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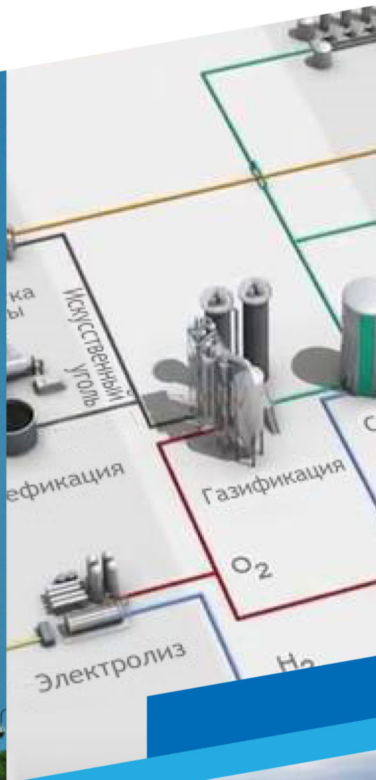
THE HYDROGEN ECONOMY –

a path towards low carbon development



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SUMMARY

The hydrogen economy is an image of the future for the global economy, in which hydrogen becomes a new global energy carrier and starts playing a role comparable to the one now played by coal, oil or gas and much more important than the current role of hydropower, nuclear power plants and bioenergy combined. According to various forecasts, this may happen overall globally after 2040; however, the hydrogen economy is already beginning to form in some regions.

In the 20th century the main driver for the development of hydrogen technologies was their economic competitiveness compared to expensive hydrocarbons. The situation is different nowadays, as the obligations of states, individual regions, companies and their associations to combat global climate change come to the fore. Hydrogen is a necessary element for the implementation of these obligations: renewable energy sources can decarbonate primarily electricity generation (although there are limitations imposed by their stochasticity) - while the energy supply of buildings, the transport sector and industry remain "outside" the scope of decarbonization - unless a new energy source can be found. Hydrogen claims to offer the solution.

More than 20 countries and 50 corporations have adopted long-term programmes for the development of hydrogen technologies, financed from budgets at different levels and supported by beneficial regimes and international technological cooperation.

Japan is one of the leaders, having set the goal of building a “hydrogen-based society”[1]. It is simultaneously developing several elements of the hydrogen chain and landmark projects of intercontinental hydrogen export from Australia, Norway and the Middle East, as well as projects for the application of hydrogen energy in millions of households. In total, there are dozens of “hydrogen communities” in the world and several hundred pilot projects, primarily in Japan, Germany, the United Kingdom, the United States, South Korea and other countries.

Hydrogen is currently produced primarily from hydrocarbons (around 65 million tonnes per year), and is consumed at production sites. In the next few decades the challenge is to create a fundamentally new industry and a market based on carbon-free hydrogen production, large-scale storage and transportation of hydrogen over hundreds and thousands of kilometers via pipelines and by tankers, by sea and onshore. The aim is to develop large-scale application of hydrogen energy in the energy sector, in transport and industry, including steel and chemical production, large gas turbines, individual energy sources for households, manufacturing and the army, where it can be used to power transport - from long-haul trucks to drones.

1 Challenges for Japan’s Energy Transition. Basic Hydrogen Strategy / Agency for Natural Resources and Energy (ANRE), Ministry of Economy, Trade and Industry (METI). October 2018, Japan.

At the same time, hydrogen production would have to grow several fold by 2050, and some segments of its technological chain would need to be upscaled hundreds of times.

Russia still remains apart from the international communities and partnerships developing hydrogen technologies. This is primarily explained by the fact that the climate agenda and decarbonization play a minor role in the energy strategy, which significantly hinders the development of not only hydrogen, but generally any low-carbon technologies (renewable energy, energy efficiency, electric transport and etc.).

At the same time, Russia has not only got enormous resources to bring to a new global market, but also its own technological developments (which are, however, for the most part far from commercialization at this point) and promising domestic demand.

The emerging hydrogen market will likely compete with hydrocarbon markets, where Russia's position now seems unshakable - and in this sense, a strategy of ignoring or even opposing the new may seem attractive in the short term. But in the long run, such a strategy will put the national economy at the risk of a slowdown- not only because of falling demand for hydrocarbons, but also as a result of restricting the development of the innovation sector in industry.

A response to these global challenges could be the incorporation of hydrogen technologies in the Russian energy strategy and the low carbon development strategy — or the adoption of a separate national hydrogen programme. The latter should focus on the three main pillars — support for technological development, long-term demand and the market and stimulating international investment. The key to success should be entering the existing international hydrogen communities and coordination of developers and stakeholders nationally.

WHY NOW? NEW INCENTIVES FOR THE DEVELOPMENT OF HYDROGEN TECHNOLOGIES

Hydrogen 1.0

Hydrogen itself cannot be called an innovation - this chemical element was discovered by the British scientist Henry Cavendish as early as 1766, and 7 years later his French colleague Jacques Alexander César Charles made the first attempt to fly in a hot air balloon filled with hydrogen[2].

1800 saw the discovery of electrolysis (the process of producing hydrogen from water using electricity) and the middle of the 19th century – of fuel cells (electrochemical devices that receive electricity from hydrogen, bypassing the combustion process). In the first three decades of the 20th century, experimental installations for steam methane reforming appeared (making it possible to produce hydrogen from light hydrocarbons). Even today, these technologies form the basis of hydrogen use in industry.

High energy value of hydrogen (combustion value 120 MJ / kg compared to 56 MJ / kg for methane) predetermined attempts to use it as a fuel for transport. The characters in the "Mysterious Island" by Jules Verne (1874) flew in a large air balloon filled with hydrogen half a century before the transatlantic hydrogen airships were actually used. Liquid hydrogen became an important fuel in the American and Soviet space programmes, primarily for Space Shuttle and Buran. The first aircraft with one of the engines powered by hydrogen fuel was created in the USSR on the basis of the TU-154 in the late 1980s. The first hydrogen cars appeared in the same period. However, these technologies did not received wide distribution for reasons of high costs and low efficiency, and nowadays the use of hydrogen as fuel is very limited.

