Czech University of Life Sciences Prague

Faculty of Economics and Management

Department of Economics

Diploma Thesis

Analysis of the trends on the hydrogen market

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Thesis title

Analysis of the trends in the hydrogen market

Objectives of thesis

The aim of the work will be to evaluate the perspectives of the use of hydrogen as an energy source. A comparison will be made between the price of energy provided by hydrogen and the price of energy from other sources

Methodology

A comparison of the advantages and disadvantages of using hydrogen as an energy source will be made. Hypotheses: hydrogen is an economically more advantageous source of energy than other energy sources (gas, diesel, coal, etc.). In this work, it will be possible to determine, which price conditions in energy markets would make hydrogen more economically advantageous.

The work will be divided into three main parts. The theoretical part will first describe the general characteristics of hydrogen, its properties and possible fields of usage. This section will describe the main methods of obtaining hydrogen and methods of calculating the price of energy provided by 1 m3 of hydrogen. The energy policy of the Czech Republic will be outlined – its goals and main vision, the topic of energy dependence, resp. independence, the main markets on which the Czech Republic depends are described. The advantages and disadvantages of individual energy sources will be compared, as well as the main producers and exporters of energy sources. The practical part of the work will begin with an analysis of the dynamics of energy prices in world markets and in the Czech Republic. This will draw conclusions about how energy prices are changing and what the effects are on the country's economy. A substantial part of the work will be the calculation and comparison of energy prices provided by hydrogen and other energy sources. Based on the work performed, it will be possible to conclude on the perspectives of the use of hydrogen as an alternative energy source in the Czech Republic

The proposed extent of the thesis

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Declaration

I declare that I have worked on my diploma thesis titled "Analysis of the trends on the hydrogen market" by myself and I have used only the sources mentioned at the end of the thesis. As the author of the diploma thesis, I declare that the thesis does not break copyrights of any their person.

In Prague on 31st March 2022 ______________________________

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Analysis of the trends on the hydrogen market

Abstract

The aim of the work is to evaluate the perspectives of the use of hydrogen as an energy source. The task of the work is also to compare the price of energy provided by hydrogen and the price of energy from other sources. A comparison of the advantages and disadvantages of using hydrogen as an energy source are made. The practical part includes an analysis of the energy market, the development of individual energy sources and the issue of emissions. The analysis clearly shows the trends of decarbonisation and the transition to the alternative energy sources. Hydrogen can be considered as an energy source and fuel of the future, but today it meets many barriers of the development. The calculation of the prices of hydrogen as an energy source (per 1 kWh) and as a fuel (per 1 km of the vehicle run) shows, that so far, the use of hydrogen is in most cases more expensive than the use of other energy sources. However, the rising price of electricity for householders in the Czech Republic, opportunity to reduce the risk of dependence on hydrocarbons, support from state policies and development of technologies are the factors, that help to develop the hydrogen usage.

Keywords: hydrogen, alternative energy, energetics, fuel, energy resources, market price, energy price, trends.

Analýza trendů na vodíkovém trhu

Abstrakt

Cílem práce je zhodnotit perspektivy využití vodíku jako zdroje energie. Úkolem práce je také porovnat cenu vodíkové energie a cenu energie z jiných zdrojů. Je provedeno srovnání výhod a nevýhod použití vodíku jako zdroje energie. Praktická část obsahuje analýzu energetického trhu, vývoje jednotlivých zdrojů energie a problematiku emisí. Analýza jasně ukazuje trendy dekarbonizace a přechodu na alternativní zdroje energie. Vodík lze považovat za zdroj energie a palivo budoucnosti, které dnes však naráží na mnohé překážky rozvoje. Z výpočtu cen vodíku jako zdroje energie (za 1 kWh) a jako paliva (na 1 km jízdy vozidla) vyplývá, že zatím je použití vodíku ve většině případů dražší než použití jiných zdrojů energie. Rostoucí cena elektřiny pro domácnosti v ČR, možnost snížit riziko závislosti na uhlovodících, podpora ze strany státní politiky a rozvoj technologií jsou však faktory, které napomáhají rozvoji využívání vodíku.

Klíčová slova: vodík, alternativní energie, energetika, palivo, energetické zdroje, tržní cena, cena energie, trendy.

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1 Introduction

Energy resources are traditionally a source of power that allows country to control the situation and relations in the world arena. Countries strive for energy self-sufficiency and differentiation of energy sources.

Hydrogen provides a clean, secure and affordable way for the energy usage. The interaction of hydrogen with oxygen occurs with the release of heat. When hydrogen is burned, pure water is obtained. That is, hydrogen fuel is produced without harm to the environment, unlike gas or gasoline.

The idea of using hydrogen in power engineering is not new. Back in the 80s of the twentieth century hydrogen-fueled engines were developed. Today there are national and international programs for the development of hydrogen energy within the renewable energy sources (RES) in the US, EU, Japan, China and other countries. Hydrogen buses run in Madrid, Rome, Amsterdam, Stockholm and other main European cities. The prime minister of Japan bought an electric car with a hydrogen engine, and Iceland is almost completely switching over to hydrogen energy: hydrogen engines are installed on boats, cars, and houses are heated with hydrogen-powered heat sources (Radchenko, Mokrushin, Tulpa, 2014).

The desire of Europe to develop alternative energy is understandable: Europe does not have its own considerable oil and gas resources. The transition to hydrogen energy using RES will allow Europe to stop depending on oil and gas suppliers – Russia and the OPEC (Organization of Petroleum Exporting Countries) countries, as well as to solve environmental problems.

A current overview of modern hydrogen technologies and this market should contribute to growth of general awareness of the current trends in energetics development. Global energy consumption and prices are rising, while energy supplies are declining. The transition to a hydrogen economy can be a viable solution, especially for the automotive industry. Supplying hydrogen is now a major business and has huge perspectives. The number of countries and enterprises that support investment in hydrogen deployment is now increasing. The US is intensively involved in research and development of hydrogen technologies, and the EU is also paying close attention to the hydrogen economy.

The issue of energy self-sufficiency is very important for the Czech Republic. The Czech Republic does not have such natural conditions that it can largely cover energy consumption by solar or wind sources, which will nevertheless have an irreplaceable place in energy. However, it is not desirable for the Czech Republic in the coming years to be dependent on the import of expensive energy from abroad due to the closure of coal resources. The significant rise in energy prices determines the importance of finding alternative energy sources for the Czech Republic.

Hydrogen can be considered as an alternative and very promising source of energy, so this thesis will be very current and relevant for countries seeking energy independence and alternative energy sources.

In connection with the high importance of energy and the growing energy needs of countries, as well as with ecological trends, the research of alternative energy sources is very topical and important.

2 Objectives and Methodology

This part defines the main aim and hypothesis of the work, describes the structure of the work and the methodological procedure used to achieve the goal of the work.

2.1 Objectives

The aim of the work will be to evaluate the perspectives of the use of hydrogen as an energy source. The task of the work will be also to compare the price of energy provided by hydrogen and the price of energy from other sources. A comparison of the advantages and disadvantages of using hydrogen as an energy source will be made.

2.2 Methodology

The work will be divided into three main parts.

The theoretical part will first describe the general characteristics of hydrogen, its properties and possible fields of usage. This section will describe the main methods of obtaining hydrogen and methods of calculating the price of energy provided by 1 m3 of hydrogen. The energy policy of the Czech Republic will be also outlined – its goals and main vision, the topic of energy dependence, resp. independence, the main markets on which the Czech Republic depends are described. The advantages and disadvantages of individual energy sources will be compared, as well as the main producers and exporters of energy sources.

The practical part of the work will contain an analysis of the energy market and the hydrogen market (from a global perspective, in the context of the EU and the Czech Republic) with an impact on the transport sector. So far, there is very little information about the hydrogen market in the Czech Republic, so the analysis is extended to the global level. It can also be assumed that hydrogen will be a commodity traded on international markets (as well as other fuels) and countries will be heavily dependent on imports / exports of this commodity. It is therefore necessary to take into account the EU market, which is very important from the point of view of the Czech Republic's foreign trade. The research period begins in 1990 and ends with the current period (at most the latest current data – mostly in 2021).

The development of the following indicators is analysed:

- energy supply (by sources, by regions),
- energy consumption (by regions, by sectors),
- CO_2 emissions (by countries, by fuel),
- detailed analysis of the transport sector: energy consumption in this sector (by sources), CO_2 emissions (by type of transport), number of registered cars in the Czech republic (by fuel),
- hydrogen production,
- hydrogen prices.

A substantial part of the work will be the calculation and comparison of energy prices provided by hydrogen and other energy sources.

Using 1 m3 of hydrogen, it is possible to get 12832,4 kJ of energy (3,56 kWh of electricity) (Neftegaz, 2017). The feasibility of switching to hydrogen fuel can be assessed by comparing the existing tariff for 1 kWh of electricity and, for example, the cost of 1 m^3 of gas or the cost of another energy carrier.

It is assumed that the price of 1 kJ of energy from hydrogen is cheaper than the price of 1 kJ from other non-renewable energy sources.

It is can be also found out how much it costs to drive petrol, diesel and hydrogen cars. Under the knowledge of fuel consumption by different types of engines and fuel prices, the average cost per 100 km of run-in cars can be calculated. Due to the fact that different cars have different fuel consumption, it is advisable to compare different cars – such as cars and buses.

It is assumed that the cost per 100 km of run-in hydrogen passenger car is lower than that of a petrol car and that the cost per 100 km of run-in hydrogen bus is lower than that of a diesel bus.

Multi-criteria analysis i salso used in this thesis. The aim of the analysis is to compare two variants in two scenarios:

Scenario 1 (variant A vs. variant B)

Scenario 2 (variant C vs. variant D)

Accessing variants are:

A. Benzine passenger car (fuel consumption: 7,5 l of benzin per 100 km)
B. Hydrogen passenger car (fuel consumption: 1 kg of hydrogen per 100 km)
C. Diesel bus (fuel consumption: 42 l of diesel per 100 km)
D. Hydrogen bus (fuel consumption: 9 kg of hydrogen per 100 km)

Furthermore, there was created a proposal of criteria according to which the variants will be assessed – see table 1, criteria a) – g). Each pair of criteria was always compared and evaluated – 0 or 1. The comparison "matrix", the number of points and the relative weights are given in Table 1. The criterion, which is more important than the other in the pair, gets 1 point („1“). A less important criterion in a pair is rated zero („0“). The relative weight of each criterion was calculated as follows: the sum of the points obtained by the selected criterion divided by the total number of points multiplied by 100 %.

Table 1 Determination of relative weight

		a	**b**	**c**	**d**	**e**	**f**	**g**	**Sum**	**Relative weight**
a	Price of fuel (EUR or CZK) – today	-	1	1	1	0	1	1	5	24 %
b	Prices of fuel (EUR or CZK) – estimated in future	0	-	1	1	0	1	1	4	19 %
c	Full tank of the fuel – posibble run-in (km)	0	0	-	1	1	1	1	4	19 %
d	CO_2 emissions (grams CO2 per km)	0	0	0	-	0	1	1	2	10 %
e	Availability of refueling points (good / bad)	1	1	0	1	-	0	1	4	19 %
f	Taxes and fees (EUR or CZK)	0	0	0	0	1	-	0	1	5 %
g	Market price of the new car (low / high)	0	0	0	0	0	1	-	1	5 %
	Sum								21	100 %

Source: own processing

Based on the work performed, it will be possible to conclude on the perspectives of the use of hydrogen as an alternative energy source in the Czech Republic.

3 Literature Review

3.1 Hydrogen – its properties and uses

The most widespread element in the universe and the third most widespread element on Earth is hydrogen (H) (Tkáč, Stehlík, 2016), makes up about a tenth of the weight of the human body (Musil, 2009). It is a colorless, light gas, tasteless and odorless (Šváb, 2006). In form of gas it almost doesn't exist on earth, because it is highly reactive and forms compounds with all the elements of the periodic table (with the exception of rare gases) – especially with carbon, oxygen, sulphur and nitrogen, which form the basic building blocks of the life. On the Earth, hydrogen most often occurs in the compound with oxygen, in the form of water (H_20). The hydrogen bond with oxygen atoms is extremely strong, which explains the anomalous physical properties of water (high boiling and melting points, etc.) (Šváb, 2006). From this point of view, hydrogen is essential for the life. In addition, the importance of hydrogen from an energy point of view is currently growing.

3.1.1 A brief history of the hydrogen invention and its usage

The production of combustible gas during the interaction of metals and acids was observed as early as the 16th century, that is, during the formation of chemistry as a science. The famous English scientist Henry Cavendish studied the substance since 1766 and gave it the name "combustible air". When burned, this gas produced water. Unfortunately, the scientist's adherence to the theory of phlogiston (hypothetical "superfine matter") prevented him from coming to correct conclusions (NII KM, 2021).

The French chemist and naturalist A. Lavoisier together with the engineer J. Meunier and with the help of special gas meters in 1783 carried out the synthesis of water, and then its analysis by means of decomposition of water vapor with red-hot iron. Thus, scientists were able to come to the correct conclusions. They found that "combustible air" is not only a part of water, but can also be obtained from it (Izhneftyanic, 2020).

In 1787, Lavoisier put forward the assumption that the gas under study is a simple substance and, accordingly, belongs to the number of primary chemical elements. He named it hydrogene (from the Greek words "hydor" – water and "gennao" – I give birth), that is, "giving birth to water" (NII KM, 2021).

Lavoisier proposed an “iron-steam method” for producing hydrogen to fill balloons (instead of the more expensive one based on the reaction of cast iron shavings with a solution of sulfuric acid). This method of producing hydrogen was used, along with others, up to the middle of the 20th century. (Leenson, 2021).

In 1803, W. Wollaston and T. Graham discovered that the metal palladium could absorb large amounts of hydrogen in the formation of metal hydride. The present invention is now the basic idea for promising technologies for the use of metal hydrides as hydrogen storage (Züttel, Borgschulte, Schlapbach, 2008).

In 1823, Johann Wolfgang Dobereiner created the first “pocket” lighter. “Dvoereiner Platinum lighter” became the first hydrogen-using product to be sold on the mass market (Züttel, Borgschulte, Schlapbach, 2008).

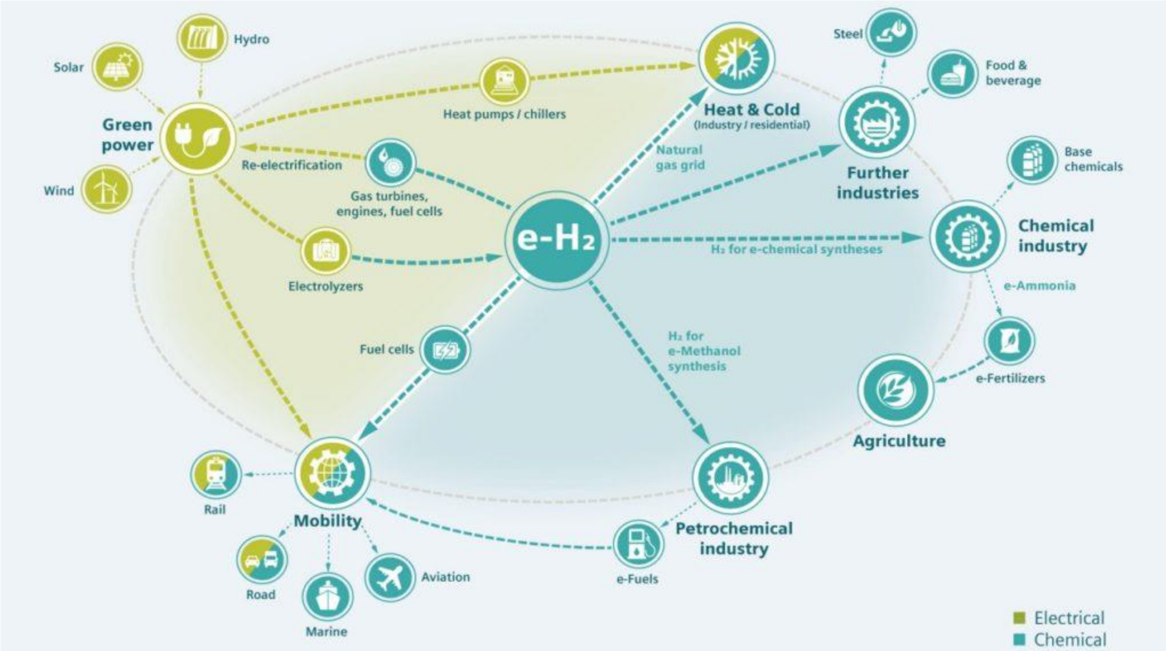
The invention of a catalyzed process that enabled the synthesis of ammonia (NH_3) from the elements hydrogen and nitrogen, for which the German chemist Fritz Haber received a Nobel prize, found its application in a number of industrialized countries, which caused a significant increase in its use. Today, 70 % of the hydrogen produced is an intermediate in the synthesis of ammonia, NH_3 (Wichterle, 2012).

