8].

Despite these challenges, the potential benefits of using hydrogen in the transport makes it an attractive solution for reducing emissions and increasing energy security. Hydrogen fuel cell vehicles produce zero emissions and offer the same driving range and refuelling time as conventional gasoline vehicles. This makes them particularly attractive for long-haul applications where battery electric vehicles may not be as practical due to their limited driving range and longer charging times. Several initiatives and projects are already underway in Europe aimed at developing hydrogen-based transportation systems.

However, there are still technological and infrastructural challenges that need to be addressed to make hydrogen-based transportation systems more practical and

cost-effective. These include developing more efficient and affordable fuel cell systems, establishing a widespread network of hydrogen refuelling stations, and addressing safety concerns associated with handling and storing hydrogen.

2.2. Energy Storage

Hydrogen has the potential to be a key component of energy storage systems, particularly in combination with RES. One of the main challenges of RES is their intermittency, which means that they may not always produce energy when it is needed. Hydrogen can help address this challenge by storing excess renewable energy as hydrogen gas through electrolysis. During periods of excess renewable energy production, electricity can be used to split water molecules into hydrogen and oxygen. The hydrogen gas can then be stored in tanks or pipelines for later use. When renewable energy production is low, the stored hydrogen can be used to generate electricity through fuel cells or burned in combustion engines. The use of hydrogen as an energy storage medium has several advantages. Unlike batteries, hydrogen storage systems can be scaled up easily and can store large amounts of energy over long periods of time. Hydrogen also has a high energy density, which means that it can store more energy per unit of volume than other storage media such as batteries [9], [13]. This makes it particularly suitable for long-term energy storage applications. While there are still technical and economic challenges associated with hydrogen energy storage, its potential to store large amounts of energy over long periods of time makes it a promising solution for integrating RES into the grid and improving energy security. Examples of hydrogen-based energy storage projects in Europe include:

- Store&Go: The Store&Go project is the EU-funded project that aims at demonstrating the feasibility of large-scale hydrogen storage using underground salt caverns. The project is being carried out in Germany, Italy, and the United Kingdom [34];
- HyBalance: The HyBalance project is a pilot project that aims at demonstrating the feasibility of producing and storing hydrogen from wind energy. The project is being carried out in Denmark and involves the use of a wind turbine to produce hydrogen through electrolysis, which is then stored in tanks for later use [35];
- H2Future: The H2Future project is another EU-funded project that aims at demonstrating the feasibility of using hydrogen as a storage medium for excess RES. The project is being carried out in Austria and involves the use of excess wind and solar energy to produce hydrogen through electrolysis, which is then stored in tanks for later use [36].

There are currently no large-scale hydrogen energy storage projects underway in the Baltic States. However, there are some initiatives and research projects exploring the potential of hydrogen energy storage, such as:

- The Baltic Energy Innovation Centre (BEIC): The BEIC is a research and development centre in Latvia that focuses on developing innovative energy solutions, including hydrogen energy storage. The centre is working on developing a hydrogen-based energy storage system that can be integrated with wind and solar power systems [37];
- Hydrogen Valley: Hydrogen Valley is a joint initiative between Estonia, Latvia, and Lithuania aimed at promoting the use of hydrogen in the region. While

the initiative does not currently include any hydrogen energy storage projects, it is focused on developing a regional hydrogen infrastructure that could support future energy storage projects [38].

These initiatives demonstrate growing interest in hydrogen energy storage in the Baltic States, but there is still much work to be done to develop and scale up these technologies. Advantages of energy storage with hydrogen include:

- scalability: hydrogen storage can be easily scaled up or down to meet changing energy demands;
- long-term storage: hydrogen can be stored for long periods of time, making it a viable option for seasonal storage of renewable energy;
- versatility: hydrogen can be used for a range of energy applications, including transportation, power generation, and heating;
- zero emissions: hydrogen energy storage produces no harmful emissions, making it a clean and sustainable energy option.

Disadvantages of energy storage with hydrogen include:

- cost: hydrogen storage can be expensive, particularly compared to other forms of energy storage like batteries;
- efficiency: the process of converting electricity to hydrogen and then back to electricity can result in significant energy losses;
- safety concerns: hydrogen is highly flammable and requires specialized handling and storage facilities;
- limited infrastructure: there is currently limited infrastructure for hydrogen storage and distribution, making it difficult to implement on a large scale [13], [18], [20].

