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Silesian University of Technology
Faculty of Transport and Aviation Engineering

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POLICE

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USE AND ANALYSIS OF HYDROGEN VEHICLES

Summary. Humans are seeking solutions for making transport green. This article shows the best solution for this problem, an analysis of the best use of hydrogen in the transportation industry, and how it solves environmental problems. Data for the study comes from many articles available on the internet. The article explains how hydrogenic transport can revolutionize the industry. What are the current and future applications of hydrogen vehicles? An analysis of operating costs in long and short-haul vehicles, also, as logistic and infrastructure analysis presented.

1. INTRODUCTION. CURRENT AND FUTURE APPLICATIONS OF HYDROGEN VEHICLES

1.1. Types of hydrogen drives engines

A hydrogen internal combustion engine vehicle (HICEV) is a type of hydrogen vehicle using an internal combustion engine as a simply modified version of the traditional gasoline-powered internal combustion engine.

A fuel cell vehicle (FCV) or fuel cell electric vehicle (FCEV) is an electric vehicle that uses a fuel cell, sometimes in combination with a small battery or supercapacitor, to power its onboard electric motor. Fuel cells in vehicles generate electricity generally using oxygen from the air and compressed hydrogen.

1.2. Means of transport where hydrogen drive can be used

The Toyota Mirai is a mid-size hydrogen fuel cell vehicle (FCV). A fuel cell vehicle (FCV) or fuel cell electric vehicle (FCEV) is an electric vehicle that uses a fuel cell, sometimes in combination with a small battery or supercapacitor, to power its onboard electric motor. Fuel cells in vehicles generate electricity generally using oxygen from the air and compressed hydrogen.

The Coradia iLint is a version of the Coradia Lint 54 train powered by a hydrogen fuel cell. Announced at InnoTrans 2016, it is the world's first production hydrogen-powered trainset. The Coradia iLint is able to reach 140 kilometres per hour and travel 600–800 kilometres on a full tank of hydrogen. The capacity of each train is 160 seats.

A hydrogen ship is a hydrogen fueled ship, power-assisted by an electric motor that gets its electricity from a fuel cell. Or uses hydrogen fuel in an internal combustion engine. The 80-car ferry MF Hydra sails in Norway, using 4 tonnes of liquid hydrogen, two 200 kW fuel cells, a 1.36-1.5 MWh battery, and two 440 kW diesel generators.

The Piper PA-46 Malibu with hydrogen fuel cell power train also known as HyFlyer demonstrator. The prototype made its maiden hydrogen-powered flight at Cranfield Airport on September 24, 2020. They have replaced the piston engine with two 130 kW (170 hp) electric motors, culminating in a 250–300 nmi (460–560 km) flight using hydrogen fuel cells.

1.3. Production of hydrogen

Currently, the cost of green hydrogen is approximately $5 per kg, compared to gray at around $1.60. The somewhat loosely defined nature of economic feasibility will most likely distinguish investors' motives.

Looking at the price, organizations could be tempted to pivot to blue hydrogen, with current costs of around $2 expected in 2025, with a 98% CCS rate – this would allow companies to achieve emissions targets at a lower cost than with green hydrogen. However, as pointed out earlier, blue hydrogen is neither sustainable nor renewable and hence should not be considered a permanent, long-term solution.

Black, brown and gray hydrogen is produced through Steam Reforming (SR) or gasification, using natural gas or methane as the feedstock (grey). During this process, the feedstock is partially oxidized to produce carbon dioxide (CO2) and hydrogen (H2), with some waste heat.

Blue hydrogen offers a less environmentally damaging option. It uses the same feedstock and process as gray hydrogen, however, 80-90% of the CO2 produced is captured within the process and is typically stored underground through industrial carbon capture and storage (CCS) methods. Importantly, this is neither sustainable nor renewable, because fossil fuels are still used within the process and some of the CO2 produced cannot be captured.

Green hydrogen offers a renewable and sustainable method of generating this fuel, with few restrictions on the quantity available. Green hydrogen is manufactured through the electrolysis of water to produce both hydrogen and oxygen gas, using renewable energy sources.