3.1.2 Hydrogen economics

With the expansion of knowledge about the possibilities of using hydrogen, there is talk of hydrogen economy: “*The main goal of the hydrogen economy is the storage of energy (accumulation), or the use of hydrogen in transport*” (Tkáč, Stehlík, 2016).

Hydrogen is used in a wide range of industrial areas, “green” energy and in clean mobility (thanks to hydrogen propulsion) (see Figure 1).

Figure 1 Hydrogen in industry and green energetics



Source: Schnettler, 2019

In the chemical industry, hydrogen is used for the production of basic chemicals, fertilizers and, last but not least, for the production of environmentally friendly fuels, such as aviation, where the use of fuel cells is difficult. In the food industry, hydrogen is used, for example, in the hydrogenation of fats. A possible prospective use of hydrogen may be in the steel industry, where hydrogen serves as a partial substitute for coal for the reduction of iron in blast furnaces. In November 2019, Thyssenkrupp started the first testing of this technology (Trnavský, 2019).

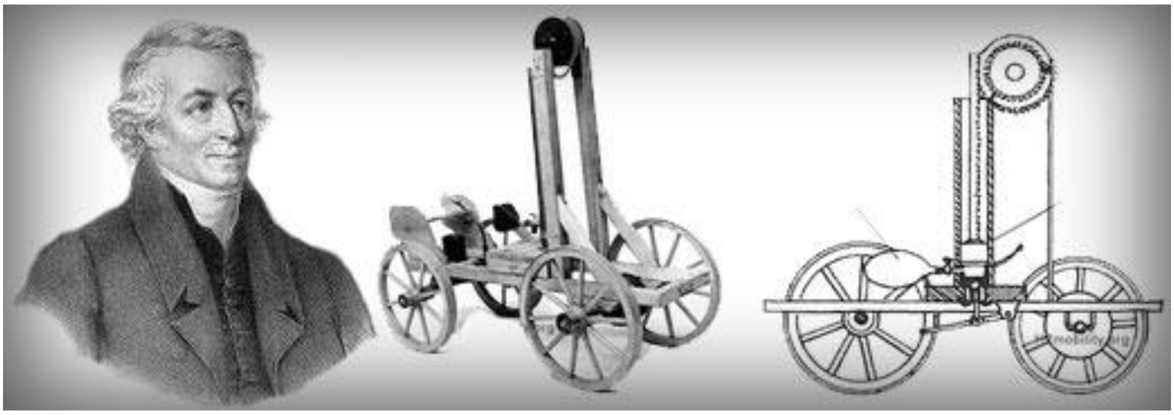
Unlike others, chemical energy in the form of hydrogen or methane can be efficiently and long-term stored, transported and, in the event of a shortage in the network, transferred back using fuel cells, cogeneration units, gas or steam power plants (Trnavský, 2019).

As for the modern use of hydrogen for propulsion, we must distinguish between its use in internal combustion engines and in fuel cells.

3.1.3 Hydrogen in internal combustion engines

Although the hydrogen combustion engine was the first patented internal combustion engine and was designed in 1807 by Francoius Isaac de Rivaz, its practical use dates back to a much later time. Hydrogen in the Rivaz engine was obtained by electrolysis of water and the design was unresolved and practically unusable. It was an explosive engine with electric ignition. He built his cart in Vevey, Switzerland, and during the first test drive, he slammed the workshop door and smashed it against a tree. The drawing of the trolley is shown in figure 1.

Figure 2 Internal combustion engine, used a mixture of hydrogen and oxygen as fuel, by F. de Rivaz



Source: Rettew Creative, 2011

The first working hydrogen combustion engine was created a hundred years after F. Rivaz's first patent, in the 1920s. Its use was first tested in Ricardo and Maybach airship engines.

Hydrogen engines therefore work similarly to "classic" petrol or diesel combustion engines. Hydrogen burns very rapidly through chain branched reaction kinetics. Due to its high calorific value, its flame is stable even with a very lean mixture with good efficiency, which can be used to reduce the emission of nitrogen oxides.

Today, hydrogen can be used as a fuel in virtually all current types of internal combustion engines, such as piston, jet or rocket.

3.1.4 Hydrogen usage in fuel cells

„*A fuel cell uses the chemical energy of hydrogen or another fuel to cleanly and efficiently produce electricity. If hydrogen is the fuel, electricity, water, and heat are the only products.*“ (Office of U.S. Department of Energy, 2020).

The principle of the fuel cell was discovered in 1838 by the Swiss scientist Christian Friedrich Schönbein, the first working prototype was then assembled in 1839 by the British scientist Sir William Grove. The name "fuel cell" was first used by Ludwig Mond and Charles Langer in 1889 for the first practical device using air and industrial coal gas. After the invention of the dynamo, the fuel cell fell partially into oblivion. The fuel cell experienced its real renaissance in the 1960s. This was mainly due to space research, because the cell has a more favorable energy / weight ratio than other sources. For example, they were equipped with Apollo spacecraft, but they are also a source of energy for current space shuttles (Züttel, Borgschulte, Schlapbach, 2008).

The fuel cell consists of plates of graphite and conductive metal, between them is a membrane. On the one hand, hydrogen is injected into the cell, from which protons are separated on the active layer of the catalyst and pass through the membrane on the other side of the cell to the metal plate. At the same time, the ventilator pushes oxygen. Then it is a matter of a simple chemical process in which an electric current is generated. It is drained by a metal plate and "waste" is water that drains (Mokříš, 2020).

The above described takes place within one cell, which handles a voltage of up to 1.5 V (like a pencil battery). Of course, hundreds of such cells are needed to power a car, including cooling systems, propulsion, regulation, and order subsystems. The energy generated by fuel cells sometimes needs to be hidden because the whole system cannot react as fast as the driver requires. Therefore, the battery in the car, similarly to electric cars, is much smaller (up to 2 kWh). It supplies voltage to the electric motor, which then drives the wheels. Above all, however, this battery serves as a place where energy is stored and where it is taken from. Thus, the system does not have to force the cells to sudden changes in the output voltage, but the whole thing is regulated according to the battery voltage, which tolerates sudden changes without problems and serves as a stabilizing element (Mokříš, 2020).

The disadvantage of a fuel cell in automobiles is the slow response to the demand for higher loads and the high cost of the installed power, associated with a decrease in efficiency in case of overload. Therefore, fuel cell vehicles have been designed as hybrid from the beginning. However, the hybrid has more weight and lower braking-acceleration relationship efficiency. Another way, therefore, is the combination of a fuel cell with an internal combustion engine (Macek, 2007).

Today's range of portable and stationary fuel cell systems ranges from small-scale watt applications to large field installations and decentralized power supplies that provide many megawatts. „*Fuel cells are unique in terms of the variety of their potential applications; they can provide power for systems as large as a utility power station and as small as a laptop computer.*“ (Office of U.S. Department of Energy, 2020).

The fuel cell does not burn anything and does not need an intermediate cell in the form of conversion to mechanical energy. It should therefore be more efficient in energy conversion. In addition, its operation is quiet and does not produce NOx or Sox fumes (Rohovský, 2020). Safe, functional and efficient fuel cell systems and related hydrogen infrastructure, such as electrolysers and hydrogen filling stations (HRS), play a key role in the successful transition to sustainable energy (TÜV SÜD Czech, 2021).

3.1.5 Hydrogen storages for solar and wind energy

It should be noted that hydrogen can be used not only in combustion engines and fuel cells in vehicles and different systems, but also as an energy carrier into which primary energy can be stored similarly to batteries. The fact that hydrogen is becoming a repository of energy – from renewable sources or nuclear reactors, and not a conventional fuel is considered key to understanding the future of the hydrogen economy (Ornst, 2020).

Why is hydrogen so important for energy? The reason is the possibility of its use as a "repository" of energy from other sources and its use at any time. It is this property that is in demand in the production of energy from RES, especially from the sun and wind. The biggest problem with the production of electricity from the sun and wind is the variable power, which depends on the current weather conditions, and the difficult regulation of their power. Excess electricity from these sources can cause destabilization of the electricity transmission system, and in exceptional cases the so-called black-out, ie a large power outage. At present, fluctuations in the network caused by solar and wind power plants are regulated mainly by power adjustment mainly by coal, gas and hydropower plants, including pumped storage hydropower plants, while regulation by coal and gas power plants is not effective and has a negative effect on air quality (Trnavský, 2019).

The problems with the production of electricity from some RES can be solved by including an accumulation (storage) element in the electricity transmission system, which will compensate for the unstable production of electricity and fluctuations in its consumption. Electricity can also be converted into chemically bound energy in the form of hydrogen or methane using PtG (Power-to-Gas) technology (Trnavský, 2019).

In connection with the development of RES in the structure of energy bowls in many countries, the potential of hydrogen "storage" is very important.

3.2 Methods of producing hydrogen

Methods of producing hydrogen can be divided to three main categories: producing from fossil fuels, water electrolysis and thermochemical cycles (Tkáč, Stehlík, 2017).

3.2.1 Producing hydrogen from fossil fuels

Producing hydrogen from fossil fuels (as methane, natural gas, coal) is the conventional method today. This type of hydrogen is often called “grey hydrogen“ and makes more than 95 % of all hydrogen produces nowadays. The popularity of this method is due to the following factors (Radchenko, Mokrushin, Tulpa, 2014, p. 25-26):

- the rather high efficiency of the process,
- its implementation at the level of large-scale production,
- relatively low (currently) cost and
- well-functioning infrastructure for the transportation of raw materials,
- as a result, the cost of hydrogen for this technology turns out to be the lowest in comparison with the cost of hydrogen obtained by other methods. However, it decreases significantly as productivity increases.

The main disadvantage of this method is its huge emissions creation: around 10 kg of CO_2 are emitted to produce 1 kilogram of hydrogen (Schnettler, 2019). Hydrogen production in the world is responsible for 830 mil. tonnes of CO2 emissions per year: "*That's the equivalent of the annual carbon emissions of the United Kingdom and Indonesia combined.*" (IEA, 2019). Utilization of emissions requires significant capital and operating costs, thereby significantly increasing the cost of the final product.

In addition, being ideal for large-scale production, the method is poorly adapted to low-capacity installations required for decentralized hydrogen production (for example, filling stations, autonomous power systems, etc.) (Radchenko, Mokrushin, Tulpa, 2014).

Another disadvantage of the method is the presence of CO and CO_2 impurities in the final product, which imposes additional requirements on hydrogen purification when it is used in a number of devices (for example, in fuel cells with an aqueous-alkaline or solid polymer electrolyte) (Radchenko, Mokrushin, Tulpa, 2014).

There is also an importance disadvantage, which lies in the long-term enhaustion of fossil fuels (Tkáč, Stehlík, 2017). Rising and volatile fossil fuel prices are another problem that can increase hydrogen production costs and complicate production planning processes.

For these reasons, the production of hydrogen from natural fuels is usually viewed as a transition technology from the existing infrastructure of the energy market to the hydrogen economy of the future. In the long term, this technology is likely to be supplanted by others (Radchenko, Mokrushin, Tulpa, 2014). Reducing emissions from the hydrogen production is one of the main challenges, that also creates an opportunity for the development of other clean methods, hydrogen capture and store (IEA, 2019).

3.2.2 Producing hydrogen from water electrolysis. Electrolytic cells

Water electrolysis technology can be divided according to the state of the incoming water into low-temperature (liquid) and high-temperature (water vapor). It can also be divided according to the charge-transfer ion into acidic (H+ ions) and alkaline (OH- ions) (Tkáč, Stehlík, 2017).

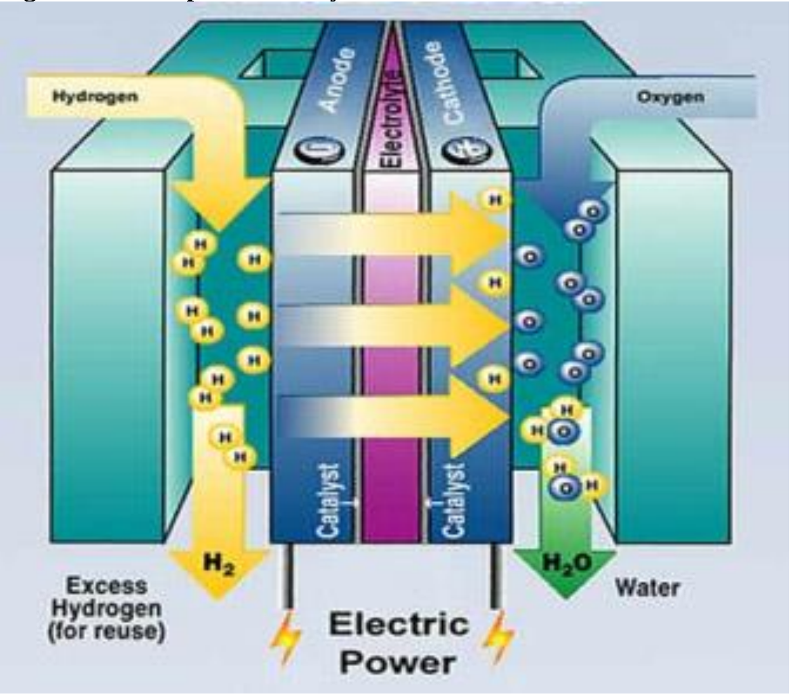
Alkaline water electrolysis is already an industrially established process, but its potential is limited by low hydrogen production efficiency and low flexibility. The disadvantage of these systems is also the limited ability to operate at variable power, which is commonly required in conjunction with renewable energy sources (eg solar and wind power plants) (Tkáč, Stehlík, 2017).

Acidic water electrolysis takes place, for example, in systems using the Proton Exchange Membrane (PEM). Thanks to the use of PEM, only clean water can circulate through the system, thus eliminating the high demands on the material of the circulatory system. The advantages of the process include the production of very pure hydrogen, compact dimensions and process flexibility, which is a good precondition for use to stabilize the electrical system. The main obstacle to the development of this technology is its high price. This is mainly due to the need to use platinum metals as a catalyst (Barbir, 2005).

High-temperature electrolysis of water is operated at temperatures from 700 to 900° C, and due to such a high temperature, it is not necessary to use a platinum metal catalyst as in the case of PEM electrolysis. High-temperature electrolysis of water, sometimes called steam electrolysis, is expected to be a promising process for hydrogen recovery in the future (Tkáč, Stehlík, 2017).

The high-temperature electrolysis is conducted by the electrolytic cell, which consists of a cathode, an anode and an electrolyte. A schematic of such a cell is shown in the Figure 3. Is is an electrochemical device in which electricity, heat and water are generated by combining hydrogen fuel with oxygen. Fuel is hydrogen, stored in a pressure vessel, therefore the system is sometimes called fuel cell. It this system oxygen is removed from the air. Due to the fact that there is no combustion process, no harmful emissions are released and the only by-product is clean water (Šrubařová, 2018). Another advantage is that only water vapor, hydrogen and oxygen circulate through the system without other chemicals, which significantly reduces corrosion problems (Tkáč, Stehlík, 2017).

Figure 3 Concept of electrolytic cell



The anode receives th hydrogen, the cathode collects the oxygen

Source: Battery University, 2021

The first fuel cell saw the light of day in 1839. It was discovered by Sir William Grove, a British judge and inventor, who assumed that the principle of water electrolysis must work the other way around. He hoped that by combining hydrogen with oxygen using the right method, he would gain electricity. He therefore built a device that mixed hydrogen with oxygen, which then actually produced electricity (MM Spektrum, 2006).

Fuel cells became very popular in the 1990s, when scientists and stock traders predicted how the world would run on a clean and inexhaustible source – hydrogen. Fuel cells were said to change the world like a microprocessor in the 1970s. Between 1999 and 2001, more than 2 000 organizations were actively involved in the development of fuel cells (Battery University, 2021). The largest electrochemical complexes are located in Canada, India, Norway, Egypt (Radchenko, Mokrushin, Tulpa, 2014). Stock prices have risen sharply, but the hydrogen dream has been tamed by many problems (Battery University, 2021).

Hydrogen is usually bound to other substances and energy is needed to "release" the gas. In terms of calorific value (NCV), it is more expensive to produce hydrogen than gasoline. Some say that hydrogen is almost energy neutral in the sense that its production needs as much energy as hydrogen itself is able to supply (Šrubařová, 2018).