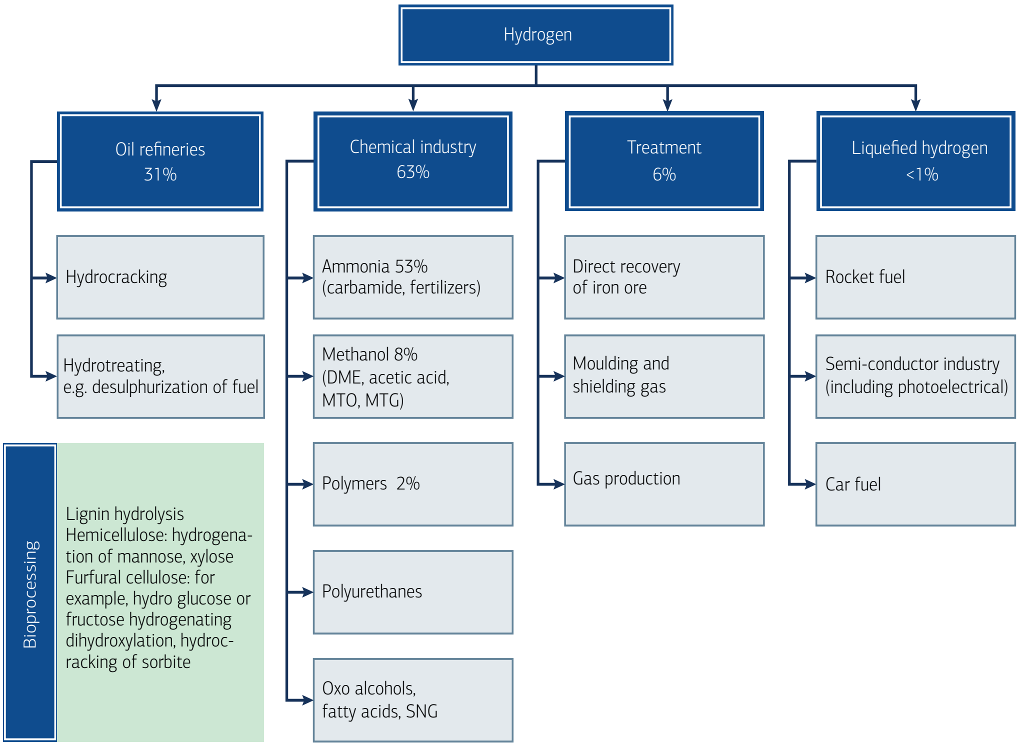
The main directions for the use of hydrogen today are in the refining and chemical industries (for the production of various goods, primarily ammonia and methanol) (Fig. 1). Energy usage of hydrogen, according to ARENA, is estimated at only 1-2% of its total consumption[3].

Total hydrogen production in the world is currently estimated by various sources at 55-65 million tonnes, with cumulative average annual growth rates over the past 20 years being low — about 1.6% (Fig. 2). Over 90% of hydrogen is produced at the point of consumption (as the so-called captive product), and less than 10% is supplied by specialized companies operating in the industrial gas market (Air Liquide, Linde, Praxair Inc., etc.).

2 Introduction to hydrogen and its properties / H. Idriss, M. Scott, V. Subramani // Compendium of Hydrogen Energy Volume 1: Hydrogen Production and Purification. Edited by V. Subramani, A. Basile and T. N. Veziroglu. - Woodhead Publishing, 2015.

3 Opportunities for Australia from Hydrogen Exports, ACIL Allen Consulting for ARENA, August 2018.

Figure 1 Directions of hydrogen use



Source: DECHEMA, DOE, Fair-PR, Linde[4]

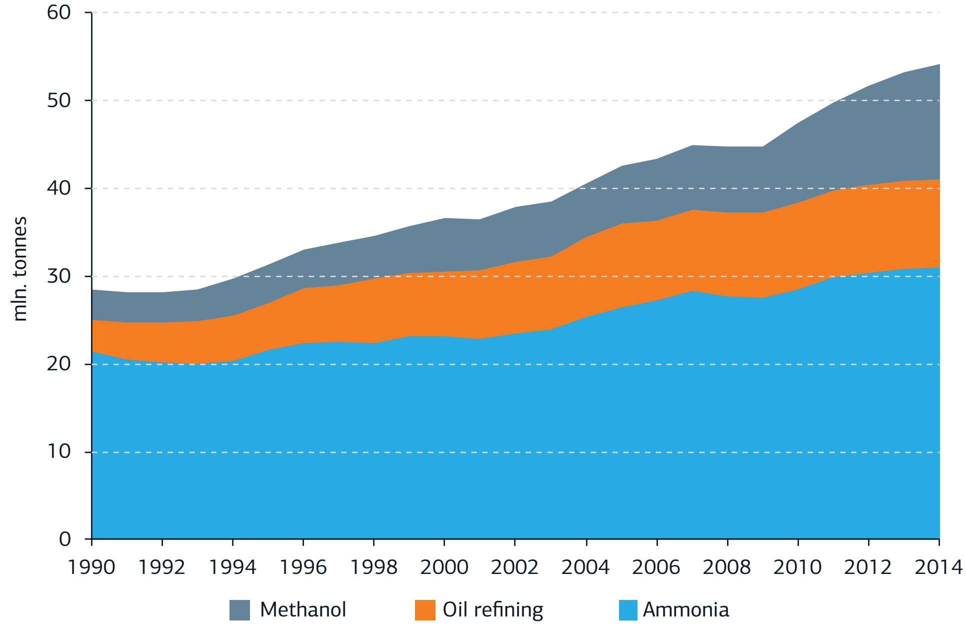
Today, hydrocarbons dominate as feedstock for hydrogen production. Over 68% of hydrogen is currently produced from natural gas, 16% from oil, 11% from coal and 5% from water using electrolysis. This is explained by comparatively cheap costs of production from hydrocarbons - according to various estimates, the cost price of hydrogen from natural gas is 2-5 times lower than of that produced via electrolysis (Fig. 2).

Therefore currently:

- hydrogen acts as one of the industrial gases that has been used for decades, primarily in the chemical industry and oil refining;
- Natural gas is the main source of energy for hydrogen production;
- steam methane reforming is the main hydrogen production method, and production volumes have been growing slowly in the past twenty years (CAGR 1.6%), reaching around 65 million tonnes annually.

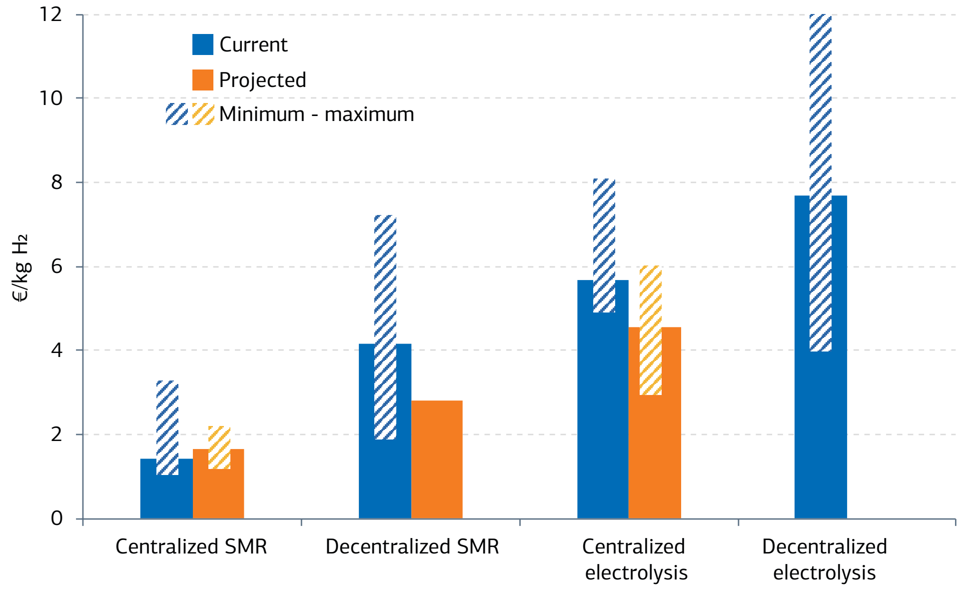
4 Hydrogen: Current Use and Future Development / DECHEMA, IEA Hydrogen Workshop, February 2019.