Pink hydrogen is similar to green in that it involves the electrolysis of water using electricity, but with nuclear energy as the source. Although this method involves almost no carbon dioxide, a distinction is made between pink and green as nuclear energy is arguably sustainable but not renewable at the present time.

In the perspective of 30 years the average costs of green-hydrogen production will drastically decline. The blue-hydrogen costs of production will slightly decline, but costs of brown, grey and black hydrogen will increase.

2. CHALLENGES FACING THE ADOPTION OF HYDROGEN VEHICLES

Hydrogen vehicles represent a promising solution to the environmental challenges posed by traditional gasoline-powered vehicles. As the world faces the urgent need to transition to cleaner and more sustainable forms of transportation, hydrogen fuel cell vehicles have gained attention for their potential to significantly reduce greenhouse gas emissions and reliance on fossil fuels. However, the widespread adoption of hydrogen vehicles is hindered by various challenges that must be analyzed and addressed.

2.1. Cost

The cost of hydrogen vehicles remains one of the most significant barriers to their widespread adoption. Currently, the production cost of a hydrogen fuel cell vehicle is substantially higher compared to conventional gasoline-powered vehicles. This cost disparity is primarily attributed to the complex and intricate nature of fuel cell technology, as well as the need for expensive materials such as platinum in the construction of fuel cells.

According to the National Renewable Energy Laboratory (NREL), the cost of producing a hydrogen fuel cell vehicle is estimated to be around $125,000, while a conventional gasoline-powered vehicle costs approximately $20,000. The high cost stems from several factors, including the expense of fuel cell stack components, such as the proton exchange membrane, catalysts, and bipolar plates.

To further compound the cost issue, there is also limited economies of scale in the production of hydrogen vehicles. The low demand and production volumes for these vehicles result in higher unit costs. However, as advancements in technology continue and production scales up, it is expected that economies of scale will help drive down the cost of hydrogen vehicles in the future.

Additionally, the cost of hydrogen fuel itself poses a challenge. While hydrogen can be produced from various sources, including renewable energy, the current methods of hydrogen production and distribution are relatively expensive compared to traditional fossil fuels. The establishment of a robust hydrogen infrastructure requires substantial investments in production facilities, storage systems, and transportation networks. As the adoption of hydrogen vehicles increases, economies of scale and advancements in technology are expected to drive down production costs. Moreover, ongoing research and development efforts are focused on finding alternative materials and improving fuel cell efficiency, which can significantly reduce the cost of fuel cell systems. Collaborative initiatives between governments, research institutions, and automotive manufacturers are essential to accelerating cost reductions and making hydrogen vehicles more affordable for consumers.

By addressing the cost challenges, such as reducing production expenses and establishing a cost-effective hydrogen infrastructure, the feasibility and attractiveness of hydrogen vehicles can be enhanced, paving the way for wider adoption and increased market competitiveness.

2.2. Infrastructure

The development of a robust and extensive infrastructure is crucial for the widespread adoption of hydrogen vehicles. However, the current infrastructure for hydrogen production, storage, and distribution is limited, which poses a significant challenge to the adoption of hydrogen vehicles.

Currently, there are only a limited number of hydrogen refueling stations worldwide compared to the extensive network of gasoline stations. According to the International Energy Agency (IEA), as of 2021, there are approximately 500 hydrogen refueling stations globally, whereas there are over 175,000 gasoline stations. This disparity in infrastructure presents a major obstacle for potential hydrogen vehicle owners, as they need a convenient and accessible refueling network to ensure the practicality and usability of their vehicles.

The establishment of an effective hydrogen infrastructure requires significant investment and collaboration among various stakeholders, including governments, industry players, and energy providers. Key components of the infrastructure include hydrogen production facilities, storage and transportation systems, and a widespread network of refueling stations.

Hydrogen can be produced through various methods, including electrolysis, steam methane reforming, and biomass gasification. Each method has its own advantages and challenges, and the choice of production method depends on factors such as availability of feedstocks, energy sources, and local conditions.

Once hydrogen is produced, it needs to be stored and transported to refueling stations. Hydrogen can be stored in compressed gas or liquid form, each with its own considerations in terms of safety, energy efficiency, and infrastructure requirements. Furthermore, the transportation of hydrogen requires specialized equipment and pipelines or delivery trucks to ensure safe and efficient distribution.