2.3. Power Generation

The use of hydrogen in fuel cells to generate electricity is a promising area for the development of a sustainable and low-carbon energy system. Fuel cells offer a highly efficient method of generating electricity with minimal emissions, making them an attractive option for a range of applications, including remote power generation and backup power supply. Here the potential applications of hydrogen fuel cells for power generation, as well as the advantages and challenges associated with this technology are explored. Additionally, we will examine current examples of hydrogen fuel cell power generation projects in Europe and the Baltic States, and discuss the implications for the future of power generation [8].

There are several examples of power generation projects in Europe that utilise hydrogen fuel cells:

- The HYDRA project in Germany is exploring the potential of hydrogen fuel cells for backup power generation in data centres. The project is being conducted by the Technical University of Munich in collaboration with several industry partners [39];
- The H2OCEAN project in France is developing a hybrid energy system that combines wind power and hydrogen fuel cells for remote power generation on offshore islands. The project is a collaboration between several industry partners and research institutions [40];
- The Haeolus project in the Netherlands is developing a hybrid power system that combines wind power, energy storage, and hydrogen fuel cells for remote power generation in the Wadden Sea. The project is being led by the Energy

Research Centre of the Netherlands in collaboration with several industry partners [41];
- The HyBalance project in Denmark is exploring the potential of hydrogen fuel cells for balancing the electricity grid. The project involves the construction of a power-to-gas plant that converts excess wind power into hydrogen, which can then be used to generate electricity through fuel cells [42];
- The BigHit project in the United Kingdom is developing a hybrid power system that combines wind power, energy storage, and hydrogen fuel cells for remote power generation on the Scottish island of Orkney. The project is being led by the European Marine Energy Centre in collaboration with several industry partners [43].

These projects demonstrate the potential of hydrogen fuel cells for power generation in Europe, particularly for remote and off-grid applications. However, continued research and development, along with increased investment in infrastructure, will be necessary to advance the adoption of this technology and realise its full potential.

There are currently no large-scale power generation projects using hydrogen in the Baltic States, but there are some research initiatives and smaller pilot projects that explore the potential of hydrogen as a fuel for power generation, for instance:
- Riga Technical University has been researching hydrogen fuel cells as a way to generate electricity for remote areas, particularly in Latvia's rural regions where grid access is limited [44];
- In 2021, Latvia's state-owned energy company "Latvenergo" launched a pilot project to test the feasibility of using hydrogen as a fuel for backup power generation at one of its power plants [45];
- Estonia's National Institute of Chemical Physics and Biophysics is also conducting research into using hydrogen fuel cells for power generation, particularly in the context of integrating renewable energy sources into the grid [46].

These projects are still in their early stages and more R&D activities are needed before hydrogen-based power generation becomes a viable option in the Baltic States. Advantages of power generation with hydrogen include:
- clean energy source: hydrogen fuel cells produce electricity without emitting pollutants or greenhouse gases;
- versatility: hydrogen can be produced from a variety of sources, including renewables, nuclear, and fossil fuels;
- high efficiency: hydrogen fuel cells are highly efficient, converting up to 60 % of the energy contained in the hydrogen to electricity;
- reliability: hydrogen fuel cells are reliable and can provide uninterrupted power for long periods of time;

Disadvantages of power generation with hydrogen include, but are not limited to:
- high cost: current hydrogen fuel cell technology is expensive and not yet competitive with other forms of power generation;
- infrastructure challenges: the development of a hydrogen infrastructure, including production, storage, and distribution facilities, requires significant investment;
- safety concerns: hydrogen is highly flammable and requires special handling and storage precautions to ensure safety;
- limited availability: while hydrogen is abundant in nature, it is not readily available in its pure form and must be extracted or produced through energy-intensive processes.

2.4. Industry

Hydrogen has been widely used in various industrial applications, especially in the production of ammonia for fertilizers and other chemical processes. Ammonia is a critical component in the production of fertilizers, which is essential for agriculture and food production. The Haber-Bosch process, which uses hydrogen and nitrogen to produce ammonia, has been used for over a century to meet the global demand for fertilizers. In addition to the production of fertilizers, hydrogen is used in several other industrial applications, such as the production of methanol, steel production, and petroleum refining. Hydrogen is also used as a reducing agent in the production of silicon and other metals. The use of hydrogen in the industry offers several benefits, including reduced carbon emissions, increased energy efficiency, and improved production processes. However, there are also challenges associated with the widespread adoption of hydrogen in industry, such as the high cost of hydrogen production and distribution, and the need for significant infrastructure investments [10], [13].