Figure 2. Global hydrogen production by industry for its own needs (captive production), mln. tonnes



Source: D. Brown, NREL, 2016[5]

Figure 3. Costs of producing hydrogen by steam methane reforming (SMR) and electrolysis



Source: LBST/Hinico 2015[6]; Grube/Höhlein 2013[7]

If the past and the present of hydrogen is linked to the term "industrial gas", its future is defined as "a new energy carrier".

5 Hydrogen Supply and Demand: Past, Present, and Future / D. Brown (NREL). GasWorld, April 2016.

6 Study on hydrogen from renewable resources in the EU / Ludwig-Bölkow-Systemtechnik GmbH (LBST), July 2015.

7 Costs of Making Hydrogen Available in Supply Systems Based on Renewables / T. Grube, B.Hohlein // Hydrogen and Fuel Cells. Springer, 2016.

Decarbonisation as the new driver of global changes

A global transformation process called "The Energy Transition" is taking place in the global energy sector. It is associated primarily with decarbonization and low carbon development. A global transformation process called "The Energy Transition" is taking place in the global energy sector. It is associated primarily with decarbonization and low carbon development[8].

Leading countries, individual regions, large corporations, cities and even individual municipalities are setting targets within their long-term strategies to reduce greenhouse gas emissions (or carbon footprint in products) in order to combat global climate change.

In particular, declarations of a number of countries (most of them were made in 2015 as part of the Paris Agreement) contain an obligation to limit emissions by 2030 by 25–40% compared to 1990 or even 2005 levels, and Germany and the United Kingdom have declared their intention to reduce greenhouse gas emissions by 80-100% by 2050 (Table 1).

Table 1. Examples of stated national goals to reduce emissions and increase absorption of greenhouse gases

Countries	Declared contribution towards mitigating climate change
US	by 2025 to reduce greenhouse gas emissions by 26 - 28% from 2005 levels
Canada	2030 - by 30% from 2005 levels
Germany	2030 - by 40-55% from 1990, 2050 – by 80-95%
France	2030 - by 40% from 1990 levels
Norway	2030 - by 40% from 1990 levels
Brazil	2025 - by 37% from 2005 levels
Mexico	2030 - by 22—36% from the baseline
China	By 2030 – to reduce greenhouse gas emissions by 1 US Dollar of GDP, carbon intensity by 65% , reaching the peak of absolute value of emissions no later than 2030
Australia	2030 - by 26 - 28% compared to 2005

Source: M. Yulkin[9], the official website of the UNFCCC secretariat[10]

Economic measures to stimulate the reduction of greenhouse gas emissions – "hydrocarbon taxes", emission trading systems – add a significant expenditure item to the operating costs of energy companies and consumers – one which did not exist a few years ago. The amount

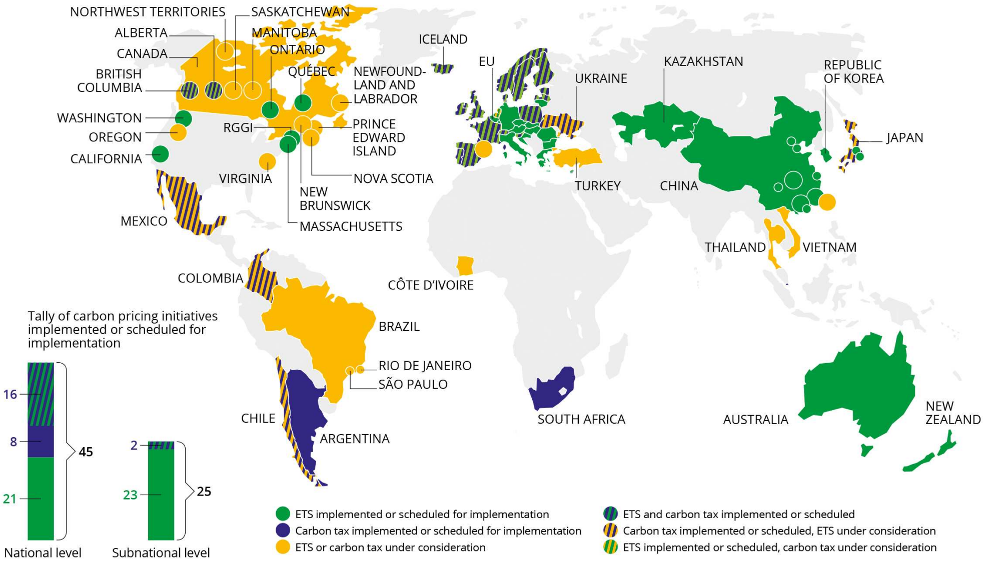
8 Please see the "Global and Russian Energy Outlook 2019" for more information on the "Energy Transition", edited by A.A. Makarova, T.A. Mitrova, V.A. Kulagin. ERI RAS - Moscow School of Management SKOLKOVO - Moscow, 2019.

9 Yulkin M.A. Low-carbon development: from a theory to practice. M., 2019. [in Russian]

10 https://www4.unfccc.int/sites/submissions/INDC/Submission%20Pages/submissions.aspx

of expenditure depends on the carbon footprint[11]. According to World Bank data, by 2018 as many as 45 countries and 25 separate regions (including, in particular, some states in the US) had either already launched a national emissions trading system or other forms of "CO_2 - charges" or were planning to do that in the immediate future (Fig. 4).

Figure 4. The status of national emission trading systems and carbon pollution pricing systems in the world as of 2018.



Source: World Bank Group, State and Trends of Carbon Pricing 2018[12]

China, the US, India, Russia, Japan, Germany, South Korea, Iran, Saudi Arabia and Canada rank among the first ten countries with most GHG emissions in absolute values. According to the European Commission data[13], these countries accounted for 67% of global emissions in 2017.

The new role of hydrogen in resolving the issue of balancing renewables-based energy systems

Electricity and heat generation is one of the main sectors of the economy which determine greenhouse gas emissions. Its share, according to various estimates, is about 25-30% (Fig. 5). Therefore, the first and the most obvious step to achieve the goals of economy decarbonisation is to increase the share of renewable energy (with an almost zero carbon footprint) and to reduce the share of fossil-fueled generation, for example, coal generation (which has a maximum carbon footprint) in electricity mix generation.