To overcome the infrastructure challenge, governments and industry stakeholders must collaborate to invest in the development of a comprehensive hydrogen infrastructure. This includes expanding the network of refueling stations, promoting standardized refueling protocols, and encouraging the use of renewable energy sources for hydrogen production.

By expanding the infrastructure, hydrogen vehicle owners will have greater confidence in the availability of refueling options, encouraging more individuals and organizations to adopt hydrogen vehicles. Increased investment and collaboration in infrastructure development will also create a positive feedback loop, leading to economies of scale and further cost reductions in hydrogen production and distribution, making hydrogen vehicles more economically viable in the long run.

2.3. Safety

Safety considerations play a critical role in the adoption of hydrogen vehicles. While hydrogen fuel cell vehicles are designed and engineered with safety in mind, concerns surrounding the handling, storage, and use of hydrogen present challenges that need to be addressed.

One of the primary safety concerns associated with hydrogen is its flammability. Hydrogen is highly combustible in the presence of an ignition source, and any leak or release of hydrogen can potentially lead to fire or explosion. However, it is important to note that gasoline and other commonly used fuels also carry fire and explosion risks.

To ensure the safe use of hydrogen as a fuel, stringent safety measures and regulations are in place. These measures encompass the design and construction of hydrogen fuel systems, training for emergency responders, and the development of safety codes and standards specific to hydrogen technologies.

The safe storage and transportation of hydrogen are critical aspects to consider. Hydrogen can be stored in high-pressure tanks or cryogenic containers, both of which require specialized engineering and safety precautions. Leak detection systems, pressure relief devices, and robust containment structures are implemented to mitigate the risks associated with hydrogen storage and handling.

Moreover, vehicle manufacturers undertake rigorous testing and validation processes to ensure the safety of hydrogen vehicles. These processes include crash testing, fire safety testing, and assessment of the structural integrity of the hydrogen fuel system.

It is worth noting that studies have shown that when safety protocols are followed, hydrogen vehicles are no more dangerous than gasoline-powered vehicles. In fact, hydrogen fuel cell vehicles have undergone extensive safety testing and have demonstrated a strong safety record.

Public education and awareness campaigns are essential to address the perception of hydrogen vehicle safety. These initiatives aim to provide accurate information about the safety features, regulations, and precautions in place to ensure the safe operation of hydrogen vehicles. By increasing awareness and understanding, public confidence in the safety of hydrogen vehicles can be enhanced.

In conclusion, while safety concerns associated with hydrogen vehicles exist, the necessary safety measures and regulations are in place to address them. Continued collaboration among governments, industry stakeholders, and regulatory bodies is vital to ensure the ongoing improvement of safety standards and practices in the hydrogen vehicle sector. Through robust safety protocols, effective training, and public education, hydrogen vehicles can be safely integrated into the transportation landscape, encouraging wider adoption and utilization.

2.4. Public perception

Public perception plays a crucial role in the adoption of hydrogen vehicles. The level of awareness, understanding, and acceptance among the general public significantly impacts the willingness to embrace this technology. However, at present, public perception of hydrogen vehicles is often characterized by limited knowledge and misconceptions, which poses a challenge to their widespread adoption.

One of the main factors contributing to the lack of public awareness is the relatively low visibility of hydrogen vehicles compared to other alternative fuel options, such as electric vehicles (EVs). Electric vehicles have received more media attention and have achieved greater market penetration, leading to a higher level of public familiarity. As a result, hydrogen vehicles often suffer from a perception of being "unknown" or "unproven" in the eyes of the general public.

To address this challenge, education and outreach efforts are crucial. Public awareness campaigns can play a significant role in disseminating accurate information about hydrogen vehicles, their benefits, and their safety. These campaigns should focus on explaining the technology, dispelling misconceptions, and highlighting the advantages of hydrogen vehicles over traditional gasoline-powered vehicles.

Collaboration between government agencies, automakers, and advocacy groups is vital in promoting hydrogen vehicle awareness. By working together, these stakeholders can develop targeted messaging and educational materials to reach a wider audience. Additionally, partnerships with academic institutions and research organizations can contribute to public perception by conducting studies and sharing credible information about hydrogen vehicle technology.