Nonetheless, the potential benefits of hydrogen in the industry make it a promising area for further research and development. Here are some examples of industrial applications for hydrogen in Europe:

- in the Netherlands, a project called H2FUTURE is being developed to use green hydrogen produced by wind power to power the steel industry. The project aims at reducing CO_2 emissions by up to 50 % [47];
- in Germany, a company called "Covestro" is using hydrogen to produce aniline, a chemical used in the production of plastics. Hydrogen is produced using RES and helps reduce the carbon footprint of the production process [48];
- in the UK, a project HyNet is being developed to use hydrogen to power industrial processes in the North West of England, including the production of chemicals, steel, and cement. The project aims at reducing CO_2 emissions by up to 10 million tonnes per year by 2030 [49];
- in Sweden, the steel manufacturer "SSAB" is using hydrogen to produce fossil-free steel in a pilot plant. The hydrogen is produced using fossil-free electricity and will help reduce the carbon footprint of the steel production process [50].

In the Baltic States, the use of hydrogen in the industry is still in its infancy, with no large-scale projects currently in operation. However, there are some initiatives exploring the potential for hydrogen in the industry. For example, in Estonia, the company "Hiiu Elektrijaam" is investigating the use of hydrogen to produce electricity and heat for industrial and residential use. Meanwhile, in Latvia, Riga Technical University is researching the use of hydrogen in the production of green fertilizers. These are promising steps towards the development of a hydrogen-based industry in the region.

Advantages of hydrogen applications in the industry include:

- hydrogen can be produced from RES, making it a potentially sustainable and low-carbon option for industrial applications;
- hydrogen has a high energy density, making it useful for high-energy industrial processes;
- hydrogen can be used as a feedstock in chemical processes, reducing the need for fossil fuels;
- use of hydrogen in the industry can help reduce GHG emissions.

At the same time, there are disadvantages that should be mentioned:

- hydrogen production can be energy-intensive and expensive, particularly if traditional fossil fuels are used as feedstock;
- hydrogen can be difficult and expensive to transport and store, particularly in large quantities;
- hydrogen has low ignition energy, making it potentially dangerous if proper safety measures are not taken;
- the development of a hydrogen infrastructure for industrial applications would require significant investment and coordination among various stakeholders.

Obviously, hydrogen has a significant potential for the industrial sector, particularly in the production of ammonia for fertilizers and other chemical processes. However, its widespread adoption faces challenges related to cost, infrastructure, and safety. Nevertheless, ongoing research and development are expected to lead to new and more efficient hydrogen technologies that can help overcome these challenges and increase the competitiveness of hydrogen in the industrial sector.

2.5. Building Sector

Hydrogen can also be used in buildings as a source of energy for heating and cooking, especially in areas where natural gas is not available or its availability is limited. The high cost of hydrogen production and the need for specialized infrastructure are currently barriers to the widespread adoption of hydrogen in building applications. However, there are several examples of hydrogen being used in buildings for heating and cooking in Europe [13], [19], such as:

- the H21 North of England project is exploring the use of hydrogen for heating in homes and businesses in the UK. The project aims at converting the gas networks in the north of England to run on hydrogen instead of natural gas [51];
- the Levenmouth Community Energy Project in Scotland is using hydrogen fuel cells to generate electricity for homes in the area. The project is also exploring the use of hydrogen for heating in the future [52];
- the European project GenComm is developing hydrogen-based energy solutions for buildings, including fuel cells and hydrogen boilers. The project is testing these solutions in a range of different buildings across Europe [53];
- The H2Nodes project aims at demonstrating the use of hydrogen in buildings [54].

These are just a few examples of the use of hydrogen in buildings for heating and cooking in Europe. There are currently limited examples of the use of hydrogen in buildings in the Baltic States. However, some initiatives and research projects are underway to explore the potential of hydrogen in this sector. In Estonia, the company "Enefit Green" is investigating the use of hydrogen as a fuel for combined heat and power plants that could supply district heating to homes and buildings. In Latvia, Riga Technical University is conducting research on the use of hydrogen as a fuel for heating and power generation in buildings, particularly in the context of energy storage and integration with renewable energy sources. In Lithuania, the Lithuanian Energy Institute is leading a project called HyLAW, which aims at developing a legal and regulatory framework for the deployment of hydrogen technologies, including their use in buildings

for heating and power generation.

These initiatives demonstrate the growing interest and potential for the use of hydrogen in buildings in the Baltic States, although significant technological and regulatory challenges remain to be addressed.