Hydrogen storage is another disadvantage. Compressed hydrogen requires heavy steel tanks and the calorific value in terms of volume is approximately 24 times lower than for liquid petroleum products. In liquid form, hydrogen has a much higher density, but needs strong insulation to keep it cool enough (Šrubařová, 2018).

Limitations of the fuel cell usage in automobile sector include slow start-up, low power, lengthy response to power change request, low load resistance, small power range, short life, and high cost. As with batteries, the performance of fuel cells decreases over time and the set of cells gradually loses efficiency. With an internal combustion engine, these power losses are much less noticeable (Šrubařová, 2018).

3.2.3 Fusion power plants

In the future, it is planned to connect high-temperature electrolysis with high-potential heat sources – especially nuclear or solar sources (Tkáč, Stehlík, 2017), or also geothermal heat sources (Smolinka, Ojong, Garche, 2015).

Nuclear reactors, which have high output temperatures of the coolant and high efficiency of the energy conversion, are suitable for connection to high temperature water electrolysis. Their working temperature should reach up to 900° C, which is a very useful temperature for electrolysis. An example of these reactors of the 4^{th} generation can be, for example, a helium-cooled HTGR reactor (HTGR – high temperature gas cooled nuclear reactor) (Tkáč, Stehlík, 2017).

Another possibility of using high-temperature electrolysis is a combination with a concentrated solar power plant. This power plant produces heat through a system of mirrors that concentrate the sun's rays to the top of the tower, where the evaporator is located. The generated heat is usually conducted to a turbine, where electricity is produced. In this case, the steam stream is divided into two parts. One part goes through the turbine and produces electricity, the other part goes to the electrolyser, where hydrogen is produced (Tkáč, Stehlík, 2017).

The concentrated solar power plant works most efficiently, for example in the desert. However, there is a problem with water supply and product consumption (Gonzalez-Aguilar, Romero, Vidal, 2015). For example, a power plant that would supply hydrogen to 1 million cars would have to have its mirrors on an area of 24,9 km2, and an electrolyser of 2,25 GW. If this process were built in the desert, then 2/3 of the hydrogen price would be the cost of transporting hydrogen from the desert to the customer (Tkáč, Stehlík, 2017).

The production price of electricity from fusion power plants will be given primarily by the high investment intensity of the implementation of fusion technologies, and, conversely, by the negligible price of fuel (Entler et al., 2021, p. 68).

For a 2 GWe fusion power plant, such as the Temelín nuclear power plant, it will be sufficient to filter only 50 m3 of water per day. Of these, 49,99 m3 will return to the water source. Fuel reserves in the water are generally available and practically inexhaustible (Entler et al., 2021, p. 68).

When implementing thermochemical cycles, very high temperatures are required, which requires significant material costs for the production of hydrogen and the result of this is the distancing of the prospects for large-scale use of hydrogen in power engineering (Radchenko, Mokrushin, Tulpa, 2014).

The combination of high-temperature electrolysis with nuclear or solar energy is a very interesting idea, but these technologies are either not yet available or must be operated in places very far from the points of consumption.

The current use of hydrogen and the vision for its use in the future are quite different. In order for these plans to be fulfilled, the amount of hydrogen produced needs to be significantly increased. However, it must be produced in the light of European targets for reducing emissions and with regard to energy policies.

3.3 Global and state energy policies

After 2000, climate change caused by the steady increase in CO2 emissions became a major global issue. In an effort to achieve joint action by national states in the field of climate and environmental protection, important international agreements have emerged over the past decade committing their parties to common decarbonisation goals. I provide basic information about these agreements below.

3.3.1 The Paris Agreement

This agreement was established in 2015 and was adopted by members of the UN Framework Convention on Climate Change. The Paris Agreement aims in particular to protect the climate and the environment. Specifically, it wants to help keep the average global temperature rise below 2° C compared to the pre-industrial period and try to keep warming below 1,5° C. At the same time, it brings a commitment for the members to reduce CO_2 emissions – "*by 2030, zero-carbon solutions could be competitive in sectors representing over 70% of global emissions*." (UN, 2021).

The Czech Republic is part of the Paris Agreement together with all other EU member states. The members of the agreement also include all major emitters of CO_2 gases, with the exception of Russia. All States party to the agreement must make national reduction contributions to achieve the objective of the agreement. Under the Paris Agreement, the Czech Republic has agreed with other EU member states to jointly reduce greenhouse gas emissions by at least 40 % by 2030 compared to 1990. By acceding to the agreement and this commitment, it will meet the common goal of the EU and its member states, adopted by the European Council as part of the European Council Conclusions on the 2030 Climate and Energy Policy Framework from 24 October 2014 (MoE, 2017).

3.3.2 Green Agreement for Europe

The Green Agreement for Europe is a document setting out the European Commission's commitment to tackling climate and environmental change. It aims to "*transform the EU into a modern, resource-efficient and competitive economy, ensuring: (a) no net emissions of greenhouse gases by 2050, (b) economic growth decoupled from resource use, (c) no person and no place left behind*." (European Commission, 2021).

It means, that this agreement fulfils a vision of achieving climate neutrality by 2050, which is at the heart of a long-term strategy on climate change. The agreement also includes a shorter-term plan for 2030, which aims to reduce greenhouse gas emissions by at least 55 % by 2030, compared to 1990 levels (European Commission, 2021).

Table 1 describes the most important pillars of the Green Agreement for Europe, through which the EU wants to transform its economy for a sustainable future.

Table 2 Main pillars of the Green Agreement for Europe

Actions	**Aims and areas of attention**
1. Climate	Gas emissions reduction target of at least -55% by 2030, compared to 1990 levels. Climate neutral Europe by 2050. Emissions mist be reduced in all sectors
2. Energy	Decarbonising of the EU’s energy system. Clean energy
3. Agriculture	A healthy food system for people and planet
4. Industry	Development of low-emission technologies, sustainable products and services.
5. Environment and oceans	Protecting the biodiversity and ecosystems, reducing pollution, circular economy, improvement of the waste management, sustainable economy
6. Transport	90% reduction in transport-related greenhouse gas emissions by 2050
7. Finance and regional development	Mobilization at least 1 trillion euro in public and private sustainable investments by the 2030 (InvestEU programme)
8. Research and innovation	Horizon Europe – the EU's research and innovation programme for 2021-2027 (supports investments to the development of new technologies , sustainable solutions etc., helps to drive partnerships)

Source: own processing based on European Commission (2021)

3.3.3 World hydrogen strategies

Expanding the energy use of hydrogen requires government support, and this support is growing. The IEA (2019) estimates that both the number of measures aimed at stimulating hydrogen technologies and the number of sectors they cover are increasing. As of 2018, there were about 50 measures in the world that directly support the energy use of hydrogen – mainly in transport (passenger transport, refuelling infrastructure, buses, freight transport) (IEA, 2019).

In 2019-2020, there is a shift in the emphasis of state policy from individual measures to comprehensive strategies for the development of hydrogen energy. It reflects the renewed interest in simultaneously unlocking the potential of hydrogen in various sectors of the economy: not only in transport, but also in industry, heat and power engineering, etc. (Gimadi et al., 2020).

Japan was the first country to formulate its own national hydrogen strategy. Basic Hydrogen Strategy emerged in December 2017, followed in 2019 by the Strategic Roadmap for Hydrogen and Fuel Cells. In 2019, the Republic of Korea revealed its strategic plans for the development of hydrogen. The views of these largest developed importers of energy resources in the Asia-Pacific region on the role of hydrogen are similar: increasing energy security through diversifying energy sources, focusing on hydrogen imports, developing technologies for export, and fulfilling climate obligations (Nakano, 2021).

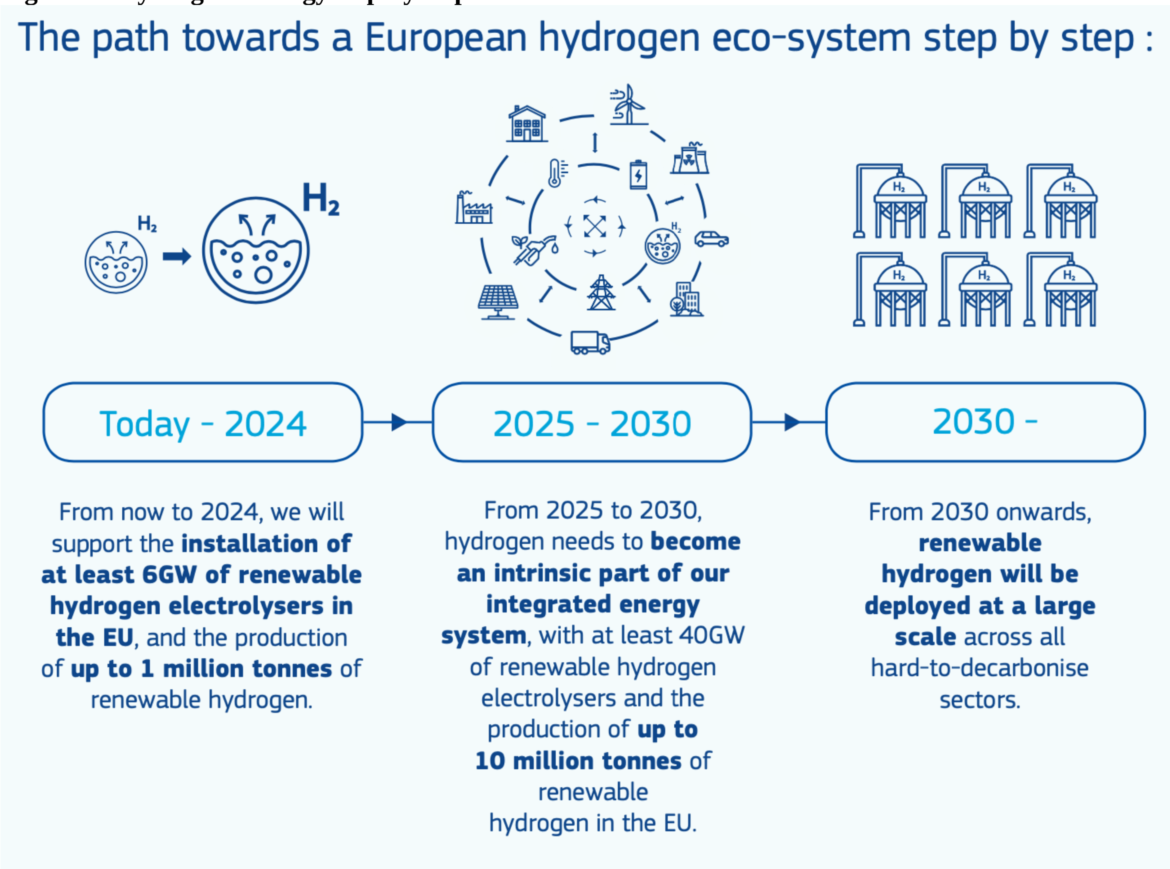
Australia, the largest exporter of energy resources in the Asia-Pacific region among developed countries, promptly responded to the interest of key regional energy consumers in hydrogen and favourable forecasts of global demand. Its national hydrogen strategy also appeared in 2019. It is aimed at strengthening export positions through the development of a new market niche and the transition to more sustainable energy technologies within the country. Australia has already partnered with Japan to develop a pilot hydrogen energy supply chain and signed a letter of intent with the Republic of Korea to achieve cooperation on hydrogen export and import (Gimadi et al., 2020).

The IEA notes that in the context of the crisis associated with the spread of Covid-19, it is important not to miss the moment to promote hydrogen technologies and not to reduce support. The growing number of hydrogen strategies (at least in the European region) makes it possible to expect that hydrogen technologies will continue to develop dynamically. In particular, the strategy of the Netherlands was approved in March 2020, Germany and Norway in June 2020, Portugal and the EU as a whole in July 2020, and France's strategy followed in September 2020. It is noteworthy that European strategies (for example, Germany and France) are presented in the context of plans for economic recovery (Hydrogen Europe, 2021).

3.3.4 European hydrogen strategy until 2050

An important part of the European decarbonisation strategy is the Hydrogen Strategy for a climate-neutral Europe. This document describes how Europe plans to use hydrogen as one of the key tools for the transition to clean energy. The main steps of the European hydrogen strategy are illustrated by the Figure 4.

Figure 4 Hydrogen strategy step by step



Source: European Commission (2020)

Although hydrogen is currently not an important part of the energy mix and has not been very successful so far, its popularity has risen sharply in recent years, especially in the context of European or global climate and decarbonisation goals. Hydrogen and its use has a strong potential to contribute to the achievement of these goals, mainly due to the fact that its use does not release CO_2 and thus does not pollute the air (European Commission, 2021).

In order to achieve the EU's goals, it is necessary to focus on the use of hydrogen produced from renewable sources, because the conventional method of hydrogen producing from the fossil fuels, is still unsuitable in terms of CO_2 emissions, consumption of non-renewable resources and EU dependence on fossil fuel imports.

It is important, that the electricity from wind and solar energy will be used in the EU to produce pure hydrogen (based on the water electrolysis method). However, this method of production is currently not competitive and its production costs are significantly higher than for fossil fuel production (European Commission, 2020)

As production from renewable sources is a priority for the EU, it is necessary to direct support and investment so that costs can be gradually reduced. The cost of producing hydrogen from renewable sources has already fallen by 60 % in the last ten years and could be halved by 2030 compared to today. In order for this to happen, it is first and foremost necessary to install new electrolysers in the EU. Production capacity should be significantly expanded by 2025. It is also necessary to expand the network of hydrogen filling stations so that hydrogen can be used more in transport (European Commission, 2020).

After 2025, hydrogen from renewable sources should gradually become competitive and begin to replace hydrogen from fossil fuels to a greater extent in various sectors. At the same time, existing fossil fuel production will be complemented by carbon capture technologies (European Commission, 2020).

The third phase is the period from 2030 to 2050, and at this stage the use of hydrogen from renewable sources should be more developed and extended to all sectors where decarbonisation is difficult. However, this is also conditioned by a high increase in electricity production from renewable sources. According to the Hydrogen Strategy for a climate-neutral Europe, up to a quarter of the electricity produced from renewable sources could be used to produce hydrogen by 2050 (European Commission, 2020).

3.3.5 Strategy of the hydrogen mobility

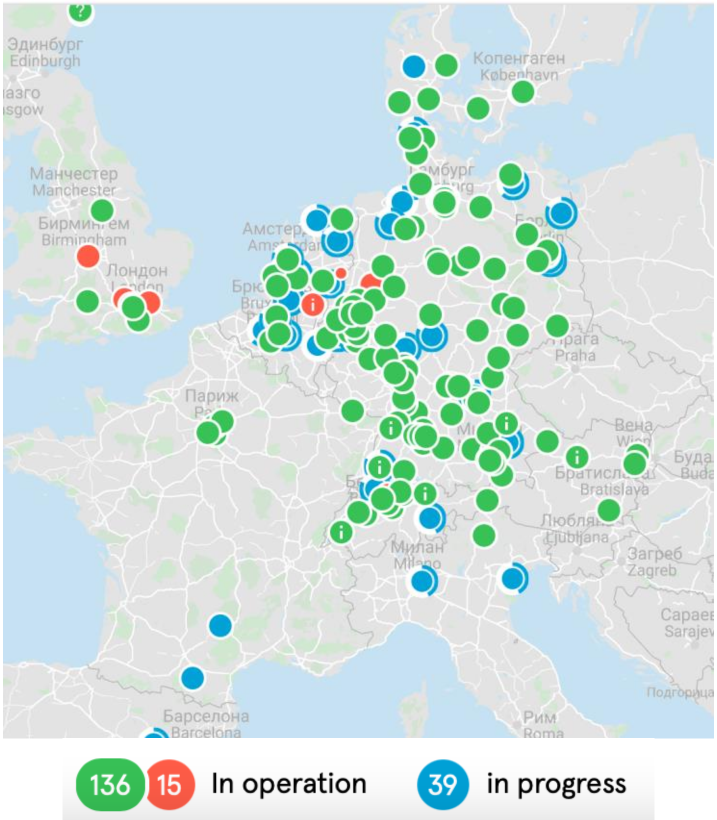
Transport is an energy-intensive and high-emission sector. The EU’s commitment tis to decline emissions from transport by 90 % by 2050 (European Commission, 2021). If the decarbonisation goals are to be met, it is essential that the transport sector have to undergo a major transformation. The fossil fuels are gradually being replaced by zero-emission alternative fuels.

Hydrogen propulsion is not yet developed in the Czech Republic, but it should also play a relatively important role in the future. Even in this case, the main goals will include market development and infrastructure expansion, however, hydrogen is only at the very beginning of development in the Czech Republic (MIT, 2020)

The Czech Republic will focus on the development of hydrogen fuel in road passenger transport, as well as in bus and freight transport. By 2030, there could be 40 000 – 50 000 hydrogen cars and 870 hydrogen buses on Czech roads.