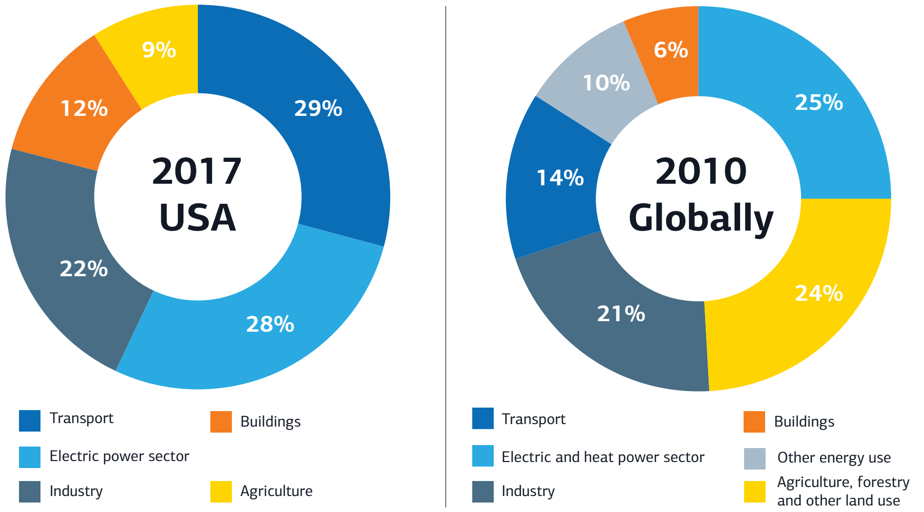
Over the past 10 years, the share of variable renewable energy (solar and wind) in the electricity sectors of a number of countries increased 3-10 fold (Fig. 6), while the reduced cost of electricity based on renewable energy has gone down by about 80% due to intensive development technologies.

11 GOST R 56276-2014/ISO/TS 14067:2013. The national standard of the Russian Federation. Greenhouse gases. Carbon footprint of goods. Requirements and guidelines on determining quality and submitting information.

12 World Bank and Ecofys. 2018. "State and Trends of Carbon Pricing 2018 (May)", by World Bank, Washington, DC.

13 EU EDGAR Database (Joint Research Centre (European Commission), 2018.

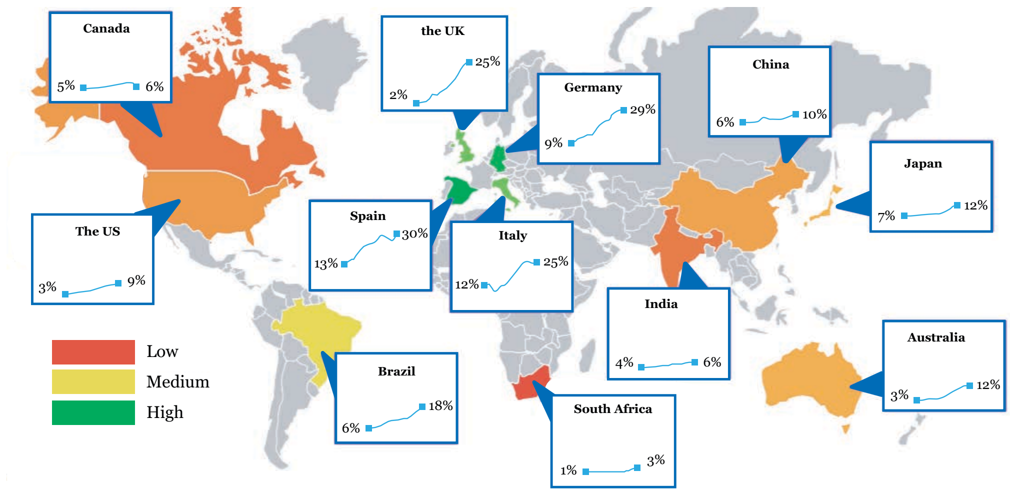
Figure 5. The contribution of various industries to greenhouse gas emissions in the US (left side, 2017 data) and globally (right side, 2010 data)



Source: EPA[14], dena[15] по данным IPCC Technical Summary[16]

In a number of countries, such as the UK, Denmark and many European countries the use of new technologies has enabled to reduce the carbon footprint in electricity generation by 100-250 g CO_2eq/kWh[17].

Figure 6. Growth in the share of variable renewables in the electricity sectors of various countries in 2006-2016



Source: BNEF[18]

14 EPA Sources of Greenhouse Gas Emissions 2017. https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions

15 Dena. Powerfuels: A missing link to a successful global energy transition. Berlin, April 2019.

16 Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Kadner, S., Minx, J. C., Brunner, S., Zwickel, T. (2014). Technical Summary. In Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

17 I. Staffell, M. Jansen, A. Chase, E. Cotton and C. Lewis (2018). Energy Revolution: Global Outlook. Drax: Selby.

18 New Energy Outlook 2017. / Bloomberg New Energy Finance.

According to a forecast by the International Energy Agency, by 2040 up to 20-35% of the world's electricity will be generated by solar and wind power plants. A forecast by Bloomberg New Energy Finance gives the figure of over 40%. In any case the share of renewable energy is projected to increase manifold.

Emerging steady demand for energy storage technologies is an important consequence of this development. This demand will compensate for output fluctuations - both short-term (second-to-second and hour-to-hour) and long-term (time horizons of up to several months).