The advantages of using hydrogen in buildings for heating and cooking are as follows:

- environmental benefits: hydrogen is a clean and renewable energy source, and its use can help reduce carbon emissions and improve air quality;
- energy security: hydrogen can be produced domestically, reducing dependence on foreign energy sources and increasing energy security;
- versatility: hydrogen can be used for both heating and cooking, making it a versatile energy source for buildings;
- potential for cost savings: while the initial investment for hydrogen infrastructure may be high, the cost of hydrogen production is expected to decrease over time, leading to potential cost savings in the long term.

However, there are also some shortcomings to using hydrogen in buildings, like:

- infrastructure requirements: hydrogen infrastructure is currently limited and expensive to build, requiring significant investment and planning;
- safety concerns: hydrogen is a highly flammable gas, and its use in buildings requires strict safety protocols and precautions to prevent accidents;
- efficiency: while hydrogen fuel cells have high efficiency in generating electricity, hydrogen combustion for heating and cooking may be less efficient than other energy sources;
- scale limitations: the use of hydrogen in buildings may be limited by the scale of production and storage facilities, which may be more suitable for larger industrial applications.

Overall, the advantages and disadvantages of using hydrogen in buildings depend on various factors, including the availability of infrastructure and the specific application. While there are some challenges to the widespread adoption of hydrogen in buildings, ongoing research and development efforts are addressing these issues. As demonstrated by the examples from Europe and the Baltic States, hydrogen-based solutions for building heating and electricity are being explored and implemented in various forms, from fuel cells to hydrogen boilers. As the technology continues to develop, hydrogen may become an increasingly important component of the transition to a more sustainable and decarbonized energy system.

2.6. Maritime Transport

Hydrogen fuel cells can provide a clean and efficient power source for shipping, where traditional fossil fuels are a major contributor to air pollution and GHG emissions. Hydrogen can be produced using RES and stored onboard ships, providing a zero-emission alternative to conventional fuels. The use of hydrogen in maritime transport is still in the early stages of development, but there is an interest to investment in this technology.

Examples of hydrogen in maritime applications in Europe include:

- HYDROVILLE, a hydrogen-powered passenger shuttle, which operates in Antwerp, Belgium. The vessel is powered by a fuel cell system and has a range of up to 35 nautical miles [55];

- HYSEAS III project aims at developing a hydrogen-powered ferry for use in Scotland. The ferry will be powered by a fuel cell system and is expected to be in operation by 2024 [56];
- ELEGANCE project, which is developing a hydrogen fuel cell system for use in maritime applications. The project is led by a consortium of companies and research institutions from across Europe [57];
- The Zemships project, which developed a hydrogen-powered passenger ferry for use in Hamburg, Germany. The vessel is powered by a fuel cell system and has been in operation since 2014 [58];
- The FLAGSHIPS project, which is developing two hydrogen-powered ferries for use in Norway. The vessels powered by fuel cell systems were expected to come into operation by 2022 [59].

These examples demonstrate the potential for hydrogen to be used in maritime transport, particularly for shipping and ferry services. Currently, there are no large-scale projects related to the use of hydrogen in the maritime transport in the Baltic States. However, the Estonian company "LMG Marin" has developed a concept for a hydrogen-powered ferry. The concept, called HySHIP [60], involves the use of a fuel cell system to power the vessel, with hydrogen produced from RES.

Advantages of hydrogen use in maritime transport include, but are not limited to:

- zero emissions: hydrogen fuel cells produce only water as a by-product, making them a clean and sustainable energy source for maritime transport;
- high efficiency: hydrogen fuel cells have a high energy density and can convert up to 60 % of the energy in the fuel into electricity;
- long range: hydrogen fuel cells can provide a long range for maritime transport, making them suitable for long-haul shipping;
- reduced noise pollution: hydrogen fuel cells produce much less noise compared to traditional diesel engines.

However, there are some disadvantages as well, such as:

- high cost: the cost of hydrogen fuel cell systems for marine applications is currently high, making them less competitive with traditional diesel engines;
- limited infrastructure: the infrastructure for producing, storing, and distributing hydrogen is currently limited, which can make it difficult for ships to refuel;
- safety concerns: hydrogen is highly flammable and requires careful handling to ensure safety;
- technical challenges: there are technical challenges associated with using hydrogen in maritime applications, such as the need for large storage tanks and the potential for corrosion.

In conclusion, hydrogen fuel cells have the potential to play a significant role in the maritime industry, particularly for shipping. While there are still technical and infrastructure challenges to overcome, ongoing projects and research show promise for the future deployment of hydrogen technologies in this sector.

2.7. Aviation

Hydrogen has been proposed as a potential fuel for aviation due to its high energy content and low emissions. Fuel cell-powered electric aircraft have been developed and tested, with a few small-scale commercial operations in the works.