In the area of hydrogen mobility, the main obstacle has long been the lack of refuelling infrastructure. However, this is gradually changing. Currently, most H2 refilling stations in Europe are in Germany (see Figure 5). Extensive construction of stations is planned, especially in Belgium and the Netherlands.

Figure 5 Map of the hydrogen fuel stations in Europe



Source: H2.live (2022)

The Renovation Wave in the EU’s Alternative Fuels Infrastructure Regulation is focused on expanding the infrastructure of recharging cars with alternative propulsion (European Commission, 2021). In Germany, 400 filling stations will be built by 2023, thus ensuring the basic possibility of the entire territory of this neighbouring country (Doucek, 2018).

The Czech Republic wants to establish international cooperation in the field of hydrogen mobility for the creation of so-called hydrogen regions. All types of hydrogen transport should be introduced in these regions and mobility should be linked to energy and other sectors. In this regard, the Czech Republic is cooperating with Germany to create a hydrogen valley, which will be partly in Germany and partly in the Czech Republic (MIT, 2020)

Last but not least, some adjustments will be needed to the regulatory framework for hydrogen mobility and, as with previous fuels, it is necessary to support hydrogen mobility research and development in order to improve technologies and projects in this sector (MIT, 2020)

Again, development will be supported through direct incentives to buy vehicles as well as direct incentives to build infrastructure (MIT, 2020).

In the Czech Republic, the Ministry of Transport has decided to support the construction of filling stations through subsidies under the Operational Program Transport (OPD).

In terms of the volume of funds in the 2014–2020 programming period, OPD is one of the largest operational programs in the Czech Republic – it accounts for approximately EUR 4,56 billion (approximately CZK 123 billion). OPD contributes to the fulfilment of the Partnership Agreement within the strategic objective "Development of transport and technical infrastructure and environmental protection", priorities for financing "Sustainable infrastructure enabling the competitiveness of the economy and adequate serviceability of the territory" (Ministry of Transport, 2021).

The Ministry of Transport wants to announce a new subsidy program for the years 2021 to 2027, in which four billion crowns will be prepared for investments in charging and filling stations. This is roughly three times compared to the same subsidy program for the years 2014 to 2020 (Souček, 2021). Although only a small part (less than 0.7 billion crowns) will be available for hydrogen filling stations, it should bring a basic impetus to the development of hydrogen mobility in the Czech Republic. Increasing support for building infrastructure is a necessary step for the Czechia to meet its objective of the National Action Plan for Clean

Mobility (NAP CM) and at the same time to respond quickly enough to the changing market situation (pressure on car manufacturers under European regulation for low-emission cars).

Subsidies under the OPD have already been approved for a number of projects in the field of hydrogen mobility. An overview of approved projects is given in Table 3.

Table 3 Approved projects in the field of hydrogen mobility for obtaining subsidies under the OPD

Project	Place of implementation	Approved contribution from EU funds
Construction of a hydrogen filling station in Genoa	Ústecký region	35,79 mln. CZK
Development of hydrogen mobility in Ostrava, 1st stage	Moravian-Silesian region	60,1 mln. CZK
Construction of hydrogen filling stations BENZINA – 2nd phase (Project 2)	Plzeň region	35,6 mln. CZK
Construction of hydrogen filling stations BENZINA – 2nd phase (Project 1)	Prague	35,6 mln. CZK
Construction of hydrogen filling stations BENZINA	Whole Czech Reoublic	89,9 mln. CZK

Source: own processing based on data from the Ministry of Transport, 2021

3.4 Summary and outline of the issues of own research

Theoretical research has led to the conclusion that hydrogen is mainly used for three purposes: (1) energy storage and re-generation of electricity in times of shortage, (2) in the transport sector and (3) in the industrial sector.

Hydrogen plays an important role for "clean" energy and serves as a "storage" for the energy obtained from RES. These are mainly solar and wind energy, the production of which is very unstable, very dependent on weather conditions and does not guarantee an uninterrupted source of energy to meet the need).

In the past two decades, more than 200 projects have started operation to convert electricity and water into hydrogen to reduce emissions – from transport, natural gas use and industrial sectors – or to support the integration of renewables into the energy system (IEA, 2019).

Expanding the use of clean hydrogen in other sectors – such as cars, trucks, steel and heating buildings – is another important challenge. There are currently around 11 200 hydrogen-powered cars on the road worldwide. Existing government targets call for that number to increase dramatically to 2,5 million by 2030 (IEA, 2019).

In the transport sector, it is the use of hydrogen in internal combustion engines and fuel cells. The latter finds its application not only in transport, but also in a number of other devices (from laptops to power plants).

Furthermore, hydrogen is used mainly in the steel, food and chemical industries.

There are two main methods of producing energy from hydrogen – fuel cells and thermonuclear fusion. The hydrogen produced is storable and reusable, however, currently storage and transport capacities are very limited, mainly due to the lack of hydrogen infrastructure. The possibilities of use and consumption of hydrogen are also greatly limited by the availability of this source on the market, prices, competition from other traditional energy sources and the attractiveness of investment in research and development in this area. On the contrary, the development of the hydrogen economy is supported by ecological trends and the propaganda of the "green" economy, the reduction of countries' oil reserves, the interests of countries to reduce dependence on imports of oil and other energy sources. Energy market analysis, including a comparison of the prices of the use of hydrogen and other energy sources, will help to examine this situation in more depth.

4 Practical Part

The practical part contains an analysis of the available data of the energy market, emissions, production, consumption and price of hydrogen, and then own calculations and comparison of energy prices from hydrogen and other sources.

4.1 Analysis of the energy market and CO_2 emissions

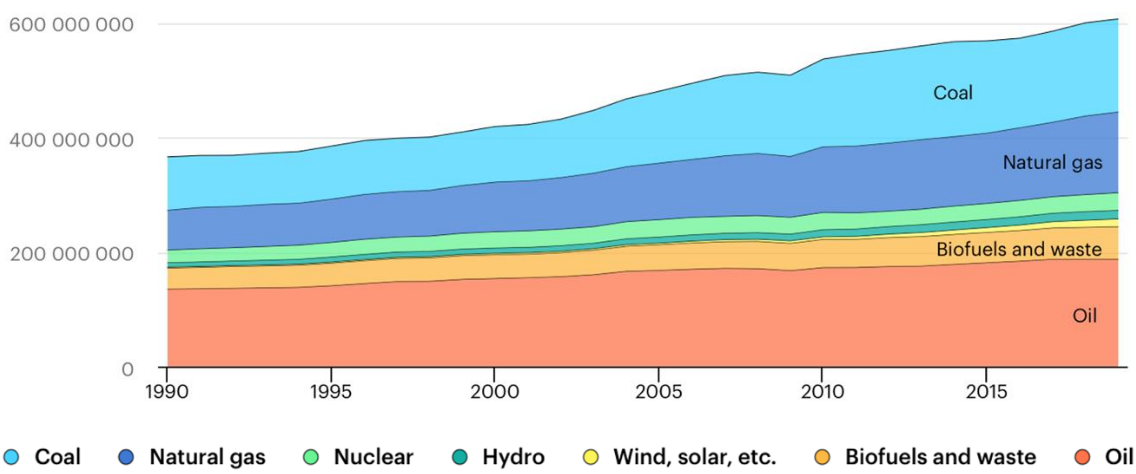
Market analysis is performed in terms of energy supply, energy consumption and CO_2 emissions. Given that the hydrogen market is global in nature (none of the countries can achieve a balance in hydrogen production and consumption), this section takes into account global statistics (world), the EU and then the Czech Republic in particular.

4.1.1 Energy supply

The most energy in the world has come from oil, coal and natural gas in the last twenty years. They all are fossil fuels that produce CO_2 when burned. Figure 6 shows the total energy supply by source in 1990-2020 in the world.

A relatively large part of the supply consists of energy from biofuels and waste and nuclear energy. Renewable sources such as hydro, wind and solar energy have a minimal share compared to fossil fuels. Over the last twenty years, the overall energy supply has increased, and the ratio of individual sources has not changed much (IEA, 2021).

Figure 6 Global energy supply by sources (in TJ*), 1990-2019

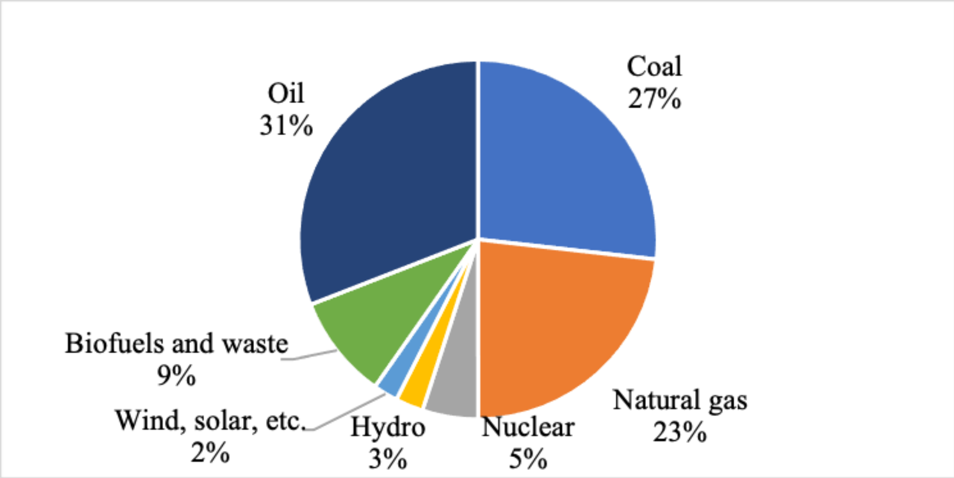


* 1 TJ = 1 x 10^{-6} EJ = 1 x 10^{12} J
Source: IEA (2021)

The figure 7 illustrates the structure of the global energy mix by source in 2019 (data are not available for 2020). The share of oil in global energy supply was 3),9 %, coal – 26,8

%, natural gas – 23,2 %. Hydro made 2,5% share on the total energy supply. It is more then the share of all other sources (2,2 %), which include geothermal, solar, wind, tide/wave/ocean, heat and other sources.

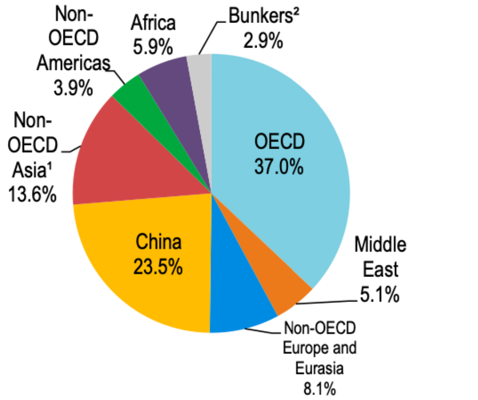
Figure 7 Global energy supply by sources (% share), 2019



Source: IEA (2021)

Geographically, OECD countries (37,0% in 2019) and China (23,5 %) account for the largest share of global energy supply (see figure 8).

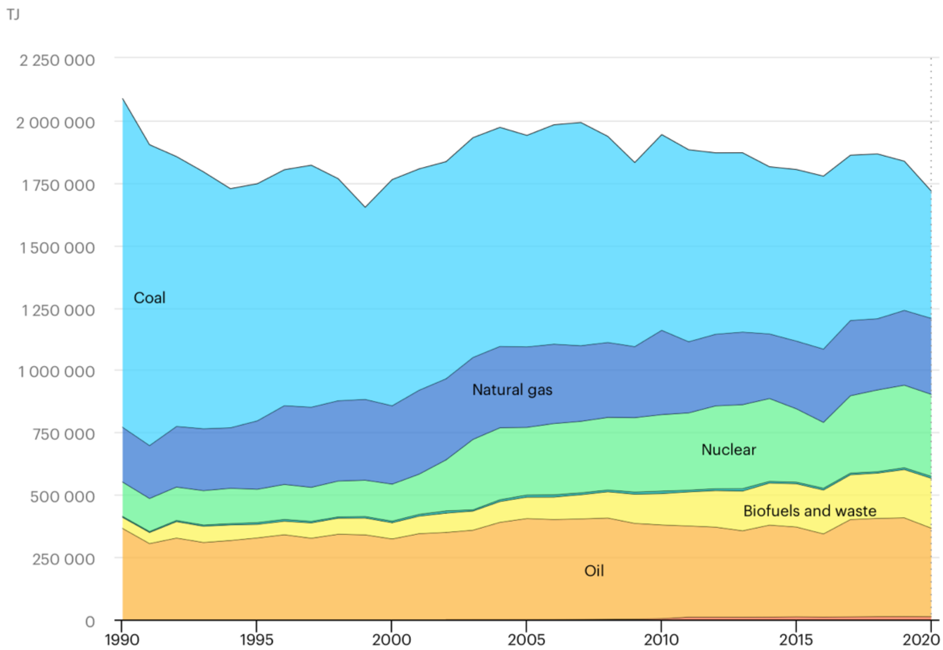
Figure 8 Global energy supply by region (% share), 2019



Source: IEA (2021, p. 8)

The next graph shows the development of the same indicator – the structure of energy supply, but for the Czech Republic. It is obvious that coal played a greater role in the energy mix of the Czech Republic, but in the last years its share decreases considerably. Nuclear, biofuels and waste sources have a growing importance – their share is considerably higher than the average in the world.

Figure 9 Energy supply by sources in the Czech Republic (in TJ), 1990-2020



Source: IEA (2021)

A detailed overview for the Czech Republic is given in the table 3.

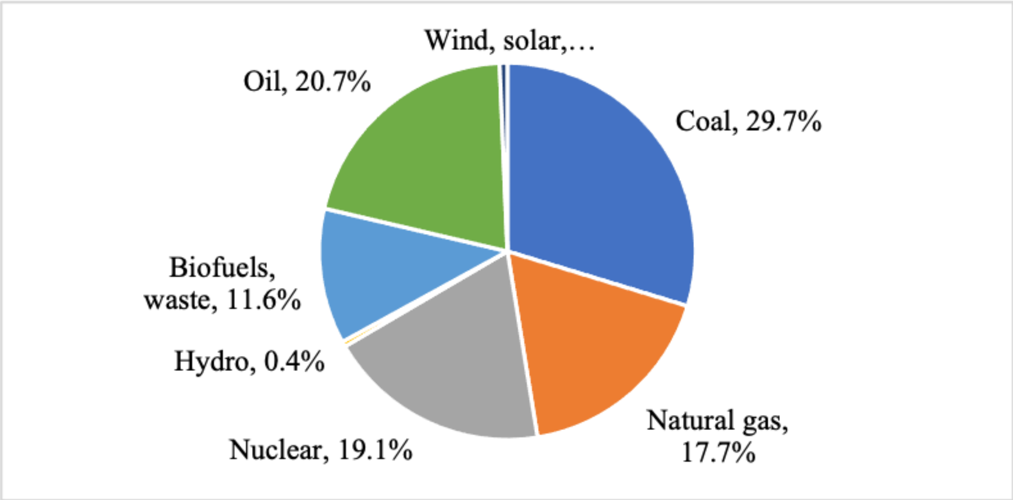
Table 4 Energy supply by sources in the Czech Republic (in TJ), 1990-2020

TJ	Coal	Natural gas	Nuclear	Hydro	Biofuels, waste	Oil	Wind, solar, etc.
1990	1316956	219711	137291	4180	44124	365392	-
1995	949936	274303	133418	7207	54143	327438	-
2000	906132	314016	148255	6329	64914	323270	4
2005	847383	322528	270856	8568	85840	404751	179
2010	784043	337856	306495	10040	125615	375424	3788
2015	687402	271420	293710	6462	173339	360010	10875
2020	509903	304646	328531	7718	199859	355028	11343
2020 (%)	29,7 %	17,7 %	19,1 %	0,4 %	11,6 %	20,7 %	0,7 %

Source: IEA (2021)

Based on the calculated shares of individual resources, the figure 7 is created, illustrating the structures of energy supply in the Czech Republic in 2020.