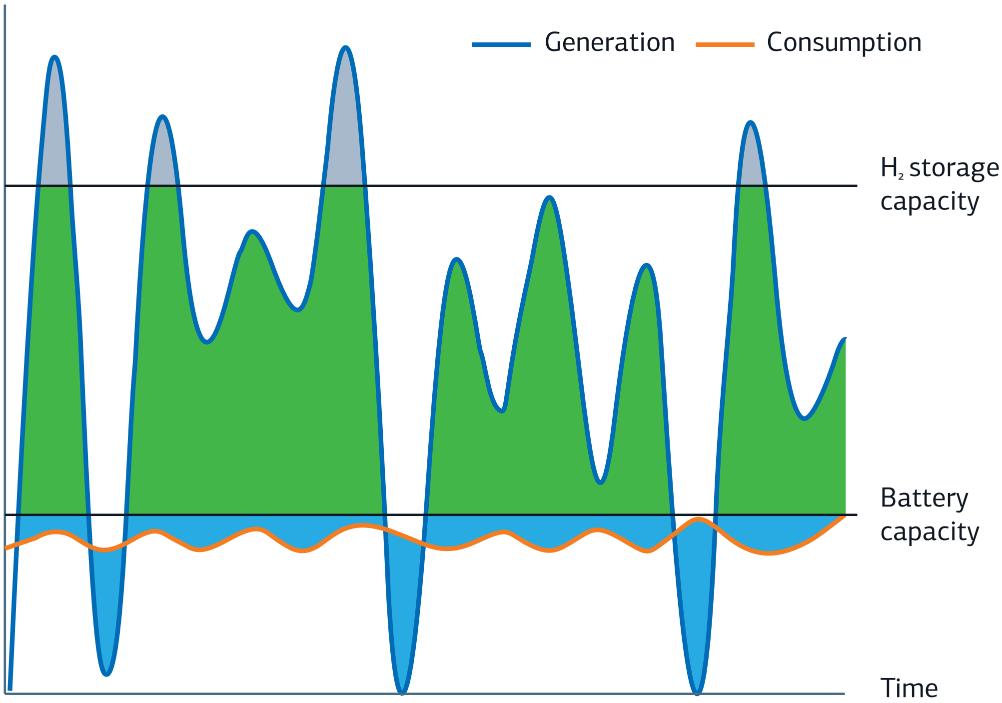
Power grids deal with renewable energy intermittency by using backup power plants, cross-country and cross-regional power flows, demand side response technologies, forecasting of renewable energy generation and traditional storage devices – hydroelectric pumped storage power plants, compressed air storage, and other sources which provide flexibility[19]. These tools are still sufficient even given a short-term growth in the share of renewable energy in the energy mix up to 90% (recorded on March 9, 2019 in Germany) or 65% (recorded during a week in the spring of 2019 in Germany). However, in order to ensure the planned two fold increase in the average annual share of renewables in Germany - up to 65% by 2030 - the available technologies will clearly have to be enhanced with new storage technologies. According to Wood Mackenzie Power & Renewables, the global market for energy storage systems could increase 13-fold from 2018 to 2024 - from 12 to 158 GWh, primarily due to the development of short-term storage devices installed, for example, in households.

Hydrogen is one of the most efficient ways to create long-term energy storage. Only hydroelectric pumped storage power plants can compete with it. At present these make up more than 99% of the storage capacity in the world. However, the potential for further growth in this sector is limited: HPPs can only be built at special sites suitable for locating two reservoirs with a specific amount of pressure between them. Storage batteries will occupy the niche of short-term storage facilities (Fig. 7).

Relatively low-cost surplus electricity from renewable energy can be used in electrolysis, during which water is converted to hydrogen and oxygen. Hydrogen produced in this way can be stored for a long period of time in various ways, including in underground storage facilities - salt caves and existing underground natural gas storage facilities - and can be used to generate electricity at the appropriate time, for example. Price arbitrage will be the source of recouping investment in this case: the difference in the price of hydrogen and electricity in different seasons should be sufficient to justify the investments made.

19 Power-Industry Transition, Here and Now: Wind and Solar Won’t Break the Grid: Nine Case Studies / G. Wynn, Institute for Energy Economics and Financial Analysis (IEEFA). USA, 2018.

Figure 7 The role of hydrogen and lithium batteries in renewables energy storage



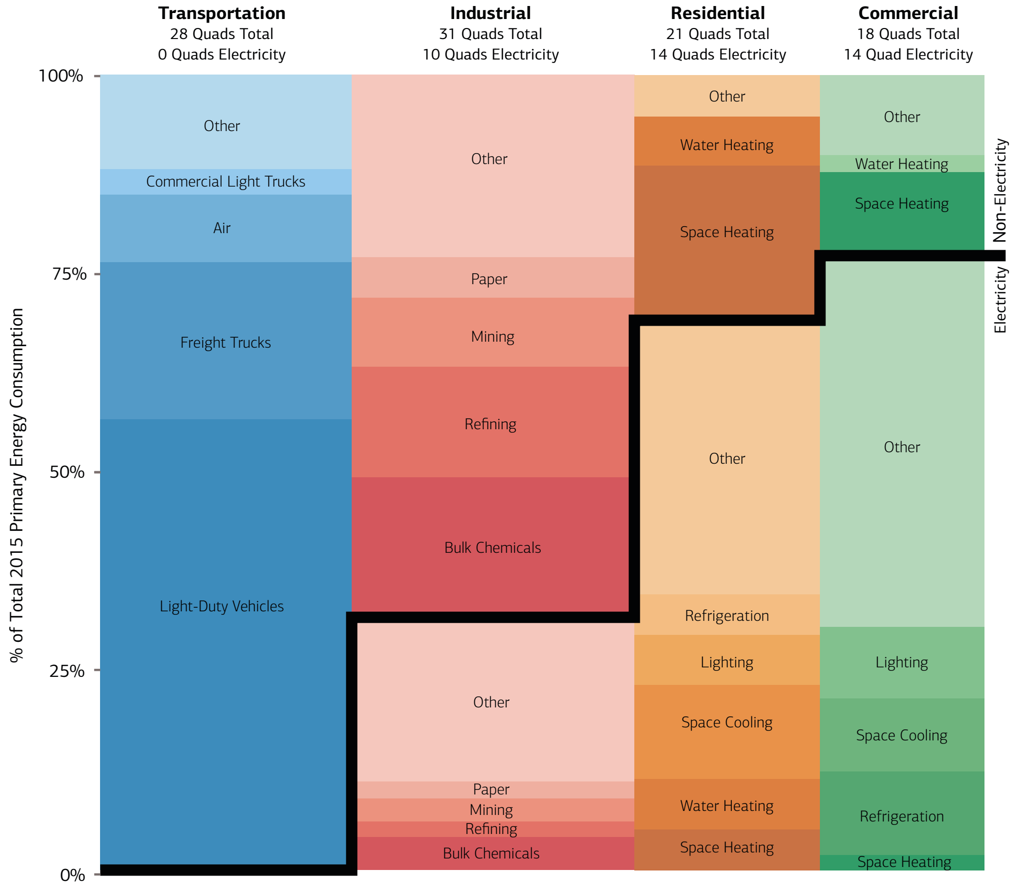
Source: Hydrogen Council, McKinsey[20]

The decarbonization of other sectors of the economy - industry, transport, energy supply of buildings - can be enhanced by increasing the amount of electricity they use, developing New electrification. This electricity, produced primarily by renewables (squeeze out) and, possibly, accumulated using hydrogen technologies, will then begin to "squeeze out" (displace) fossil fuels in these sectors.

Electricity is undoubtedly the most convenient energy carrier, but electrification has its limits. According to NREL, electricity provides more than 60% of energy in the United States in the residential and public buildings sector alone. Manufacturing and - especially - transport are electrified to a much lesser degree, although there is potential to increase electrification in the segments of passenger cars or the production of bulk chemicals. At the same time, there are serious barriers for the direct use of electricity in aviation, long-haul freight, maritime transport and heavy industry.