In addition, hydrogen can be used in gas turbine engines as a direct replacement for jet fuel, with only minor modifications to the engine. However, the high cost of producing and distributing hydrogen, as well as the lack of infrastructure, are significant challenges to the widespread adoption of hydrogen in aviation. Currently, there are limited examples of hydrogen use in aviation in Europe. However, several research and development projects are underway, including:

- The European Union's Clean Sky 2 programme, which is developing and testing new aircraft technologies, including hydrogen fuel cells [61];
- Airbus' ZEROe concept aircraft, which would be powered by hydrogen fuel cells and could enter service by 2035 [62];
- The H2FLY project, which aims at demonstrating the feasibility of using hydrogen fuel cells for aviation through test flights [63];
- The HyFlyer project, which is developing hydrogen fuel cell-powered aircraft for commercial passenger flights [64];
- The Hy4 project, which has developed a four-seat aircraft powered by a hydrogen fuel cell [65].

These projects and initiatives indicate that hydrogen has the potential to play a role in the aviation industry in the future. Currently, there are no examples of the use of hydrogen in aviation in the Baltic States. However, the Baltic countries have expressed interest in the potential of hydrogen in aviation, with Latvia's Ministry of Transport plans to develop a national strategy for sustainable aviation, including the use of hydrogen.

Advantages of hydrogen use in aviation would include:

- hydrogen has a high energy content, which makes it a potentially attractive fuel for aviation as it could result in longer flight times and reduced fuel consumption;
- hydrogen combustion produces only water as a by-product, making it a zero-emissions fuel, which is particularly important for the aviation industry to meet sustainability goals;
- use of hydrogen fuel cells could potentially reduce the weight and noise of aircraft.

The disadvantages are as follows:

- production of hydrogen fuel is currently energy-intensive and expensive, which could limit its commercial viability for aviation;
- hydrogen fuel requires significant storage space and infrastructure, which could be challenging for the aviation industry;
- the use of hydrogen fuel cells in aviation is still in the early stages of development and would require significant investment to become a viable alternative to traditional jet fuel.

In conclusion, hydrogen has the potential to play a significant role in the aviation industry, particularly for short-haul flights. While there are still significant technological and infrastructure challenges that must be overcome, ongoing research and development in this field hold promise for the future of hydrogen in aviation.

3. CONCLUSIONS

Hydrogen has the potential to play a significant role in decarbonization of various sectors in the EU, and examples of hydrogen development projects demon-

strate that there is a growing interest in the use of hydrogen as a clean energy source. However, the deployment of hydrogen technologies also faces various challenges such as high production costs, lack of infrastructure, and safety concerns. Nonetheless, continued research and development of hydrogen technologies can lead to new and more efficient ways of producing, storing, and distributing hydrogen, which can help reduce costs and increase the competitiveness of hydrogen.

Advantages and disadvantages of hydrogen applications vary depending on the sector and the specific application. For example, hydrogen fuel cell vehicles offer zero-emission transportation, but their high production costs and lack of refuelling infrastructure can be major obstacles. Hydrogen energy storage can help integrate RES, but the efficiency of hydrogen production and storage is lower than other energy storage options. Hydrogen power generation can provide backup power and off-grid power generation, but the high costs of fuel cells and the need for hydrogen supply chains are challenges.

Governments, research institutions, and private companies are investing in the development of hydrogen technologies, which can help overcome the challenges and drive the deployment of hydrogen technologies forward. In conclusion, the widespread adoption of hydrogen technologies is a long-term goal that requires the cooperation of various stakeholders and the development of innovative and cost-effective solutions. The current state of hydrogen applications and ongoing projects in Europe and the Baltic States demonstrate that hydrogen has the potential to play a significant role in the transition to a sustainable and low-carbon future.