Another aspect of public perception relates to concerns about the safety and reliability of hydrogen vehicles. As discussed earlier, safety measures are in place to address these concerns. However, public perception can still be influenced by misconceptions and sensationalized media coverage of isolated incidents. Clear and transparent communication about safety features, testing procedures, and regulatory standards is essential to build trust and address public concerns.

To shape public perception positively, industry stakeholders must prioritize effective marketing and public relations strategies. Highlighting the environmental benefits, technological advancements, and real-world success stories of hydrogen vehicles can help generate interest and improve public perception. Engaging with influencers, media outlets, and community organizations can also aid in raising awareness and fostering a positive perception of hydrogen vehicles.

In conclusion, addressing public perception challenges requires a multifaceted approach involving education, outreach, and targeted communication. By enhancing public awareness, providing accurate information, and dispelling misconceptions, the perception of hydrogen vehicles can be positively influenced, leading to increased acceptance and adoption of this promising technology.

2.5. Competition

Hydrogen vehicles face competition from other zero-emission vehicle technologies, particularly electric vehicles (EVs). Each technology has its own advantages and disadvantages, and the choice of technology depends on various factors such as cost, range, infrastructure, and consumer preferences.

Electric vehicles have gained significant market share and public attention in recent years. They offer several advantages, including a well-established charging infrastructure, longer driving ranges, and a wide variety of vehicle models available. The advancements in battery technology have also contributed to the increased popularity of EVs.

On the other hand, hydrogen vehicles have unique advantages that make them attractive in certain scenarios. One key advantage is their faster refueling time compared to EVs, which can take several hours to charge. Hydrogen vehicles can be refueled within a few minutes, offering a more convenient and familiar experience for consumers. Additionally, hydrogen vehicles typically have a longer driving range, making them suitable for applications that require extended distances, such as commercial fleet operations.

The competition between hydrogen vehicles and EVs can be viewed as complementary rather than a zero-sum game. Both technologies contribute to reducing greenhouse gas emissions and dependence on fossil fuels. Furthermore, advancements in one technology can often benefit the other. For example, developments in battery technology for EVs may lead to improved energy storage systems for hydrogen production and fuel cells.

Collaboration and synergy between stakeholders involved in hydrogen and electric vehicle technologies are essential. Governments, industry players, and research institutions should work together to develop a comprehensive strategy that considers the strengths and limitations of each technology and leverages their respective benefits.

Additionally, market dynamics, consumer preferences, and policy frameworks will influence the adoption of both hydrogen and electric vehicles. Governments can play a crucial role in shaping the competitive landscape by providing supportive policies, incentives, and regulations that foster the growth of zero-emission vehicles as a whole.

In conclusion, while hydrogen vehicles face competition from electric vehicles, both technologies have their place in the transition to sustainable transportation. By understanding the unique advantages and addressing the challenges associated with each technology, stakeholders can foster a collaborative environment that drives innovation, expands infrastructure, and provides consumers with a wider range of zero-emission vehicle options.

3. ANALYSIS OF OPERATION COSTS OF USING HYDROGEN DRIVES IN LONG- AND SHORT- DISTANCE VEHICLES

Nowadays, many transport companies are considering switching to ecological alternatives to traditional trucks with internal combustion engines. For this purpose, the purchase of hydrogen or electric trucks is increasingly being considered. In both cases, these solutions have the potential to reduce the emission of harmful substances into the atmosphere and contribute to environmental protection.

3.1. Costs related to the introduction of hydrogen and electric drives in long-distance transport-purchase and maintenance costs

The cost of buying a hydrogen truck is complex and depends on many factors. They include e.g. power electronics, air compressor, steering pump. Nevertheless, the biggest cost is related to the fuel cells and the hydrogen tank and the appropriate battery, which must be optimized to work with hydrogen propulsion [4].

The chart below shows the average cost of purchasing a new hydrogen truck in Europe. It includes such variables as:

- Indirect costs, which include: research and development of hydrogen infrastructure, marketing, distribution, warranty expenses and profit margin,
- A battery that will be properly integrated with the hydrogen drive,
- Hydrogen tank,
- Fuel cell,
- Electric drive,
- Trailer,
- Base glider [3].