20 Hydrogen scaling up: A sustainable pathway for the global energy transition / Hydrogen Council, November 2017.

Figure 8 The share of electricity in final consumption in the main sectors in the US (dark colours indicate the areas with the largest potential for electrification, light colours show those with the least potential)



Source: NREL[21]

Barriers in the electrification of individual processes and sectors, in turn, create barriers for deep decarbonization of the economy. To overcome these, it is necessary to find a new global energy carrier that would combine the convenience of application in all sectors and a minimum carbon footprint. The future of hydrogen is linked to this.

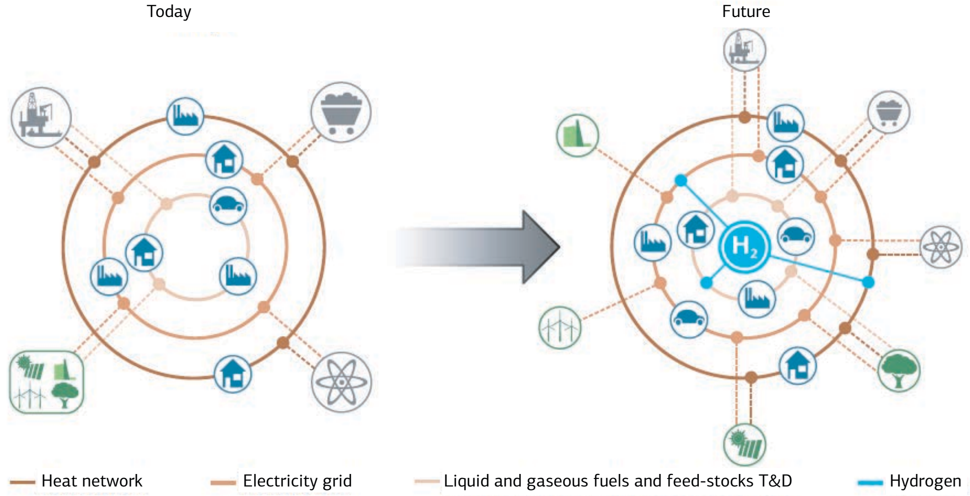
A new global energy carrier

Indeed, hydrogen can be used as follows (Fig. 9):

- in the "big" electric power industry
- in transport (replacing petroleum products);
- in the construction sector (for heating and electricity, including autonomous, replacing natural gas or petroleum products);
- in industry - as feedstock and a substitute for traditional hydrocarbons.

21 Jadun, Paige, Colin McMillan, Daniel Steinberg, Matteo Muratori, Laura Vimmerstedt, and Trieu Mai. Elec-trifica-tion Futures Study: End-Use Electric Technology Cost and Performance Projections through 2050. Golden, CO: National Renewable Energy Laboratory (NREL), 2019.

Figure 9 The place of hydrogen as a new global energy carrier in the integrated energy complex



Source: IEA[22]

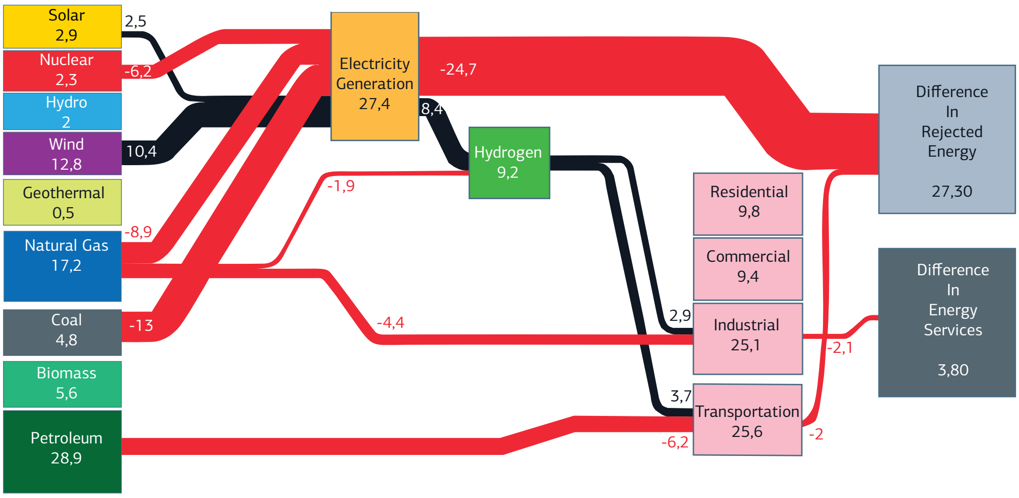
Hydrogen is also notable for the relative convenience of long-term large-scale storage and transportation over any distance, including via the existing infrastructure used for natural gas (including LNG). Transportation of hydrogen therefore becomes an alternative to the development of main power transmission lines - and this opens up new opportunities for quite a few regions of the world which are rich in renewable energy, but located far from energy consumption centers.

The systemic effect is also complemented by new opportunities for economic development — hydrogen technologies are science-intensive and technology-intensive, are at the very beginning of the "learning curve" and have great potential to increase efficiency and reduce costs.

In one of the scenarios of the integration of hydrogen technologies into the US energy complex, considered by the laboratories of the USA DOE, by mid- century hydrogen will take the role of the second overall energy carrier after electricity (Fig. 10). Electricity will provide over 90% of energy for the production of hydrogen, while primary demand for coal, gas and oil will fall by 73%, 34% and 18% respectively, and the share of renewable energy sources will increase 4-5 fold (primarily due to wind power).

22 Hydrogen and Fuel Cells Technology Roadmap / IEA, 2015.

Figure 10. Changes in the diagram of energy flows in the US in 2040 in the case of hydrogen technology integration – compared to the "as usual" scenario (red colour marks flows which have contracted, red colour – those which have expanded), quadrillion BTU[23]



Sources: Lawrence Livermore National Laboratory, DOE USA[24]

The implementation of this ambitious role for hydrogen requires tremendous efforts from governments and businesses[25]. That is why one can observe a serious increase in international activity in this sector in recent years, analyzed in the next section.

The status of programmes for the development of hydrogen technologies

The development of hydrogen technologies is given strategic importance by the governments of several countries, as well as in the corporate sector. We are talking about hundreds of large and small companies around the world participating in thousands of project initiatives.

Germany[26] and UK[27] are the most active countries **in the European Union**. However, 2017 saw the launch of an all-European initiative **Fuel Cells and Hydrogen Joint Undertaking (FCH JU)**. As of May 2018 it already numbered 89 regions and cities in 22 European countries (Fig. 11) among its members. The participants of this European initiative declare their desire to use hydrogen technologies in their energy strategies as part of the "Energy Transition", including the implementation of projects of around 1.8 billion Euros over the next five years.