REFERENCES

1. Jansons, L., Zemite, L., Zeltins, N., Geipele, I., & Backurs, A. (2023). Green and Sustainable Hydrogen in Emerging European Smart Energy Framework. *Latvian Journal of Physics and Technical Sciences, 60* (1), 24–38. doi: 10.2478/lpts-2023-0003
2. Jansons, L., Zemite, L., Zeltins, N., Bode, I., Geipele, I., & Kiesners, K. (2022). The Green Hydrogen and the EU Gaseous Fuel Diversification Risks. *Latvian Journal of Physics and Technical Sciences, 59* (4), 53–70. doi: 10.2478/lpts-2022-0033
3. Jansons, L., Zemite, L., Zeltins, N., Bode, I., Vempere, L., & Jasevics, A. (2022). The Potential of the Hydrogen Underground Storages: their Types, Development Challenges and the Latvian Situation. *The 63rd Annual International Scientific Conference on Power and Electrical Engineering of Riga Technical University* (RTUCON 2022). doi: 10.1109/RTUCON56726.2022.9978776
4. Vempere, L., Zemite, L., Vempers, G., Bode, I., & Jasevics, A. (2022). Assessment of Prospective Energy Storage Options for the Heat Plant – A Case Study. *The 63rd Annual International Scientific Conference on Power and Electrical Engineering of Riga Technical University* (RTUCON 2022). doi: 10.1109/RTUCON56726.2022.9978881
5. Kleperis, J., Dimanta, I., Sloka, B., & Zemite, L. (2022). What Hydrogen can Bring to Rural Development: Review and Results of Entrepreneurs Survey in Latvia. *Research for Rural Development, 37*, 273–279. doi: 10.22616/rrd.28.2022.039
6. Mezulis, A., Kleperis, J., Lesnicenoks, P., & Zemite, L. (2022). Prospects of Decarbonizing Industrial Areas in the Baltic States by Means of Alternative Fuels. *Journal of Ecological Engineering, 23* (8), 152–161. doi: 10.12911/22998993/150748

7. Kleperis, J., Boss, D., Mezulis, A., Zemite, L., Lesnicenoks, P., Knoks, A., & Dimanta, I. (2021). Analysis of the Role of the Latvian Natural Gas Network for the Use of Future Energy Systems: Hydrogen from RES. *Latvian Journal of Physics and Technical Sciences, 58* (3), 214–226. doi: 10.2478/lpts-2021-0027
8. Kobzars, V., Zemite, L., Jasevics, A., Kleperis, J., Dimanta, I., Knoks, A., & Lesnicenoks, P. (2021). Appropriateness of Hydrogen Production in Low-Power Hydropower Plant. *The 62nd International Scientific Conference on Power and Electrical Engineering of Riga Technical University* (RTUCON 2021). doi: 10.1109/RTUCON53541.2021.9711687
9. Wang, M., Wang, G., Sun, Z., Zhang, Y., & Xu, D. (2019). Review of Renewable Energy-Based Hydrogen Production Processes for Sustainable Energy Innovation. *Global Energy Interconnection*, *2* (5), 436–443. doi: 10.1016/j.gloei.2019.11.019.
10. Boongaling Agaton, K., Talosig Batac, K. I., & Reyes Jr., E.M. (2022). Prospects and Challenges for Green Hydrogen Production and Utilization in the Philippines. *International Journal of Hydrogen Energy*, *47* (41), 17859–17870. doi: 10.1016/j.ijhydene.2022.04.101.
11. Levene, I., Mann, J., K., Margolis, M., & Milbrandt, A. (2007). An Analysis of Hydrogen Production from Renewable Electricity Sources. *Solar Energy, 81* (6), 773–780. doi: 10.1016/j.solener.2006.10.005.
12. Dash, S.K., Chakraborty, S., & Elangovan, D. A. (2023). Brief Review of Hydrogen Production Methods and Their Challenges. *Energies, 16*, 1141. doi: 10.3390/en16031141
13. IEA. (2022). *Executive Summary – Global Hydrogen Review 2022*. Available at https://www.iea.org/reports/global-hydrogen-review-2022/executive-summary
14. Department of Energy. (n.d.). *Hydrogen Production: Biomass Gasification*. Available at https://www.energy.gov/eere/fuelcells/hydrogen-production-biomass-gasification
15. Zhang, B., Zhang, S. X., Yao, R., Wu, Y.-H., & Qiu, J.-S. (2021). Progress and Prospects of Hydrogen Production: Opportunities and Challenges. *Journal of Electronic Science and Technology*, *19* (2), 100080. doi: 10.1016/j.jnlest.2021.100080.
16. Agyekum, E.B., Nutakor, C., Agwa, A.M., & Kamel, S. A. (2022). Critical Review of Renewable Hydrogen Production Methods: Factors Affecting Their Scale-Up and Its Role in Future Energy Generation. *Membranes, 12*, 173. doi: 10.3390/membranes12020173
17. Sarker, A.K., Azad, A.K., Rasul, M.G., & Doppalapudi, A.T. (2023). Prospect of Green Hydrogen Generation from Hybrid Renewable Energy Sources: A Review. *Energies*, *16*, 1556. doi: 10.3390/en16031556
18. Ishaq, H., Dincer, I., & Crawford, C. (2022). A Review on Hydrogen Production and Utilization: Challenges and Opportunities. *International Journal of Hydrogen Energy*, 47 (62), 26238–26264. doi: 10.1016/j.ijhydene.2021.11.149.
19. Hosseini, S. E., & Wahid, M. A. (2016). Hydrogen Production from Renewable and Sustainable Energy Resources: Promising Green Energy Carrier for Clean Development. *Renewable and Sustainable Energy Reviews*, *57*, 850–866. doi: 10.1016/j.rser.2015.12.112.
20. Riera, J. A., Lima, R. M., & Knio, O. M. (2023). A Review of Hydrogen Production and Supply Chain Modeling and Optimization. *International Journal of Hydrogen Energy, 48* (37), 13731–13755. doi: 10.1016/j.ijhydene.2022.12.242.
21. Abdelghany, M. B., Shehzad, M. F., Liuzza, D., Mariani, V., & Glielmo, L. (2021). Optimal Operations for Hydrogen-Based Energy Storage Systems in Wind Farms via Model Predictive Control. *International Journal of Hydrogen Energy*, *46* (57), 29297–29313. doi: 10.1016/j.ijhydene.2021.01.064.
22. Hao, J., Yang, Y., & Xu, C. (2022). A Comprehensive Review of Planning, Modeling, Optimization, and Control of Distributed Energy Systems. *Carb Neutrality, 1*, 28. doi: 10.1007/s43979-022-00029-1