Here is an assumption that the price of the trailer and the base glider will remain at the same level over the years, as there is no clear data on the potential increase or decrease in the prices of these elements. The most important from the point of view of the analysis is the fact that the costs of both fuel cells, hydrogen tanks and batteries will decrease with each passing year [3].

The table above shows that the cost of purchasing a new hydrogen truck in 2022 was around €365,500. Currently, it is about 350,000, while in 2030 the costs should decrease significantly and oscillate around 192,000 euros. However, the exact cost is not fully known. Different sources quote different retail prices [3].

Operating costs related to technical inspections and repairs should also be taken into account. By analyzing various sources, the cost of maintaining a hydrogen-powered truck was developed. These costs are reported on an annual basis. Repairs and technical inspections include: inspections of the drive system, hydrogen tanks, battery replacement, maintenance of fuel cells and hydrogen supply systems to the drive unit.

Table above shows that, the repair and maintenance costs in 2022 amounted to 16,440 Euro, while the same maintenance activities are expected to be much lower in 2030 and should amount to 11,960 Euro per year. The decrease in this value is mainly related to the predictions that by 2030 there will be an increase in the hydrogen infrastructure, and thus the number of relevant parts, places for repairs and staff will increase [13].

The operating costs also include costs related to road taxes in the European Union. Due to the very different toll costs in different countries, an average value of EUR 573 per year has been worked out. The cost of purchasing an electric truck is related to many factors such as the cost of the battery, the cost of the power electronics, the cost of the electric motor and the cost of additional equipment such as thermal management systems and air conditioning [13].

As shown in the chart below, the purchase costs of electric trucks are also high. The average purchase price for an electric truck in 2022 was €388,000. However, as in the case of hydrogen trucks, the cost of purchase will decrease every year, which is mainly related to the growing popularity and propagation of zero-emission drive systems and the increase in the production of batteries. In 2030, the cost of purchasing an electric truck is estimated at around €177,000, which is about €15,000 less than a hydrogen-powered truck [14].

The repair, maintenance, maintenance and overhaul costs of electric trucks are also lower than for hydrogen trucks. In 2022, these costs amounted to EUR 12,600, and in 2030 they should amount to EUR 8,400. These costs include inspections and replacement of batteries as well as inspections and repairs of the drive system. As with hydrogen trucks, the toll costs for electric trucks are the same at €573 per year [13].

3.2. Costs of electricity and hydrogen - now and in the future

Electricity and hydrogen are two key energy carriers that are playing an increasingly important role in today's world. Electricity is produced from a variety of sources such as coal, wind, solar and nuclear power plants and is widely used in industry, transport and households. On the other hand, hydrogen, although difficult to obtain, can be used as an energy carrier and is considered one of the future solutions for the production of clean energy [5].

The costs of electricity and hydrogen are important factors that influence the choice of energy carrier. Currently, the cost of electricity varies and depends on the source of generation, as well as on the geographic region. The costs of hydrogen are significantly higher than those of electricity, mainly due to the difficulties in obtaining and storing it. However, the development of technology and innovation contributes to the reduction of hydrogen production costs, which may make it more competitive in relation to other energy carriers in the future [3].

The chart below shows what the electricity costs for non-domestic consumers looked like (e.g. in the case of charging electric cars at charging stations) in the last several years in Europe. Based on the graphs, it can be seen that each year since 2008, electricity prices have been steadily increasing. However, 2021 saw a surge in electricity prices, which accelerated even further in 2022. As you can see, in 2022 the cost of electricity including all taxes was around €0.21/kWh (€0.10/kWh in 2008). The reason for this is the crisis related to the COVID-19 pandemic and the outbreak of war in Ukraine. In addition, Europe and the whole world are struggling with a raw material and economic crisis, which also increases the cost of electricity [15].

Considering the above and the pressure of the relevant authorities to introduce electric vehicles, it can be assumed that the costs of electricity will continue to grow in the coming years. However, 3 scenarios (low, baseline and high) of electricity growth from 2023 to 2040 have been developed here. [15, 5].