Figure 10 Energy supply by sources in the Czech Republic (% share), 2020

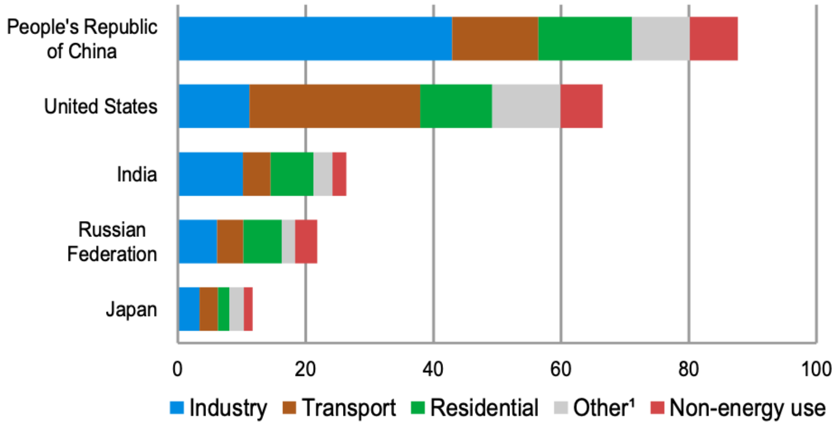


Source: IEA (2021)

4.1.2 Energy consumption

Top five countries in the world by the total final consumption are China, United States, India, Russian Federation and Japan (see figure 9). The United States contributes the most to consumption in the transportation sector, while China, India, and Russia contribute more to the industrial sector.

Figure 11 Top five countries by total final energy consumption by sector, 2019 (EJ*)



*1 EJ = 1 x 10^{18} J
Source: IEA (2021, p. 43)

An overview of data on global energy consumption by sector and the calculation of the share of individual sectors in total consumption is given in Table 2. Total energy consumption almost doubled from 261,1 EJ in 1990 to 418 EJ in 2019 (IEA, 2021). The year-on-year changes of the total consumption are also calculated. It is clear that the growth rate of total energy consumption has slowed down over the last decade to just over 6 % per year.

Three sectors contribute to the energy consumption the most: industry (28,9 % of total energy consumption in 2019), transport (28,9 %) and residential sector (21 %).

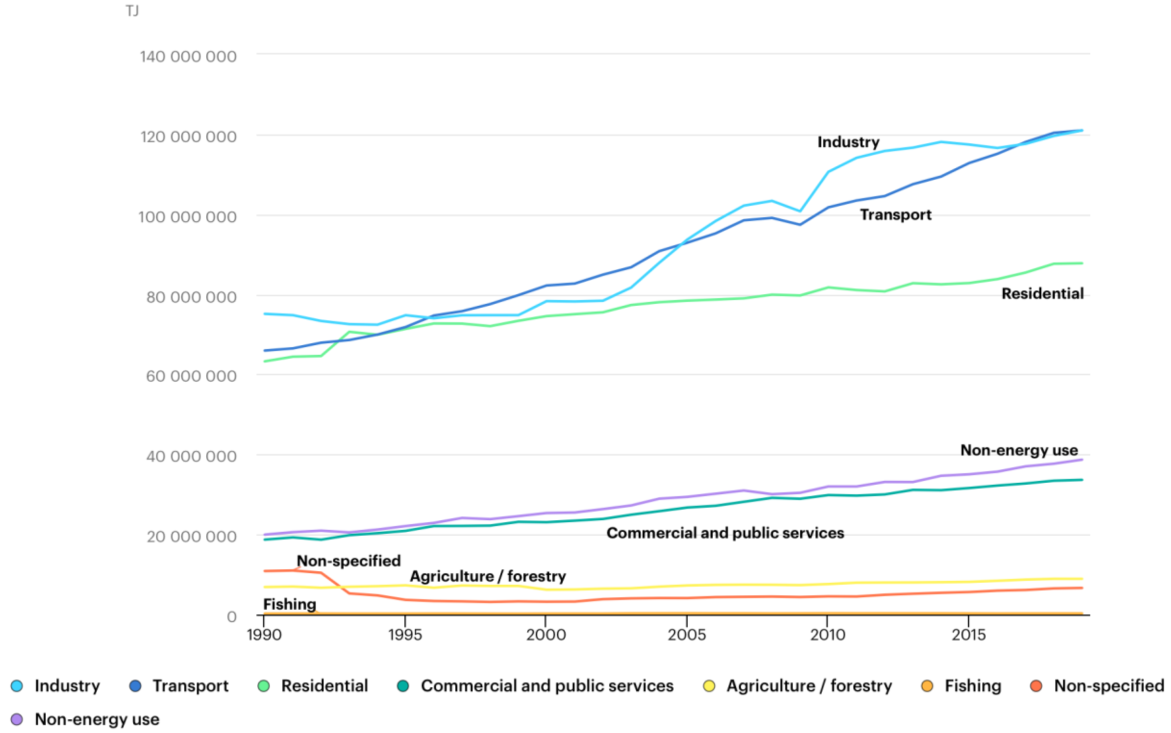
Table 5 Global energy consumption by sectors (EJ), 1990-2019

EJ	Industry	Transport	Residential	Commercial &public services	Agriculture / forestry	Fishing	Non-specified	Non-energy use	Total consumption	Changes year-on-year (%)
1990	75,1	66,0	63,3	18,7	6,9	0,3	10,9	20,0	261,1	
1995	74,8	71,8	71,4	20,9	7,3	0,3	3,7	22,1	272,3	4,3 %
2000	78,3	82,2	74,6	23,1	6,2	0,3	3,2	25,4	293,2	7,7 %
2005	93,7	92,9	78,4	26,7	7,3	0,3	4,1	29,4	333,0	13,6 %
2010	110,6	101,8	81,7	29,9	7,6	0,3	4,5	32,0	368,5	10,7 %
2015	117,4	112,8	82,8	31,6	8,2	0,3	5,6	35,1	393,9	6,9 %
2019	121,0	121,0	87,8	33,7	8,9	0,3	6,7	38,7	418,0	6,1 %
Share, %										
1990	28,8%	25,3%	24,2%	7,2%	2,6%	0,1%	4,2%	7,7%	100,0%	
1995	27,5%	26,4%	26,2%	7,7%	2,7%	0,1%	1,3%	8,1%	100,0%	
2000	26,7%	28,0%	25,4%	7,9%	2,1%	0,1%	1,1%	8,7%	100,0%	
2005	28,1%	27,9%	23,6%	8,0%	2,2%	0,1%	1,2%	8,8%	100,0%	
2010	30,0%	27,6%	22,2%	8,1%	2,1%	0,1%	1,2%	8,7%	100,0%	
2015	29,8%	28,6%	21,0%	8,0%	2,1%	0,1%	1,4%	8,9%	100,0%	
2019	28,9%	28,9%	21,0%	8,1%	2,1%	0,1%	1,6%	9,3%	100,0%	

Source: own processing based on data IEA (2021)

Industry and transport have traditionally contributed the most to energy consumption. Figure 10 illustrates the development of total energy consumption by sector in the world. In 2019, the total energy consumption of the transport sector was 120,9 million TJ (28,9 % of total energy consumption), only slightly less than the industry sector, which consumed 121 million TJ (28,9 %) (IEA, 2021).

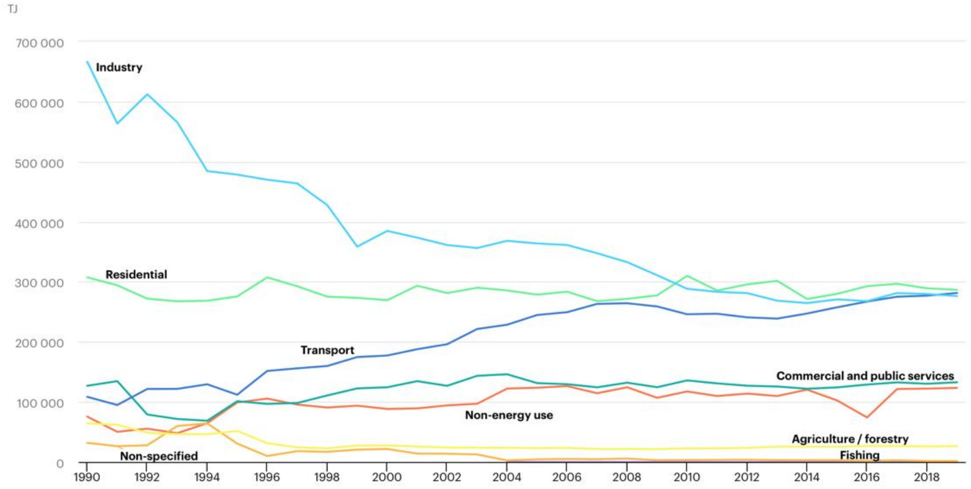
Figure 12 Global energy consumption by sectors (TJ*), 1990-2019



* 1 TJ = 1 x 10^{-6} EJ = 1 x 10^{12} J
Source: IEA (2021)

In the Czech Republic (figure below), the opposite trend can be seen: energy consumption in the industrial sector has been declining since 1990, which is a positive factor in terms of energy safety and emissions. Consumption of the resident sector didn't change almost at all during this period. The consumption of the transport sector is growing, which is a risk factor.

Figure 13 Energy consumption by sectors in the Czech Republic (TJ), 1990-2019



Source: IEA (2021)

A detailed overview for the energy consumption in the Czech Republic is given in the table 3. It is clear that three sectors had almost the same share in consumption: industry (32,4 %), transport (33 %) and residential (33,6 %).

Table 6 Energy consumption by sectors in the Czech Republic (TJ), 1990-2019

TJ	Industry	Transport	Residential	Commercial &public services	Agriculture / forestry	Fishing	Non-specified	Non-energy use	Total consumption	Changes year-on-year (%)
1990	666328	108493	307451	126864	64309	-	31862	75484	714463	-
1995	478484	112001	275652	101175	51660	-	30582	99102	670172	-6,2 %
2000	384765	177268	269463	124413	27626	-	21678	88347	708795	5,8 %
2005	363865	244759	278676	131312	23157	33	4429	123639	806005	13,7 %
2010	288369	245956	309976	135834	22730	29	3336	117470	835331	3,6 %
2015	270735	257539	279903	124218	25307	33	3028	102535	792563	-5,1 %
2019	276211	281432	286661	132804	26496	38	1615	123399	852445	7,6 %
2019 (%)	32,4 %	33,0 %	33,6 %	15,6 %	3,1 %	0,0 %	0,2 %	14,5 %	100 %	

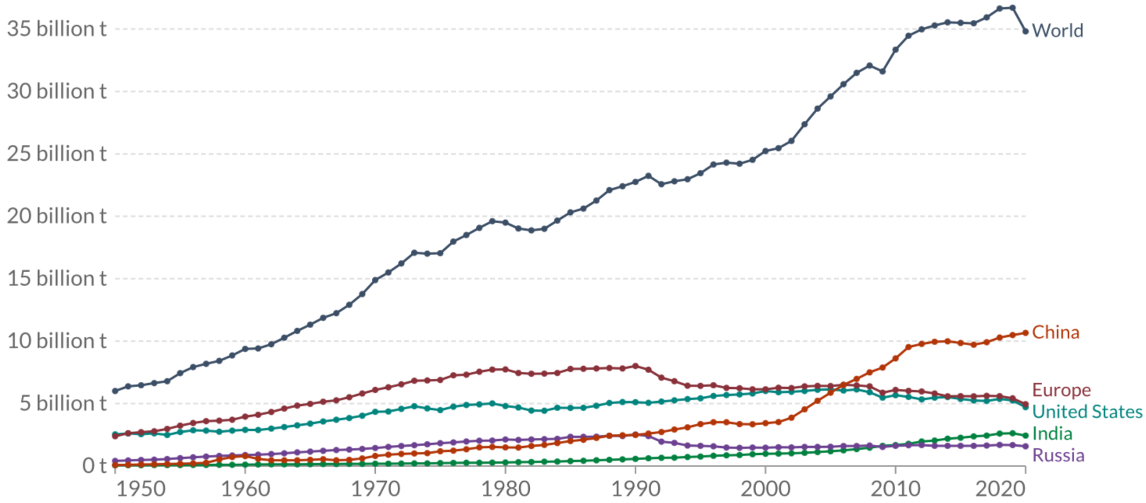
Source: own processing based on the IEA data (2021)

4.1.3 CO_2 emissions

The use and greater development of alternative fuels, whether in transport or in other areas, has been a matter of the last few years, and today the planet is still burdened by huge amounts of CO_2 emissions. Figure 11 shows the development of global CO_2 emissions in billions of tons from 1950 to 2020. It was in the middle of the last century that the number of annual emissions began to increase and since then has moved from more than five billion tons of CO_2 per year to about 36 billion tonnes of CO_2 produced each year.

The country that produces the most emissions each year is China. The United States, India and Russia follow. Europe as a whole produces about the same amount of CO_2 emissions as the United States (Ritchie, Roser, 2021). CO2 emissions of the Czech republic accounted to 94,3 Mt, it is 8,84 tCO_2 per capita (IEA, 2021, p. 62-63).

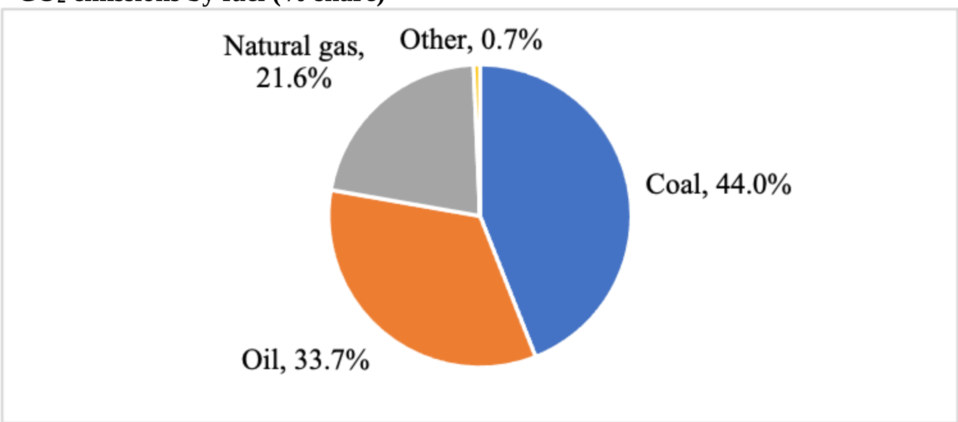
Figure 14 CO_2 emissions – global and by country (billion t), 1950-2020



Source: own processing based on Ritchie and Roser (2021)

Emissions from coal combustion (44 % in 2019) account for the largest share of CO_2 emissions, followed by oil (33,7 %) and natural gas (21,6 %). Other energy sources contribute to CO_2 emissions insignificantly (0,7 %) – see figure 12.

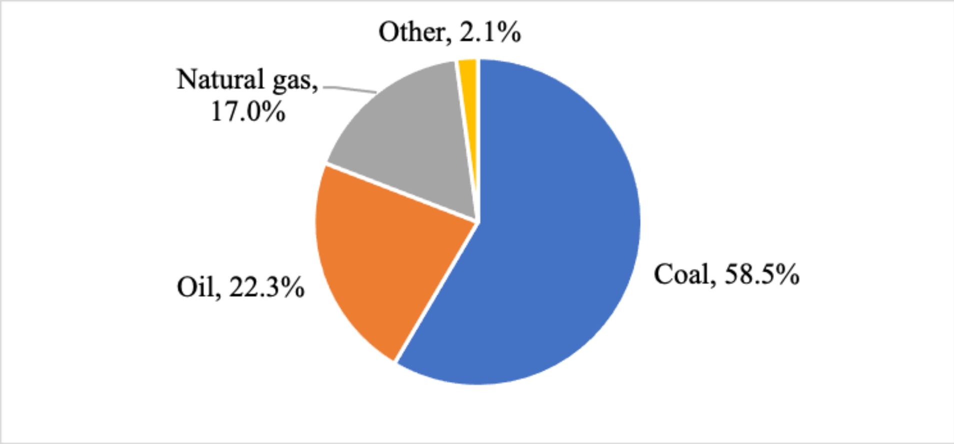
Figure 15 CO_2 emissions by fuel (% share)



Source: own processing based on the IEA data (2021)

In the Czech Republic (see figure below), coal (58,5%) contributes significantly more to emissions (than the world average). The contribution of oil and natural gas is lower than in the world, but it is still high – 22,3 % and 17 %. It is clear that these resources are key to energy in the transport sector.

Figure 16 **CO_2 emissions by fuel in the Czech Republic (% share)**



Source: own processing based on the IEA data (2021)

The above statistics indicate total growing energy consumption and a still huge share of fuels on the energy supply and consumption, which contribute significantly to CO_2 emissions. The course on decarbonization and environmental protection should lead to an increase in interest in alternative fuels, including hydrogen.

4.2 Analysis of the transport sector and usage of alternative fuels

It is worthwhile to look more closely at the transport sector, which is one of the sectors with the most significant benefits in terms of energy consumption and CO_2 emissions.