23. H2 Nodes. (n.d.). *Riga*. Available at https://www.h2nodes.eu/en/regions/riga.html
24. Lui, J., Chen, W.-H., Daniel C.W. Tsang, D.C.W., & You, S. (2020). A Critical Review on the Principles, Applications, and Challenges of Waste-to-Hydrogen Technologies. *Renewable and Sustainable Energy Reviews, 134,* 110365. doi: /10.1016/j.rser.2020.110365.
25. Kumar, S. S., & Himabindu, V. (2019). Hydrogen Production by PEM Water Electrolysis – A Review. *Materials Science for Energy Technologies, 2* (3), 442–454. doi: 10.1016/j.mset.2019.03.002.
26. Hydrogen Mobility Europe. (n.d.) Available at https://h2me.eu/
27. JIVE. (n.d.). *Fuel Cell Electric Buses*. Available at https://www.fuelcellbuses.eu/projects/jive/
28. CLEAN HYDROGEN PARTNERSHIP (n.d.). H2PORTS. Available at https://h2ports.eu/
29. Interreg NEW. H2Share (n.d.) *Hydrogen Solutions for Heavy-Duty Transport*. Available at https://www.nweurope.eu/projects/project-search/h2share-hydrogen-solutions-for-heavy-duty-transport/
30. H2GO Hydrogen Mobility. (n.d.). Available at https://h2go.site
31. Gasworld. (2021). *Riga Hydrogen City to Deploy10FuelCellBuses.* Availableathttps://www.intelligenttransport.com/transport-news/21136/riga-hydrogen-powered-trolleybuses/#:~:text=Latvian%20public%20transport%20operator%20Rigas,%2Dfloor%20hydrogen%2Dpowered%20trolleybuses.
32. Hydrogen Fuel News. (2021). *Lithuanian Company Developing Hydrogen-Powered Truck*.
33. Estonian World. (2020). *Estonian Company Developing Innovative Hydrogen Production Technology*.
34. EC. Cordis. (2020). *Understanding the Neural Mechanisms of Multisensory Perception Based on Computational Principles.* Available at https://cordis.europa.eu/project/id/646657
35. HyBalance. (n.d.). *Green Energy Project Denmark*. Available at https://hybalance.eu
36. H2FUTURE Green energy. (n.d.). Available at https://h2future-project.eu
37. Baltic Energy Innovation Centre. (n.d.). *Innovative Energy Technology for a Sustainable Future*. Available at https://www.beic.nu
38. Clean Energy Partnership. (2022). *REPowering the EU with Hydrogen Valleys: Clean Hydrogen Partnership Invests EUR 105.4 million for Funding 9 Hydrogen Valleys across Europe*. Available at https://www.clean-hydrogen.europa.eu/media/news/repowering-eu-hydrogen-valleys-clean-hydrogen-partnership-invests-eur-1054-million-funding-9-2023-01-31_en?utm_source=Google&utm_medium=email&utm_campaign=Hydrogen+call+22
39. Clean Power Net. (2018). *Planning Guideline for Fuel Cell Back-Up Power Supplies*. Available at https://www.cleanpowernet.de/wp-content/uploads/2019/03/Planning-Guideline-UPS-and-EPS-with-Fuel-Cells.pdf
40. H2ocean Project. (n.d.). Available at https://www.h2ocean-project.eu
41. Haeolus. (n.d.) Available at https://www.haeolus.eu
42. EC. Cordis. (2020). *HyBalance Project.* Available at https://cordis.europa.eu/project/id/671384
43. EMEC. (2022). *BIG HIT*. Available at https://www.emec.org.uk/projects/hydrogen-projects/bighit
44. Labs of Latvia. (2023). *RTU Scientists Devise New Method for Producing Hydrogen*. Available at https://labsoflatvia.com/en/news/rtu-scientists-devise-new-method-for-producing-hydrogen
45. Latvenergo. (2021). *Sustainability and Annual Report.* Available at https://latvenergo.lv/storage/app/media/parskati/2021/IGP_2021_ENG.pdf
46. Segev, G., Kibsgaard, J., Hahn C., Hu, Z.J., Cheng, W.-H., … & Houle, F. (2022). The 2022 Solar Fuels Roadmap. *Phys. D: Appl. Phys.,* 55, 323003, doi: 10.1088/1361-6463/ac6f97