Assumptions:

Low:

- from 2023 to 2025, an increase of 15% year on year;
- from 2025 to 2030 an increase of 8% year on year;
- from 2030 - 5% year on year.

Basic:

- from 2023 to 2025 - 20% increase year on year;
- from 2025 to 2030 - 10% increase;
- from 2030- 5% increase.

High:

- from 2023 to 2025 - 30% increase year on year;
- from 2025 to 2030 - 20% increase;
- from 2030- 10% increase.

From 2035 for positive and basic scenarios electricity costs should stabilize and fluctuate around 1/2% year on year. A drop in prices after 2030 is also possible. In the comparative analysis, the average values from the baseline scenario were used.

With regard to the cost of hydrogen, the situation is completely different than in the case of electricity. These costs are not related to the global energy crisis but to the currently poorly developed hydrogen infrastructure and low availability of hydrogen and hydrogen refueling stations. However, in the analysis, we assume that hydrogen prices will decrease with each subsequent year due to the development of hydrogen infrastructure. This is a fundamental and very important difference compared to electricity, where the costs will increase year by year. As in the case of electricity, 3 scenarios have been developed here: low, basic and positive. The reference point is 2023, where the costs of €/kg hydrogen for individual scenarios are as follows [5]:

- Low scenario - 10 €/kg;
- Basic scenario - 11 €/kg;
- High scenario - 12 €/kg.

Assumptions for subsequent years:

Low:

- from 2023 to 2025- from 10 €/kg to 8 €/kg
- from 2025 to 2030- from 8 €/kg to 6 €/kg
- from 2030 - from 6 €/kg to 4 €/kg
- from 2035 to 2040- from 4 €/kg to 3 €/kg

Basic:

- from 2023 to 2025 - from 11 €/kg to 9 €/kg
- from 2025 to 2030 - from 9 €/kg to 7 €/kg
- from 2030 to 2035- from 7 €/kg to 5.50 €/kg
- from 2035 to 2040- from 5.50 €/kg to 4.50 €/kg

High:

- from 2023 to 2025 - 12 €/kg to 10 €/kg
- from 2025 to 2030 - from 10 €/kg to 8 €/kg
- from 2030 to 2035- from 8 €/kg to 7 €/kg
- from 2035 to 2040- from 7 €/kg to 6 €/kg

In the analysis, we use the costs from the baseline scenario [5, 3, 15].

The table below contains electricity costs for each of the scenarios described above. It can be seen that energy costs will continue to increase, while hydrogen costs should decrease with each subsequent year. For 2023 the base cost of electricity is about 0,21 €/kWh. For hydrogen is 11 €/kg. And for the future, for example 2035 it will be: 0,53 €/kWh and 5,50 €/kg for hydrogen [3, 5, 15].

As you can see on the table below in this part of the costs, we also include the costs associated with the purchase of batteries for electric trucks and a breakdown of the cost of purchasing a fuel cell. These costs have also been taken into account for future years. Here it can be seen that currently batteries are definitely cheaper than fuel cells, however, in 2040 the difference will be marginal for both the baseline, low and high scenarios. [5] The chart also shows the prices of hydrogen in subsequent years, however, the average subsidy for refueling hydrogen in the amount of 3 €/kg has also been included here. As you can see, such an undertaking would significantly reduce the cost of hydrogen. For example, in the mid-level scenario in 2030, the cost including subsidies could be slightly more than 4 €/kg. The graph also shows separate costs for obtaining hydrogen and the costs incurred by the refueling station (transport of hydrogen to the station, etc.). These two variables make up the total hydrogen cost in €/kg [3].

3.3. Refueling costs, charging time - differences between an electric truck and a hydrogen truck

Very important parameters in the comparative analysis are two factors whose impact is much more important on the final result than the purchase or energy/hydrogen costs. These factors are:

- time to refuel the hydrogen truck to charge the battery of the electric truck;
- the range of a hydrogen powered truck compared to an electric truck [1].

The hydrogen refueling time compared to the charging time is definitely shorter. Refueling hydrogen takes only 10-15 minutes, while charging an electric battery in a truck takes 90 minutes with a 375 kW charger.