4.2.1 Energy consumption in the transport sector

Global energy consumption of the transport sector was 120,972 EJ in 2019 (28,9 % share on total energy consumption in the world) (IEA, 2021). 91,3 % of the energy (110,5 EJ) is conducted from oil products, 4,1 % from natural gas and 3,3 % - form biofuels and waste (see table 4).

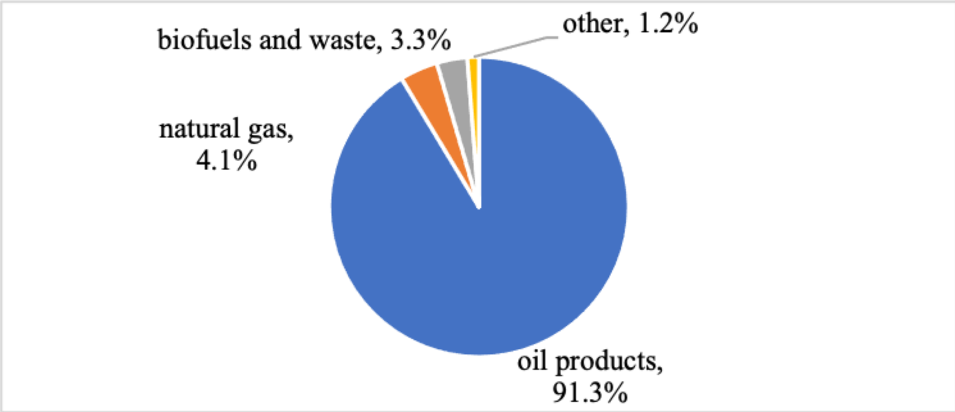
Table 7 **Supply and consumption of energy by the global transport sector by sources (2019)**

	coal	crude oil	oil products	natural gas	nuclear	hydro	biofuels, waste	other	total
EJ	0,04	0	110,471	4,963	-	-	3,987	1,51	120,972
share %	0,0 %	0,0 %	91,3 %	4,1 %	-	-	3,3 %	1,2 %	100,0 %

Source: own processing based on the IEA data (2021)

The structure of the energy supply and consumption of the transport sector is shown by the figure 17.

Figure 17 Supply and consumption of energy by the global transport sector by sources (2019)

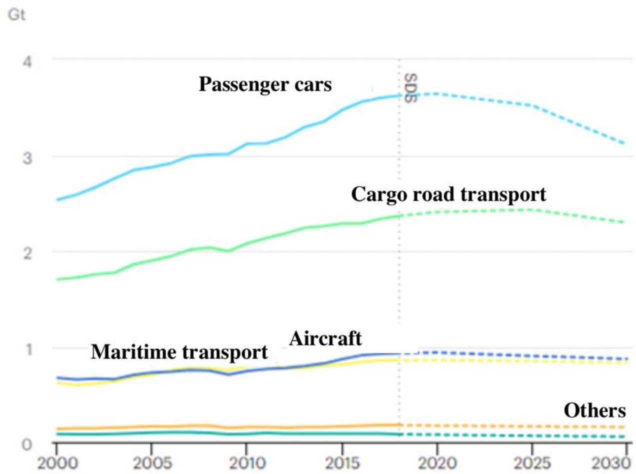


Source: own processing based on the IEA data (2021)

4.2.2 Contribution of the transport sector to the CO_2 emissions

In addition to currently leader ranking in energy consumption, transport is also a sector in which a significant proportion of CO_2 emissions are generated. In 2019, this was about 24 % of the total emissions from fuel combustion globally (IEA, 2021). Passenger cars had the largest share in these emissions (3,2 billion metric tons of CO_2 globally in 2019, compared to 2,2 billion metric tons in 2000) (Statista, 2021). It is followed by road freight vehicles, aviation, shipping, rail transport and others (see Figure 18). These are, in the same order, the transport sectors with the highest energy demand (IEA, 2021).

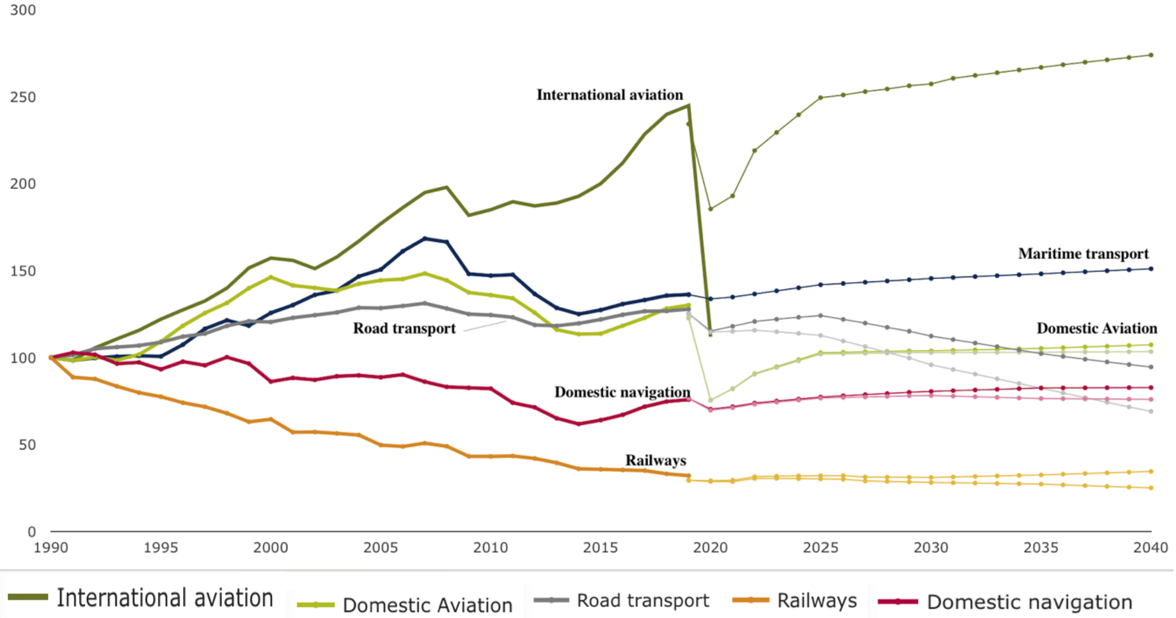
Figure 18 CO_2 emissions in transport sector (Gt), 2000-2019, estimation by 2030*



Source: IEA (2021)

In terms of the growth rate of emissions, the situation is a bit different – the highest growth rate is recorded by the aircraft transport. Nevertheless, it was a significant increase in emissions between 2000 and 2019 almost for all transport types, including road transport (see figure 19).

Figure 19 CO_2 emissions in transport sector in the EU, 2000-2019, estimation by 2030*
Changes in emission levels from 19990 (index 1990 = 100)



Source: EEA (2021)

In 2019, CO2 emissions of road transport accounted for 127,8 % of emissions from 1990 (EEA, 2021). By 2030, however, the IEA expects a relatively strong reduction in CO_2 emissions from cars and lorries under the Sustainable Development Scenario. Growth has been lower in aviation and shipping, but the decline by 2030 will not be as rapid as there will be no significant decarbonisation in these sectors (IEA, 2021). An overview of changes in the volume of emissions of individual modes of transport (since 1990) is given in the table 8.

Table 8 CO_2 emissions in transport sector in the EU, 2000-2019, estimation by 2030*
Changes in emission levels compared to 1990 level

	2000	**2010**	**2019**	**2030**
International aviation	57,2 %	85 %	144,8 %	157,3 %
International maritime transport	25,7 %	47,1 %	36,3 %	45,5 %
Domestic aviation	46,2 %	35,9 %	30,2 %	3,9 %
Road transport	20,5 %	24,5 %	27,8 %	12,4 %
Domestic navigation	-13,8 %	-17,8 %	-24,2 %	-19,3 %
Railways	-35,5 %	-56,8 %	-67,9 %	-68,9 %

Source: EEA (2021)

By 2030, there should be at least 30 million zero-emission vehicles in Europe. For comparison, in 2019, out of a total of 243 million passenger cars, only 615 thousands were emission-free, which is only about 0,25 % (Baroch, 2020) Another goal is that one hundred European cities should be climate-neutral, double-speed rail transport should be doubled, public transport for distances shorter than 500 km should be carbon neutral, automated transport will be significantly expanded and zero-emission ships will be ready for the market. A little later, by 2035, zero-emission aircraft will be ready for operation (European Commission, 2020).

By 2050, almost all road vehicles will be emission-free, rail freight will double and high-speed rail will triple, and a multimodal trans-European transport network equipped for intelligent high-speed transport will be operational (European Commission, 2020).

It is also appropriate to focus on the situation in the Czech Republic – the development of the transport sector and its contribution to emissions.

4.2.3 Transport sector in the Czech Republic

Table 9 shows the annual increase in the number of passenger cars by type of fuel from 2012 to 2019. The table shows that cars using alternative fuels have only a minimal share among newly registered vehicles and the vast majority are petrol and diesel cars. Of the alternative fuels, compressed natural gas is the most represented. On the other hand, electric cars are the least represented after liquefied natural gas.

Table 9 Number of registered cars by fuel in 2012-2019, Czech Republic

	benzine	**oil**	**CNG**	**LPG**	**electro**	**hybrid**	**total**	**Changes**
2012	97 067	72012	470	514	89	362	174009	-
2013	91 389	69746	379	647	37	438	164736	-5,3 %
2014	106786	80128	1402	1402	197	386	192314	16,7 %
2015	124131	99298	2751	2751	268	1024	230857	20,0 %
2016	141691	110575	2843	2843	262	1541	259693	12,5 %
2017	158796	102641	2890	2890	387	2826	271595	4,6 %
2018	175276	78991	1936	1936	703	4831	261437	-3,7 %
2019*	123514	46993	1270	1270	527	5143	175340	-32,9 %
Share, %								
2012	55,8 %	41,4 %	0,3 %	0,3 %	0,1 %	0,2 %	100,0 %	
2013	55,5 %	42,3 %	0,2 %	0,4 %	0,0 %	0,3 %	100,0 %	

2014	55,5 %	41,7 %	0,7 %	0,7 %	0,1 %	0,2 %	100,0 %	
2015	53,8 %	43,0 %	1,2 %	1,2 %	0,1 %	0,4 %	100,0 %	
2016	54,6 %	42,6 %	1,1 %	1,1 %	0,1 %	0,6 %	100,0 %	
2017	58,5 %	37,8 %	1,1 %	1,1 %	0,1 %	1,0 %	100,0 %	
2018	67,0 %	30,2 %	0,7 %	0,7 %	0,3 %	1,8 %	100,0 %	
2019*	70,4 %	26,8 %	0,7 %	0,7 %	0,3 %	2,9 %	100,0 %	

*2019 – January-August
Source: Ministry of Transportation, 2021

Table 10 shows the targets for the number of vehicles and public infrastructure. The table shows that of all alternative drives, electric cars and liquefied petroleum gas vehicles should be the most used by 2030. Hydrogen passenger cars, which are almost non-existent on Czech roads today, could also record a relatively large development. The Czech Republic's strategy also includes support for EV buses and hydrogen buses. Compressed natural gas and liquefied natural gas should also be represented in transport.

Table 10 Targets for the number of vehicles and public infrastructure by 2030, Czech Repbulic

Vehicles	**Target – by 2030**
Electric cars	220 000 – 500 000
EV buses	800 – 1 200
CNG passenger cars	20 000 – 33 600
CNG buses	1 740 – 2 650
LNG trucks	3 500 – 6 900
LPG	170 000 – 250 000
Hydrogen passenger cars	40 000 – 50 000
Hydrogen buses	870
Charging points / filling stations	**Target – by 2030**
Electric	19 000 – 35 000
CNG	350 – 400
LNG trucks	30
Hydrogen	80

Source: MIT, 2020

In order to achieve an increase in the number of cars with alternative propulsion, it is necessary to expand the charging and filling infrastructure. By 2030, there should be 19 000 – 35 000 charging points for electric cars. There must also be more CNG, LNG and hydrogen filling stations. Specifically, it is about of the construction of 80 hydrogen filling stations by 2030 (MIT, 2020).

Summary and outline of the issues of own research

The results of the analysis conclude that increasing energy consumption, the high share of the transport sector in energy consumption and its significant contribution to CO2 emissions, as well as high oil and gas contributions to CO2 emissions - are threatening factors that determine the importance of research. Furthermore, attention should be focused on the hydrogen market (production, prices) and its use in the transport sector.

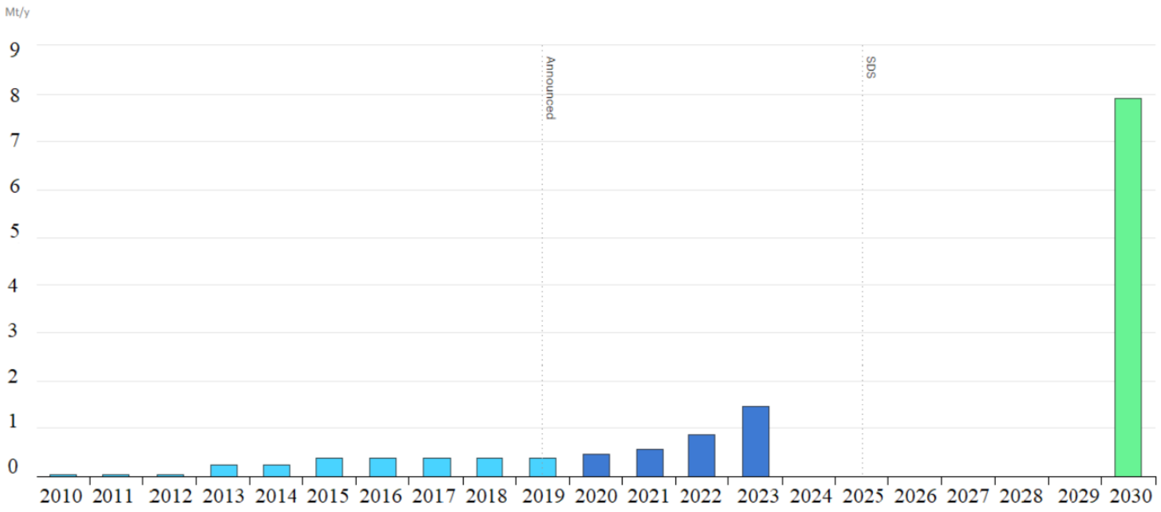
4.3 Hydrogen production

Today only a minimum of hydrogen is produced and most is produced from fossil fuels. Hydrogen now accounts for less than 2 % of total energy consumption in Europe, and 96 % of hydrogen is produced from natural gas in a way that releases large amounts of CO_2 (European Commission, 2021).

Hydrogen production in industrialized countries is about 500 normal m^3 or 50 kg per capita per year. Because hydrogen is usually prepared at the point of consumption, it is a small item in world trade. At the same time, its price is relatively high, because its production is very energy-intensive (Wichterle, 2012).

Low-emission hydrogen production has so far been very limited by high costs, however, as the number of electrolysers increases and the overall production capacity expands, the price gradually decreases and hydrogen production will increase accordingly, as shown in Figure 20. The production should be almost 8 millions tons (Mt) per year by 2030 (IEA, 2020).

Figure 20 Development of low-emission hydrogen production until 2030 (Mt/y)



Source: IEA, 2020

The Czech Repbulic currently produces 100 000 tons of hydrogen per year and the estimated production will increase to 1,7 million tons per year till the 2050 (Pirodsky, 2021).

The use of hydrogen does not yet affect many sectors. Today, it is mainly used in connection with the production of chemical products, such as fertilizers, or in refineries. Interest in hydrogen varies greatly from one EU Member State to another, as does their potential production capacity. Other barriers to hydrogen development also include insufficient infrastructure, higher prices or insufficient production. Higher costs for this production are also a barrier to zero-emission hydrogen production (European Commission, 2020).

4.4 Hydrogen prices

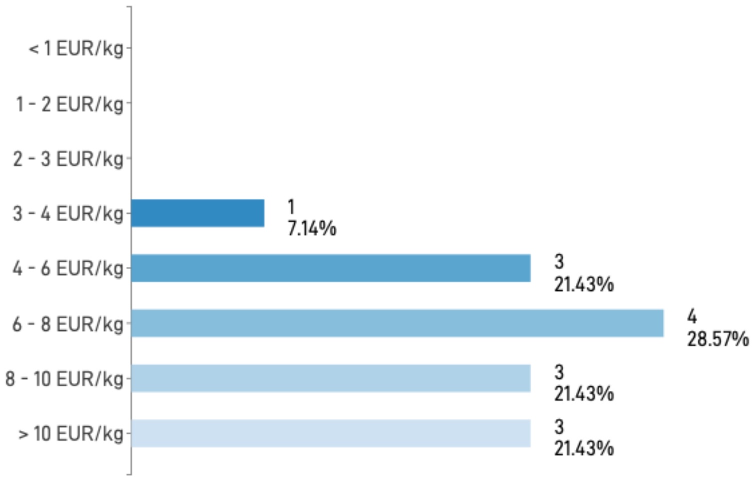
Since hydrogen is not yet a commonly used fuel, it is quite difficult to find statistics on its production and sales prices. Another reason is that the price strongly depends on the type and method of production, distribution and state of hydrogen uptake in the country.