47. EHA. (n.d.). Available at https://www.h2euro.org/hydrogen-applications/industrial-production
48. Covestro. (2022). *Fortescue Future Industries and Covestro Announce Plans to Enter a Long-term Green Hydrogen Supply Agreement*. Available at https://www.covestro.com/press/fortescue-future-industries-and-covestro-announce-plans-to-enter-a-long-term-green-hydrogen-supply-agreement
49. HyNet North West. (n.d.). Available at https://hynet.co.uk
50. SSAB. (2021). *HYBRIT: SSAB, LKAB and Vattenfall First in the World with Hydrogen-Reduced Sponge Iron.* Available at https://www.ssab.com/en/news/2021/06/hybrit-ssab-lkab-and-vattenfall-first-in-the-world-with-hydrogenreduced-sponge-iron
51. H21. (n.d.). Available at https://h21.green
52. Fife Council. (2020). *Climate Fife: Sustainable Energy and Climate Action Plan (2020–2030).* Available at https://www.fife.gov.uk/__data/assets/pdf_file/0028/219970/Climate-Fife-Sustainable-Energy-and-Climate-Action-Plan-2020-2030.pdf
53. Interreg NEW. (2020). *GENCOMM: GENerating Energy Secure COMMunities.* Available at https://www.nweurope.eu/projects/project-search/gencomm-generating-energy-secure-communities
54. H2NODES. (n.d.). Available at https://www.h2nodes.eu/en
55. Covestro. (2021). *Covestro and NPRC Plan to Use Hydrogen-Powered Barges*. Available at https://www.covestro.com/press/covestro-and-nprc-plan-to-use-hydrogen-powered-barges
56. H2Bulletin. (2021). *AqualisBraemar Partners CMAL's Hyseas III Project.* Available at https://www.h2bulletin.com/aqualisbraemar-partners-cmals-hyseas-iii-project
57. Global Trade. (2022). *Nuvera Celebrates Fuel Cell Engine Achievements on National Hydrogen and Fuel Cell Day.* Available at https://www.globaltrademag.com/nuvera-celebrates-fuel-cell-engine-achievements-on-national-hydrogen-and-fuel-cell-day
58. EC. (n.d.). *Zemship*. Avaiable at https://webgate.ec.europa.eu/life/publicWebsite/index.cfm?fuseaction=search.dspPage&n_proj_id=3081
59. Flagship. (n.d.). *Clean Waterborne Transport in Europe*. Available at https://flagships.eu
60. HyShip. (n.d.). Available at https://hyship.eu
61. Clean Aviation. (n.d.). Available at https://www.clean-aviation.eu
62. Airbus. (n.d.). *Zero-Emission Journey.* Available at https://www.airbus.com/en/innovation/zero-emission-journey
63. Fuel Cell Works. (2022). *H2FLY Assumes Leadership Role for Project HEAVEN Hydrogen Fuel Cell Aviation Initiative*. Available at https://fuelcellsworks.com/news/h2fly-assumes-leadership-role-for-project-heaven-hydrogen-fuel-cell-aviation-initiative
64. EMEC. (n.d.). *HyFlyer Projects*. Available at https://www.emec.org.uk/projects/hydrogen-projects/hyflyer
65. Kallo, J. (2015). DLR Leads HY4 Project for Four-Seater Fuel Cell Aircraft. *Fuel Cells Bulletin*, *11*, 13. doi: 10.1016/S1464-2859(15)30362-X.