In addition, hydrogen trucks have a longer range than electric trucks - around 400/450 km for hydrogen compared to 300/375 km for electric batteries. Thanks to this, using hydrogen-powered trucks, you can save time and, at the same time, transport more goods. This time saving allows you to drive about 150 km more with a one-time difference between refueling and recharging.

The graphic below with the table shows a comparative analysis between a hydrogen-powered truck and an electric-powered truck. The data contained in the table have been calculated and developed on the basis of the information collected so far. This table includes [12]:

- Purchase costs of a new hydrogen and electric truck,
- Maximum range on one refueling,
- Annual refueling/charging costs,
- Annual repair and maintenance costs,
- Saving time on refueling compared to charging,
- TCO- (total cost of ownership) for 5 years of use.

From all calculations, it is clear that the 5-year cost of ownership is lower for a hydrogen-powered truck. In the initial analysis, it may seem that the situation is reversed and that electric trucks are cheaper in the end. However, if we take into account the increasing costs of electricity, with the decreasing costs of hydrogen, a greater range for hydrogen, and thus a smaller number of full refuelings (lower cost of the entire trip) and the time saved on refueling, it is clear that drives will be a much better solution hydrogen for heavy long-distance transport. Even if the energy costs did not increase according to the calculations presented in the previous chapter (5.3), but would remain at a similar level, due to the range itself and the charging time until refueling, a hydrogen-powered truck will be better. However, such a situation only takes place under the assumption that by 2030 there will be a significant increase in the hydrogen network, and hydrogen will be mainly obtained from renewable energy sources [17].

Another very important aspect that should be taken into account here is the type of terrain on which the passage of heavy goods vehicles takes place. The greater the elevation, the more energy is needed to overcome it. Electric trucks would have to draw this energy from batteries. This would cause the battery to lose its power faster and it would have to be charged more often. In addition, the weight of such a vehicle would be much greater and could exceed the permissible limits. This state of affairs is influenced by the fact that much heavier and more capacious batteries with higher processing power should be placed [18].

The case of hydrogen propulsion is completely different and is definitely more efficient. The losses result only from the combustion of hydrogen itself. This can be compared to a diesel engine, which only uses more fuel to climb a hill. In this process, the battery is only an auxiliary, it does not play such an important role as in a purely electric drive. Considering that Europe has a lot of mountainous and upland areas, implementing a hydrogen drive in trucks will be much more beneficial [1, 3, 15].

3.4. Comparative example for two trucks - electric and hydrogen

In order to accurately illustrate the effects of the comparative analysis, the two most popular models of electric and hydrogen-powered trucks have been selected. For the electric drive it is Scania Electric, while for the hydrogen drive it is Hyundai Motor's XCIENT Hydrogen. Both vehicles are used for long-distance operations. Their total weight and maximum towing weight are almost the same [19-21].

Information on the hydrogen tank capacity, battery capacity in the electric drive, maximum range, hydrogen consumption per 100 km and energy consumption per 100 km were read from the manufacturer's data. Together with the input data, which are: calculated and proposed refueling and charging costs, power of currently and future available chargers for charging electric trucks, approximate refueling and charging costs for individual models were calculated [19-21].

For the hydrogen propulsion we have the following calculation scheme:

Total cost of fuelling= cost of hydrogen* tank capacity

For the electric drive we have the following calculation scheme:

Total cost of charging= electricity cost* battery capacity

Thus, the costs of refueling hydrogen to the full for individual years:

1. Cost of refueling (2023): 363 €;
2. Cost of refueling (2030): 231 €;
3. Cost of refueling (2035) 181 €.

Full battery charging costs for individual years:

1. Charging cost (2023): 131 €;
2. Cost of charging (2030): 262 €;
3. Cost of charging (2035): 330 €.

The calculated values of refueling costs indicate that currently in 2023 the costs of refueling hydrogen are almost 2.5 times higher than the costs of charging with electricity. Therefore, even saving time on charging may not compensate for financial losses. However, the situation changes after 2035, when charging costs exceed refueling costs. So, we assume that 2035 will be the year when hydrogen drives will become fully profitable over electric drives. However, the turning point will be 2030 [13, 15].