The price of hydrogen production depends mainly on the method of production. In addition, for the production of green hydrogen, it is necessary to take into account the different prices in different parts of the world, depending on how much it costs to produce electricity from renewable energy sources. According to the International Energy Agency, the price of hydrogen production is in the following figures (Hytep, 2022):

- steam reforming of natural gas: 1 – 3,5 USD per kg,
- coal gasification: 1,2 – 2,2 USD per kg,
- water electrolysis: 3 – 7,5 USD per kg.

In the world, the price of hydrogen used for mobility is for the end user from 3 to more than 10 EUR per kg (The Hydrogen Valleys Platfrom, 2022). The figure 21 includes information on the number and the share of all Hydrogen valleys having the respective hydrogen cost.

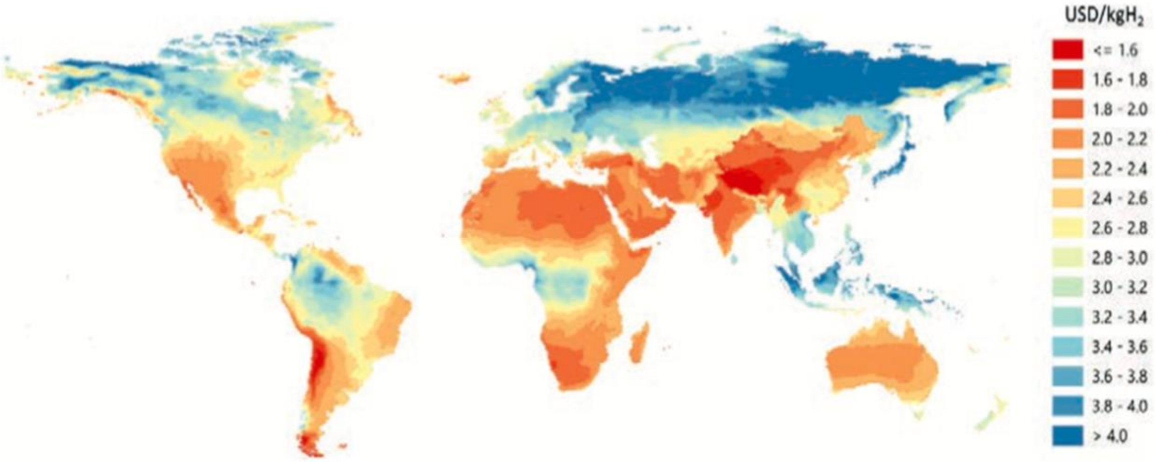
Figure 21 External sales price of hydrogen for mobility (number (share) of Valleys)



Source: Hydrogen Valleys Platfrom (2022)

The average prices of the hydrogen in the world are shown by the map below (Figure 22). According to this map, the cheapest hydrogen is available in China, India and north part of Africa. The prices of electricity from RES in these countries is the determining factor of the low prices (Madej & Srb (2021, p. 9).

Figure 22 Prices of the hydrogen in the world (map), USD/kg



Source: Madej & Srb (2021, p. 9)

For the end user, the price of hydrogen per kg is currently set at 9,5 euros in Germany (where most filling stations are located) (Hytep, 2022). Germany has big plans for the development of hydrogen production. Currently, an important agreement between Germany and Namibia, which envisages investing about 40 million euros in the development of the high potential of the hydrogen economy in Namibia. In return, Germany plans to import huge volumes of cheap hydrogen from this country. It will be produced by electrolysis and its price will be the lowest in the world 1,50 – 2,00 EUR per kg (Radowitz, 2021).

The cost of driving a low-carbon hydrogen carriage could fall to the level of diesel use by 2027. This follows from the Hydrogen Strategy of the Czech Republic, which was approved by the government this week. According to the Hydrogen Strategy of the Czech Republic, by 2027 the price of hydrogen for driving cars could fall to such a level that the costs are comparable to driving on diesel. This corresponds to a price of about 3,5 EUR (89,70 CZK) per kilogram of hydrogen. About three years earlier, hydrogen is expected to start competing with oil in the places where it will be produced. (Bednář, 2021).

According to another estimate (Rethink Energy cit. Paul, 2022), hydrogen prices should fall to almost 1 USD per kg by 2035 and to about 0,75 USD per kg by 2050.

Three main factors should be the reason for the fall in prices (Hydrogen Council, 2020, p. 36):

- production of cheaper hydrogen,
- larger and better used distribution system,
- larger and better used hydrogen filling stations.

The latter factor has the largest share of the value chain costs and contributes around 4 – 5 EUR per kg of total costs in 2020 and will fall to around 0,7 – 1 EUR per kg in 2030 (Hydrogen Council, 2020, p. 36).

4.5 Calculation of the prices of the hydrogen as an energy source

This chapter is devoted to calculating the price of energy from various sources and comparing it with the price of energy from hydrogen.

The calculation is based on the actual average price of hydrogen, produced from the water electrolysis, – 9,5 euros per kg (Hytep, 2022).

The price of 1 kWh of hydrogen energy is calculated as following:

1 m3 of hydrogen = 0,0852 kg of hydrogen (bottle filling pressure is 200 bar) (Esvarovani, 2020). Therefore, 1 kg of hydrogen = 11,74 m3 of hydrogen.

Using 1 m3 of hydrogen, it is possible to get 12832,4 kJ of energy (3,56 kWh of electricity) (Neftegaz, 2017).

1 m3 of hydrogen => 3,56 kWh (Neftegaz, 2017).

1 kg of hydrogen => 3,56 * 11,74 = 41,78 kWh.

1 kg of hydrogen costs 9 eur, so the prices of 41,78 kWh of energy is 9,5 eur.

The prices of 1 kWh of hydrogen energy is: 9,5 / 41,78 = 0,23 eur.

Prices of energy from other sources (nuclear, natural gas, coal etc.) are taken from different analysis – LCOE analysis (2021) and EON (2022). The calculations are made in the table 11. The current exchange rate is used: 1 EUR = 24,69 CZK (Kurzy.cz, 2022).

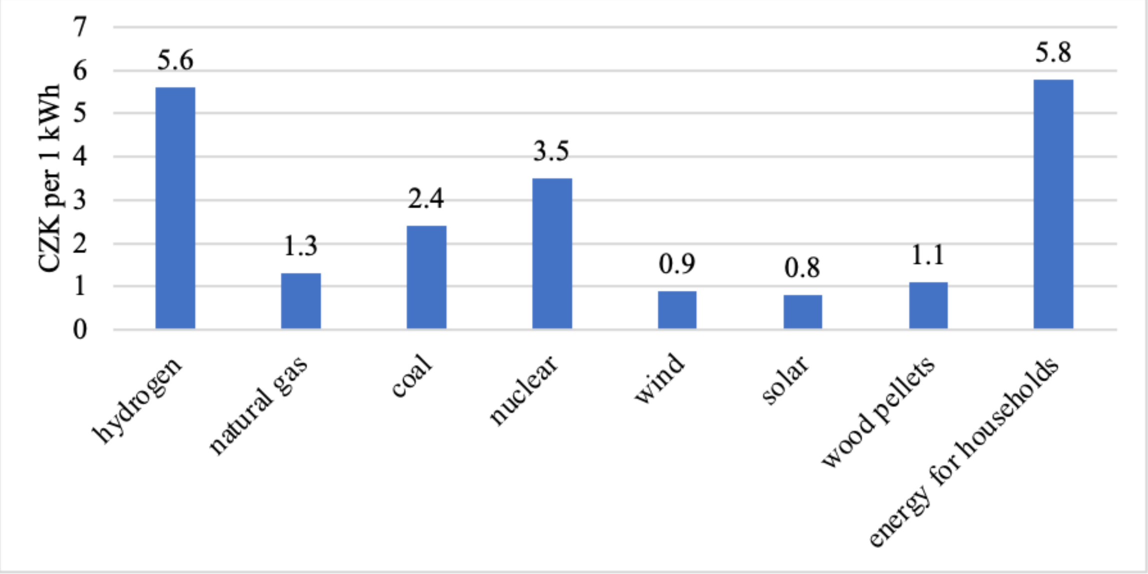
Table 11 Comparison of the prices of energy from different sources (EUR and CZK per kWh)

Source	Price per 1 kWh (EUR)	Price per 1 kWh (CZK)
hydrogen	0,23 EUR	5,6 CZK
natural gas	0,05 EUR	1,3 CZK
coal	0,10 EUR	2,4 CZK
nuclear	0,14 EUR	3,5 CZK
wind	0,04 EUR	0,9 CZK
solar	0,03 EUR	0,8 CZK
wood pellets	0,04 EUR	1,1 CZK
energy for households	0,23 EUR	5,8 CZK

Source: own processing based on own calculations and data of Eon (2022), LCOE (2021)

The comparison can be made using the figure 23, which illustrates the prices of energy from the selected sources (in CZK per 1 kWh).

Figure 23 Comparison of the prices of energy from different sources (CZK per kWh)



Source: own processing based on own calculations and data of Eon (2022), LCOE (2021)

It is obvious that the price of energy offered directly to consumers (households, according to Eon (2022)) is the highest due to dramatic growth in recent times and amounts to 5.8 CZK per 1 kWh of energy. It is even slightly higher than the price of hydrogen, as determined from our own calculations. However, according to LCOE (2021), the price of energy from other sources is significantly lower than the price of hydrogen.

4.6 Calculation of the prices of the hydrogen as a fuel

This chapter is devoted to calculating the price of different fuels, used in mobility, and comparing them with the price of hydrogen fuel. Calculations are conducted for two examples – passenger car (benzine and hydrogen) and public bus (diesel and hydrogen).

4.6.1 Example of the hydrogen passenger car

Consumption is 0,8-1,2 kg of hydrogen per 100 km depending on load and driving style (Bednář, 2021) or on average 1 kg of hydrogen per 100 km (Kopecký, 2019).

If the calculation is based on the average price of hydrogen, set at gas stations in Germany – 9,5 euros per kg (Hytep, 2022), it can be found that the price of 100 km of hydrogen by car will be 9,5 euros (231,47 CZK).

The average price of benzine is 37,2 CZK (1,53 EUR) as of 17.2.2022 (Kurzy.cz, 2022). The cost per 100 km by car with an average consumption of 7,5 liters of benzine is 279 CZK.

If the car has an average annual run-in of 15 000 km, the difference in annual costs is more significant and amounts to 7 129 CZK. This means that the driver of a hydrogen car spends CZK 7 129 less per year than the driver of a benzine car. The total annual cost of a benzine car is 41 850 CZK (1 718 EUR per 1 125 l of benzine), a hydrogen car – 34 720 CZK (1 425 EUR per 150 kd of hydrogen). Obviously, these calculations are based on a constant price, but fuel prices are changing during the year. An overview of the calculation is given in the table 12.

Table 12 Calculation of the fuel cost for the passenger car

	Benzine passenger car	Hydrogen passenger car
Consumption of the fuel	7,5 l of benzin per 100 km	1 kg of hydrogen per 100 km
Average fuel price	1,53 EUR per l	9,50 EUR per kg
	37,20 CZK per l	231,47 CZK per kg
Cost of 100 km run-in	11,45 EUR per 100 km	9,50 EUR per 100 km
	279,00 CZK per 100 km	231,47 CZK per 100 km
Average annual run-in	15 000 km	15 000 km
Annual consumption of the fuel	1 125 l	150 kg
Cost of annual run-in	1717,63 EUR	1425,00 EUR
	41850,00 CZK	34720,13 CZK

Source: own calculation based on data from Kopecký (2019), Hytep (2022), Kurzy.cz (2022)

The calculation shows that using a hydrogen passenger car is a bit more economical than using a benzine car (219 CZK via 279 CZK per 100 km). Given the upward trend in petrol prices and, conversely, the expected decline in hydrogen prices, the use of hydrogen cars can be very beneficial.

4.6.2 Example of the hydrogen bus

As already mentioned, 870 hydrogen buses should be introduces by 2030 in the Czech Republic (MIT, 2020).

The average hydrogen consumption is 9 kg per 100 km for a 12-meter bus (Doucek, 2017, p. 16). The average consumption of diesel of the conventional bus is 42 l per 100 km during heavy urban public transport (Veselá Schauhuberová, 2013, p. 7).

The price of diesel as of 17 February 2022 is CZK 36,12 per l in the Czech Republic (Kurzy.cz). The cost per 100 km of diesel bus travel in this case is 1517,04 CZK (62,26 EUR) – this is 42 liters of diesel. If hydrogen is used, the price of which is 9,5 euros per kg at gas stations in Germany (Hytep, 2022), the bus needs 9 kg of hydrogen for 2083 CZK (85,5 EUR). The calculation shows that the diesel bus is more economically advantageous than the hydrogen bus.

It is thus possible to calculate the difference in annual costs. The average annual run-in of city bus is 80 000 km (Veselá Schauhuberová, 2013, p. 10). According to this, the average annual fuel consumption for this run-in can be calculated: it is 33 600 l of diesel or 7 200 kg of hydrogen. The annual cost of the diesel bus is 1,214 millions CZK and cost of the hydrogen bus is higher – 1,667 millions CZK (see Table 13).

Table 13 Calculation of the fuel cost for the bus

	Diesel bus	Hydrogen bus
Consumption of the fuel	42 l of diesel per 100 km	9 kg of hydrogen per 100 km
Average fuel price	1,48 EUR per l	9,50 EUR per kg
	36,12 CZK per l	231,47 CZK per kg
Cost of 100 km run-in	62,26 EUR per 100 km	85,50 EUR per 100 km
	1517,04 CZK per 100 km	2083,21 CZK per 100 km
Average annual run-in of the city bus	80 000 km	80 000 km
Annual consumption of the fuel	33 600 l	7 200 kg
Cost of annual run-in	49 810,47 EUR	68 400,00 EUR
	1 213 632,00 CZK	1 666 566,00 CZK

Source: own calculation based on data Doucek, 2017, Hytep (2022), Kurzy.cz (2022), Veselá Schauhuberová, 2013

From the performed calculations it is evident that the actual run-in of a hydrogen passenger car is more economically advantageous than the run-in of the benzine car, but the run-in of a hydrogen bus is less advantageous than a diesel one. However, it is clear that petrol prices are currently rising sharply and are expected to rise further. On the contrary, hydrogen prices should fall, so hydrogen mobility can be expected to become more advantageous.

4.6.3 Multi-criteria analysis

The comparison of selected vehicle variants is performed using the multi-criteria analysis method. Scenario 1 concerns the comparison of a benzine car and a hydrogen passenger car, Scenario 2 – diesel bus and hydrogen bus. Criterion (a) includes the price of fuel needed by the vehicle for the average range – the assessment is based on previous calculations (current fuel costs). Criterion (b) is based on an analysis of the hydrogen market and is based on the finding that future hydrogen prices are likely to fall significantly. So far, the size of the fuel tank is better addressed in conventional cars than in hydrogen cars (criterion c). It's obvious that hydrogen cars do not have any CO_2 emissions. There is a high probability that the tax burden or possibly fees will be higher for cars that burden the environment. The supply of hydrogen cars is still very small on the market as is the range of infrastructure for refueling.

The evaluation is always performed within one pair of variants: A vs. B, C vs. D. The variant, which is better from the point of view of the selected criterion, gets a rating of 1 point, while the second variant - zero (0). The evaluation is multiplied by the weight (see Methodology of work), which is assigned to each criterion in the comparison. Subsequently, the sum of points for each variant and the weighted sum are calculated. The results are as follows:

A is worse than B (42,9 % vs. 57,1 %): a petrol passenger car is worse than a hydrogen car, which is mainly due to the calculation of the mileage price and the expected fuel price (a drop in hydrogen prices in the future).

C is better than D (66,7 % vs. 33,3 %): the hydrogen bus is worse than the diesel. The evaluation was influenced mainly by the result of the calculation of the fuel price, which showed that a ride on a hydrogen bus is more expensive than a diesel one.