23 1 quadrillion BTU = 25.21 mtoe

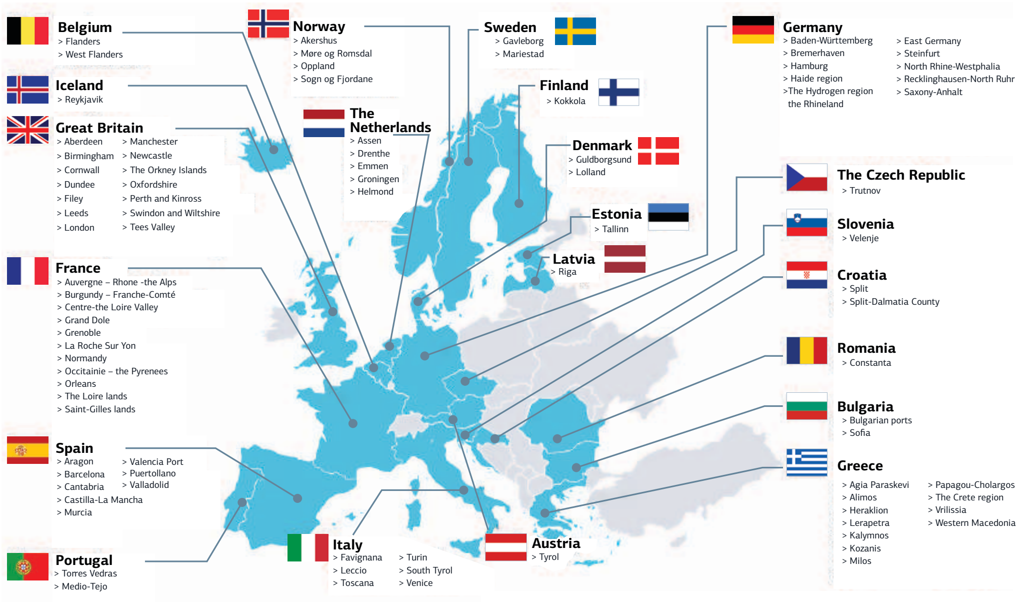
24 H_2 at Scale: Deeply Decarbonizing our Energy System / DOE, April 2016.

25 IEA. World Energy Outlook 2018.

26 The German NIP Programme (The national innovation program hydrogen and fuel cell technology) started in 2007, receiving financing of 700 million Euros in the period up to 2017

27 The British H2FC SUPERGEN initiative (The Hydrogen and Fuel SUPERGEN Hub) started in 2012 as a platform to unite the scientific society. As of 2014, it numbered 450 members.

Figure 11 Members of the FCH JU European hydrogen programme



Source: FCH JU[28]

The Japanese programme - **Strategic Roadmap for Hydrogen and Fuel Cells** was launched in the summer of 2014. The programme aims to broaden the technological or climate agenda - to start building a "hydrogen-based society"[29]. The roadmap contains specific key indicators for several technological chains at once - in production, storage, transportation and use of hydrogen - with milestones in 2020, 2025, 2030 and 2050. Therefore the goal in terms of hydrogen use in Japan is up from the current 200 tonnes per year to 10 million tonnes in 2050 (a 50 thousand fold increase!). In 2017 the amount of state funding for the programme was about 310 million Euros, and the total amount is estimated at several billion Euros[30] by 2040.

Japan's leadership is recognized internationally - in October 2018, a thematic meeting of energy ministers was held in Tokyo for the first time. The Hydrogen Energy Ministerial Meeting was attended by the representatives of 19 countries[31], as well as the European Union and the International Energy Agency. The leaders agreed on the four main directions in international cooperation aimed at developing a hydrogen economy:

- Collaboration on Technologies and Coordination on Harmonization of Regulation, Codes and Standards;

28 Fuel Cells and Hydrogen for Green Energy in European Cities and Regions. A Study for the Fuel Cells and Hydro-gen Joint Undertaking / Roland Berger, October 2018.

29 Challenges for Japan's Energy Transition. Basic Hydrogen Strategy / Agency for Natural Resources and Energy (ANRE), Ministry of Economy, Trade and Industry (METI). October 2018, Japan.

30 Case Study Report: Hydrogen Society (Japan) / Ville Valovirta, Joint Institute for Innovation Policy for the European Commission. February 2018.

31 Australia, Austria, Brunei, Canada, China, Germany, Italy, Japan, the Netherlands, New Zealand, Norway, Poland, Qatar, South Africa, South Korea, Spain, United Arab Emirates, the UK, the US, the European Union, IEA.

- Promote Information Sharing, International Joint Research and Development emphasizing Hydrogen Safety and Infrastructure Supply Chain;
- Study and Evaluate Hydrogen's Potential across Sectors including its Potential for Reducing both CO_2 Emissions and Other Pollutants;
- Communication, Education and Outreach.

The **US** hydrogen programme has been operating since the 1970s under various names. In the XXI century, the program received the second impetus - the annual funding of the **US DOE Hydrogen and Fuel Cells Programme** reached 120 million US Dollars (it was approximately double that amount in 2004-2011)[32].

California, Australia and South Korea announced their hydrogen strategies in 2018 and the beginning of 2019.

The Hydrogen Council is the most well-known association in the field of hydrogen technologies **at the corporate level**. The organisation, founded in 2017 in Davos, brought the number of its members up to 53 corporations from 11 countries with the total number of employees of 3.8 million and annual earnings of 1.8 trillion Euros by the end of 2018. In its programme study, the Hydrogen Council stated that its members were willing to invest at least 1.9 billion Euros annually in R&D and market development[33] in 2018-2022. The long-term vision of the organisation is to create a market for hydrogen and hydrogen technologies worth 2.5 trillion US Dollars by 2050, create 30 million jobs and increase the role of hydrogen as an energy carrier from 0% to 18% of world final energy consumption.

For comparison, the IEA estimates the amount of global government investment in R&D in the energy sector at around 25 billion US Dollars a year, and the value of corporate investment is around 90 billion US Dollars annually[34]. Aggregate R&D budgets of automotive companies are in the lead (around 40 billion US Dollars), while the minimum amount is invested by nuclear power plants (around 2 billion US Dollars).

Evaluation of investments in R&D in hydrogen technologies is still difficult: they are calculated simultaneously in the transportation, energy storage, oil and gas, electric power, heating for buildings and other sectors. But the potential market volume of hydrogen technologies is an equally important parameter.