With regard to refueling time for hydrogen, it was assumed that the throughput is 0.4 kg per minute, so full refueling takes about 12 minutes. In the case of charging the batteries, we assume that the capacity of the batteries is 624 kWh, while the power with which they are charged oscillates around 375 kW. Then it takes about 90 minutes to fully refuel. Based on the range, approximate values of hydrogen and electricity consumption per 100 km were developed. These assumptions are for the route in optimal conditions, which means no significant weather phenomena and no mountainous areas. The calculated values of refueling costs indicate that currently in 2023 the costs of refueling hydrogen are almost 2.5 times higher than the costs of charging with electricity. Therefore, even saving time on charging may not compensate for financial losses. However, the situation changes after 2035, when charging costs exceed refueling costs. So, we assume that 2035 will be the year when hydrogen drives will become fully profitable over electric drives. However, the turning point will be 2030 [13, 17, 18].

The chart below shows the ratio of TCO (€) to tonnes per kilometer for an electric and hydrogen truck. The variable for electric drive is marked with blue, green for electric drive, and the black line is diesel drive, which was omitted in this analysis. The chart was prepared using previously calculated fuel and electricity costs (50%), differences in time savings (25%), repair and maintenance costs (5%), powertrain (10%), non-powertrain (10%) [12].

The chart was prepared for the current and future years, starting from 2020 and ending in 2050. As you can see, with each subsequent year, both the TCO for hydrogen and electric drives are decreasing [12].

The graph presents two cases:

- MDT for regional transportation with range in tank 500 km;
- HDT for long-haul transportation with range in tank 600 km.

In this analysis, the case of long-distance trucks was mainly considered, but the case of regional transport is also worth mentioning. As the graph shows, both for regional transport, the choice of hydrogen drives will be the best choice. The green line is below the blue line, which clearly indicates the advantage of hydrogen drives in terms of the variables that have been introduced [12].

This graph is a general summary of the comparative analysis between hydrogen and electric propulsion in long-haul transport. It can be concluded that the use of hydrogen drives will be the best solution for any calculations made [12].

4. POLICY INITIATIVES AND GOVERNMENT SUPPORT FOR HYDROGEN VEHICLE

Government policies serve as a catalyst for the widespread adoption of hydrogen vehicles by creating an enabling regulatory environment and incentivizing the market. These policies play a crucial role in shaping the future of sustainable transportation and accelerating the transition to a cleaner and greener future.

One aspect of policy initiatives for hydrogen vehicles revolves around the establishment of a regulatory environment that ensures the safe operation and integration of these vehicles. Governments set safety standards, licensing requirements, and regulations that govern the manufacturing, sale, and usage of hydrogen vehicles. These regulations provide clarity and confidence to manufacturers, consumers, and infrastructure developers, fostering trust and facilitating the widespread adoption of hydrogen vehicles.

In addition to the regulatory framework, governments employ policies that stimulate market demand for hydrogen vehicles. These policies are designed to incentivize both individual consumers and fleet operators to choose hydrogen vehicles as their preferred mode of transportation. One example is fleet purchase incentives, where governments provide financial support, grants, tax credits, and other favorable financing options to encourage businesses and organizations to incorporate hydrogen vehicles into their fleets. These incentives not only make hydrogen vehicles more affordable but also demonstrate the government's commitment to promoting sustainable transportation solutions.

5. LOGISTIC ANALYSIS. CONCLUSIONS

At the moment Shell is the biggest investor in production of hydrogen fuel. Currently in Europe there are 99 refueling stations in Germany, 34 in France, 16 in UK, 7 in Swiss, 6 in Netherlands, 8 in Denmark,5 in Norway, 4 in Sweden, 2 in Poland.

In Poland, until 2035, 30 hydrogen station will be built. The first green hydrogen electrolyzer is placed in Warsaw. It will be able to produce over 1,000 kg of hydrogen per day. The target production is to reach 40 tons per day. In turn, ready fuel will be delivered to 30 stations scattered in the largest Polish cities in special hydrogen tank lorries. The location of the stations on the map is to outrun range of electric cars with fuel cells.

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