Table 14 Multi-criteria analysis

		Scenario 1				Scenario 2			
		A		B		C		D	
a	Price of fuel (EUR or CZK) – today	1	0,0 %	0	23,8 %	1	23,8 %	0	0,0 %
b	Prices of fuel (EUR or CZK) – estimated in future	0	0,0 %	1	19,0 %	0	0,0 %	1	19,0 %
c	Full tank of the fuel – posibble run-in (km)	1	19,0 %	0	0,0 %	1	19,0 %	0	0,0 %
d	CO_2 emissions (low / high)	0	0,0 %	1	9,5 %	0	0,0 %	1	9,5 %
e	Availability of refueling points (good / bad)	1	19,0 %	0	0,0 %	1	19,0 %	0	0,0 %
f	Taxes and fees (EUR or CZK)	0	0,0 %	1	4,8 %	0	0,0 %	1	4,8 %
g	Market price of the new car (low / high)	1	4,8 %	0	0,0 %	1	4,8 %	0	0,0 %
	Sum	**3**	**42,9 %**	**4**	**57,1 %**	**4**	**66,7 %**	**3**	**33,3 %**

Source: own processing

4.7 Impact of hydrogen development on the stock market

Decarbonisation trends and the trend towards alternative energy sources, significant investments in hydrogen infrastructure and the emergence of hydrogen cars – these are factors that can positively affect the success of hydrogen-using companies. Investment company JPMorgan draws attention to the shares of 3 companies, the price of which could increase by more than 100% this year (Tym Instaforex, Kurzy.cz, 2022).

Hyzon Motors

It is a hydrogen mobility company, an American company that produces hydrogen-powered vehicles. In addition to ecological passenger cars, it also produces heavy trucks with zero emissions and buses. Last year, it exceeded its target for commercial deliveries of heavy hydrogen vehicles.

„*The Company is in the early stages of designing its SuperH2Truck, a purpose-built hydrogen-powered truck with a fuel cell optimized chassis.*“ (Patria.cz, 2022).

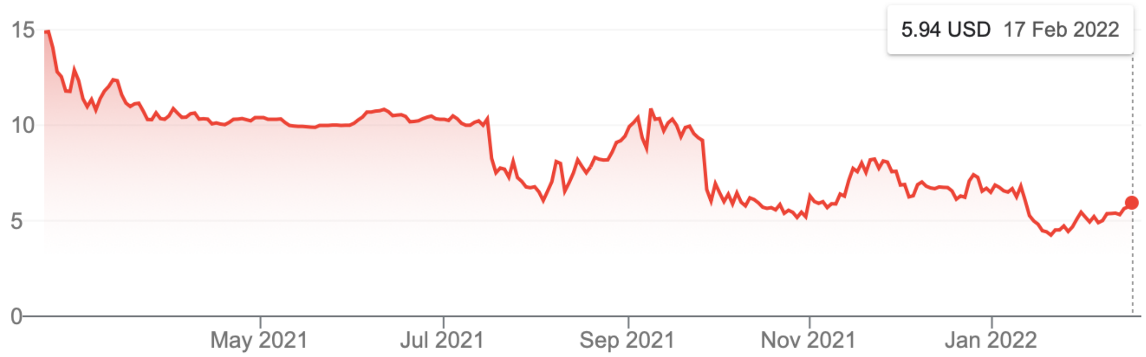
The company operates in New York, Europe, Singapore, Australia and China.

For the nine months ended September 30, 2021, Hyzon Motors Inc. sales increased from 0 USD to 962 000 USD. Net income was 14,8 million USD, compared to a loss of 3 000 USD. Revenues reflect an increase in demand for the Company's products and services due to favorable market conditions.

The company's management has promised to make every effort to make 2022 a decisive year for global hydrogen mobility. JPMorgan believes that the company's shares could skyrocket by 108 % in 2022 (Kurzy.cz, 2022).

As of February 17, 2022, the stock market price was 5,94 USD and has risen 23,24% over the past month (Google Finance, 2022).

Figure 24 Price of the Hyzon Motors share (2.2021-2.2022), USD



Source: Google Finance (2022)

Bloom Energy

Another company that could make money on the upcoming energy revolution is California's Bloom Energy. For more than 20 years, it has been developing solid oxide fuel cells used in electricity generation. Her clients include the largest American corporations. In addition, the demand for its products is constantly growing. According to analysts at JPMorgan, Bloom Energy has all the prerequisites for further growth due to the large volume of orders. The price of its shares could rise by more than 120% this year (Kurzy.cz, 2021).

„*For the nine months ended 30 September 2021, Bloom Energy Corp revenues increased 16% to $629.7M. Net loss increased 1% to $131.1M. Revenues reflect an increase in demand for the Company's products and services due to favorable market conditions. Higher net loss reflects Sales and marketing - Balancing value increase of 75% to $50.3M (expense), Research and development increase of 29% to $60.7M (expense).*“ (Patria.cz, 2022).

As of February 17, 2022, the stock market price was 18,94 USD and has risen 11,15% over the past month (Google Finance, 2022).

Figure 25 Price of the Bloom Energy share (2.2021-2.2022), USD

Source: Google Finance (2022)

Plug Power

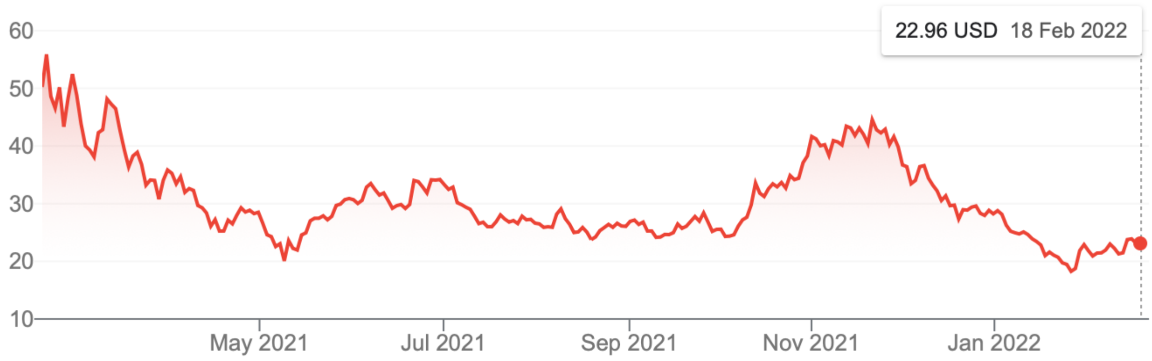
The American company Plug Power is developing hydrogen fuel cell systems that replace traditional car batteries and electrically powered devices.

Plug Power was established as a joint venture between DTE Energy and Mechanical Technology Inc. The company went public in 2002 and soon began delivering hydrogen-powered forklifts to customers such as Nike, BMW and Home Depot. In 2017, Plug Power began supplying fuel cell engines for supply to, for example, UPS. It is worth noting that Amazon.com bought more than 50 million shares of Plug Power in 2017 and subsequently entered into an agreement to use hydrogen technology for forklifts in its warehouses. The company recently introduced Progen 125 kW fuel cell engines for Class 6, 7 and 8 trucks and heavy off-road equipment (Mlýnek, 2022).

According to the company's management, its revenues could double in three years to approximately 3 billion USD. The outlook for JPMorgan analysts is also positive. The bank estimates that the shares of this producer of hydrogen fuel cells could increase by almost 130% this year (Kurzy.cz, 2022).

Market prices of the Plug Power stock is 22,95 USD on 18.2.2022 (Google Finance, 2022).

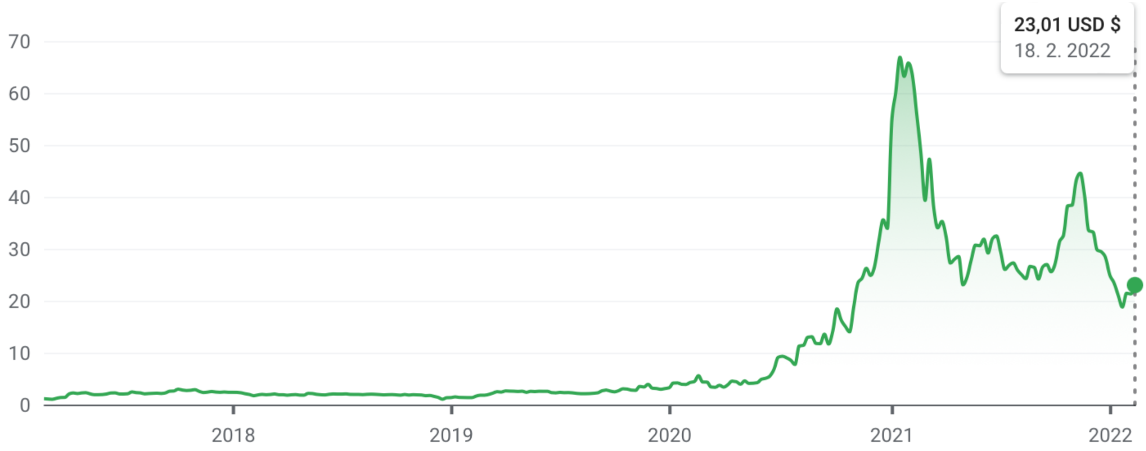
Figure 26 Price of the Plug Power share (2.2021-2.2022), USD



Source: Google Finance (2022)

During the last month, a small price increase of + 0.35% is evident. Over the last five years, however, stocks have risen 1930,96% (Google Finance, 2022) – see figure 27.

Figure 27 Price of the Plug Power share (2018-2022), USD



Source: Google Finance (2022)

Other major hydrogen technology companies listed on the stock exchanges are Ballard Power in Canada, Volvo Group subsidiary – Powercell Sweden, Nel Hydrogen (Nel ASA) in Norway, Air Liquide in France and Linde in Germany.

The example of selected hydrogen companies shows that their share prices are highly volatile, but some growth has been seen since the beginning of 2022, which is related to the strategic plans for the development of the hydrogen market. Hydrogen stocks as a form of hydrogen investment are becoming more and more interesting. However, many investors see clear potential here (Mlýnek, 2022; Tácha, 2021).

5 Summary of results

this part is devoted to defining the advantages and disadvantages of using hydrogen as an energy source, which can be done on the basis of the analysis in the practical part.

Advantages of the hydrogen include:

- zero exhaust emissions,
- reducing dependence on hydrocarbons,
- does not contain lithium batteries – production is more environmentally friendly,
- short refueling time,
- higher range than battery electric cars,
- effective usage of fuel,
- higher hydrogen energy density than batteries.

The basic advantage of hydrogen in road transport over conventional fuels is that when it is used in a fuel cell, no emissions are generated and the only waste substance is water. Although this is no different from battery electric cars, which also do not produce any emissions, they nevertheless use lithium batteries, the production of which represents an environmental burden and subsequently it is necessary to address its recycling. This is not a problem with the fuel cell (IEA, 2019).

Hydrogen engines do not need oil, the reserves of which are not infinite and, moreover, are concentrated in a few countries. This allows the oil states to dictate prices on the market, which is disadvantageous for developed economies (Zujkova, 2021). Using of the hydrogen engines can reduce the dependence on the hydrocarbons import and their prices.

Hydrogen cars also have shorter refuelling times than battery electric cars. Battery electric cars can be charged at home, at work or at public charging stations, but the charging time can be very high if the vehicle is not charged at very fast charging stations. Even in this case, the minimum charging time is about 30 minutes (Honda, 2021). Hydrogen refueling, on the other hand, takes only a few minutes.

Another advantage of hydrogen cars is their range, which is comparable to many conventional cars and higher than that of battery electric cars. This is also related to the energy density of hydrogen, which is about 120 times higher in weight than with lithium batteries, and a relatively small fuel tank is enough to achieve the same range as electric cars (Frei, 2021).

Usage of fuel is in the case of the internal combustion motor it is about 35 %, and in the case of hydrogen motor is higher – about 45 %. The hydrogen car can pass on 1 kg of hydrogen in 2,5-3 times more, than with the 3,8 l of benzine (i tis equivalent to the 1 kg of hydrogen by the energy intensity and volume per gallon) (Zujkova, 2021).

Disadvantages of hydrogen include:

- high purchase price,
- lack of infrastructure,
- lower energy efficiency,
- the production of "non-green" hydrogen causes emissions and environmental pollution.

The high price of hydrogen results from the calculation and comparison of the mileage of hydrogen and diesel buses (per km), hydrogen energy and electricity prices (per kWh), conducted in the practical part of the thesis. Hydrogen vehicles are also quite expensive and their offer is limited on the market.

The high purchase price is one of the main barriers for hydrogen cars. Their competitiveness is influenced by three main factors, namely the price of fuel cells, the price of the hydrogen tank in the car and also the cost of the infrastructure of hydrogen filling stations (IEA, 2019).

Hydrogen batteries contain platinum, one of the most expensive metals in the world. Additional safety measures also make the engine expensive: in particular, special storage systems and carbon fiber tanks to avoid explosion (Zujkova, 2021).

A fuel cell that converts hydrogen to electricity in hydrogen cars is an essential component of these cars. At present, however, fuel cells are low in production and their production costs are high. In recent years, however, production costs have started to fall sharply and should continue to fall, especially if they start producing in larger quantities (IEA, 2019).

Tanks in hydrogen cars are also very expensive, as they are made of special expensive materials. Here, too, a gradual decline in the cost of production is expected, but slower than for fuel cells (IEA, 2019).

The absence of a refuelling infrastructure is another major barrier to hydrogen mobility. One of the reasons why there are not enough refuelling stations is again the high price, especially for the compressor, which is necessary for compressing hydrogen and storage tanks, which usually have to be large due to lower hydrogen density. This problem should also be addressed to some extent in the future by economies of scale if the capacity of hydrogen filling stations is increased. Further price reductions should come with increased production of these components (IEA, 2019).

6 Conclusion

The aim of the work was to evaluate the perspectives of the use of hydrogen as an energy source. The task of the work was also to compare the price of energy provided by hydrogen and the price of energy from other sources. A comparison of the advantages and disadvantages of using hydrogen as an energy source was made.

The work included an analysis of the energy market, the development of individual energy sources and the issue of emissions. The analysis clearly shows the trend of growing interest in alternative energy sources and the high share of some economic sectors in emissions (eg transport sector). Recently, there has been a growing worldwide interest in global decarbonisation and the transition to alternative energy sources. Hydrogen is considered to be one of the sources that could replace oil, gas and coal. It can be named as the fuel of the future and the rising demand for green energy can be expected in the coming years.

In this work, calculations of the price of energy obtained from hydrogen and other energy sources were performed. The results show that the price of hydrogen energy is still much more expensive than the price of energy from other sources (nuclear, coal, solar, wind etc.). Nevertheless, the comparison of the energy prices for the end consumers in the Czech Republic with the calculated price of hydrogen energy showed, that the prices of energy for householders is higher by the 0,2 CZK per 1 kWh. The limitation of the research was insufficient and diverse information on hydrogen prices. Rising prices of energy from conventional sources in the world and, conversely, the expected decline in hydrogen prices due to the development of technology may change these conclusions in the future.

Another part of the research included a multi-criteria analysis of the usage of hydrogen, benzine and diesel as fuels in passenger cars and buses. The results show that the price of range of the hydrogen passenger car is lower than the price of range of the benzine car. This does not apply to buses, because the range of diesel bus is cheaper than range of hydrogen bus. Insufficient infrastructure and a small supply of hydrogen-powered vehicles are so far factors that worsen the evaluation of hydrogen vehicles at the expense of conventional vehicles.

Some important conclusions need to be made in relation to the assessment of future development prospects. In relation to this, it should be noted that the use of hydrogen as an energy source is associated with the decarbonisation of the economy. Without decarbonisation (mainly due to energy losses in production), greater hydrogen involvement would not make economic sense in most sectors. On the contrary, taking into account decarbonisation, hydrogen plays a dual role: allows greater involvement of RES in the energy mix, and allows decarbonization of many economic sectors (especially industry, transport). These two functions are interconnected.

Due the inefficient energy accumulation, it does not make sense at present to store energy from RES in hydrogen unless there is additional demand for hydrogen itself. It does not make sense also to "decarbonise" economy with cheaper grey hydrogen, where the emission source only moves, for example, from the vehicle motor to the refinery.

However, although these hydrogen functions are interconnected, an imbalance between supply and demand within each country is likely. For example, in industrialized countries, the demand for hydrogen in sectors that already use it or where it can replace fossil fuels may be higher than the country is able to produce economically (e.g. in EU). Conversely, in countries with less developed industries but with suitable geographical conditions (e.g. in Africa), there may be great potential for the production of relatively cheap green hydrogen. Whereas it can be argued that hydrogen will be an important commodity on the international market. However, it is necessary to address the issues of economic storage of energy from this source and its distribution.

The development of the hydrogen market is significantly signaled by strategic and investment plans at the level of national governments (eg Germany) and companies. Shares of hydrogen companies are clearly becoming an attractive opportunity for investors.

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