32 https://www.hydrogen.energy.gov/budget.html

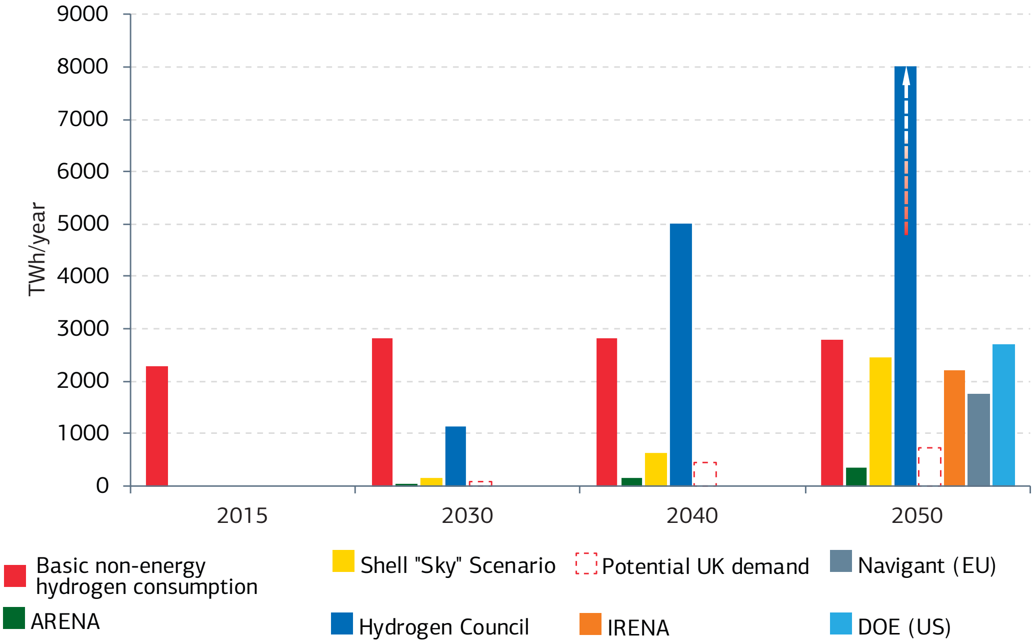
33 How hydrogen empowers the energy transition / Hydrogen Council, McKinsey. January 2017

34 IEA World Energy Investments 2019

Outlook for the world hydrogen technology market

Most of the well known forecasts of the global hydrogen market are contradictory and inconsistent (Fig. 12).

Figure 12 Outlook for the global hydrogen market by 2050, TW/h



Sources: Hydrogen Council[35], Shell[36], ARENA[37], UK Committee on Climate Change[38], IRENA[39], Navigant[40], DOE[41]

If conservative estimates of IRENA, Shell, ARENA are nearing the lower end of the range - around 500-2000 TWh of hydrogen in 2050 globally - then the Hydrogen Council orientates towards a much greater figure - 16100 TWh, or 18% of world energy consumption. The more complex country and regional estimates made by the DOE in 2016, the UK Committee on Climate Change in 2018 and Navigant in 2019 show that by 2050 its share would be in the range of 12-19% of final energy consumption in the US , UK and EU respectively within their scenarios of maximum application of hydrogen energy.

According to the IEA, in 2017 only three types of fossil fuels occupied comparable shares over 12-19% in the world final energy consumption: gas - (22%), coal (27%) and oil (32%)[42]. This means that by 2050 the role of hydrogen in the world energy sector could become comparable to

35 Hydrogen scaling up: A sustainable pathway for the global energy transition / Hydrogen Council, November 2017.

36 Shell Scenarios. Sky: The Emergence of a Hydrogen Economy / David Hone, Chief Climate Change Advisor, Shell International Ltd., November 2018.

37 Opportunities for Australia from Hydrogen Exports, ACIL Allen Consulting for ARENA, August 2018.

38 Hydrogen in a low-carbon economy / UK Committee on Climate Change, November 2018.

39 IRENA (2018), Hydrogen from renewable power: Technology outlook for the energy transition. / International Renewable Energy Agency, Abu Dhabi.

40 Gas for Climate. The optimal role for gas in a net-zero emissions energy system / Navigant Netherlands B.V., re-viewed by Kees van der Leun and Prof. Dr. Kornelis Blok. March 2019.

41 H_2 at Scale: Deeply Decarbonizing our Energy System / DOE, April 2016.

42 IEA World Energy Outlook 2018.

that currently played by each of these resources and will be much more important than the current role of hydropower, nuclear power plants and bio-energy combined.

In any case we are talking about the maximum growth potential of the hydrogen market by around 6.5 fold (if we talk about an increase in the absolute volumes of its production from its current, non-energy use) - or with a CAGR of around 6% up to 2050. But it would be more correct to speak about creating a new market based on the use of hydrogen for the decarbonisation of the global economy, that is, hydrogen with a minimum carbon footprint, which is hardly being produced now and which is not a product of global trade.

This potential cannot be realized without a fundamental change and / or scaling up of all technologies in the production chain. The following section focuses on their analysis.

TECHNOLOGIES OF THE HYDROGEN ECONOMY OF THE FUTURE

Hydrogen production: how to differentiate grey from green

Nowadays, hydrogen is mainly produced by steam methane reforming (SMR) - from natural gas or by coal gasification. This cheap process, which is well established on an industrial scale, will not have any competitors for a long time in terms of the cost of hydrogen produced (1-2 US Dollars / kg, depending on the prices of gas and coal).

However, in the era of the Energy Transition, the carbon footprint of production processes becomes an equally important cconsideration. Steam methane reforming releases carbon dioxide emissions - 10 kg CO_2 / kg H_2. Therefore, this **hydrogen** is called "**grey**". Depending on the feedstock (gas or coal), it is either comparable to ordinary natural gas, or 2.5 times worse than it by this indicator[43]. Clearly, from the point of view of the decarbonisation, it is better to use natural gas rather than "grey" hydrogen - therefore it cannot be part of the future hydrogen economy.

One of the alternatives is the production of "grey" hydrogen only in combination with carbon capture and storage technologies (CCS)[44]. Hydrogen obtained in this way is called "**blue**". Unlike SMR, CCS technology is still far from full-scale commercialization. According to the Global CCS Institute, in 2018 there were only 18 large projects with CO_2 capture technology in the world, another 5 were under construction and 20 were at various stages of development[45] . There are three projects in the world which integrate steam methane reforming, partial capture, transportation and storage of CO_2. These are Port Arthur in the US, Quest in Canada and Tomakomai in Japan. According to IEA GHG[46], the addition of CCS increases CAPEX of the SMR technology by up to 87%, and OPEX by up to 33%. Present value of hydrogen produced in this way grows nearly one and a half times - up to 1.8 Euros per kg, and the cost of CO_2 utilization — up to 70 Euros per tonne of CO_2.

In April 2019, a pilot project concept for the production of "blue" hydrogen from brown coal of the Latrobe Valley basin in Australia was positively assessed by an environmental commission. Within this project, hydrogen will be exported to Japan - Hydrogen Energy Supply Chain, developed under the leadership of Japan's Kawasaki. For Australia, this is a step towards potential utilization of vast coal reserves within the low carbon economy. This example shows that "blue" hydrogen has good prospects in the countries which export fossil resources, where its price is moderate – although commercializing the CCS technology still requires significant efforts.

43 More about the carbon footprint of "grey" hydrogen: Balcombe et al. (2018). The carbon credentials of hydrogen gas networks and supply chains, Renewable and Sustainable Energy Reviews, https://www.sciencedirect.com/science/article/pii/S1364032118302983.

44 Another way to reduce the carbon footprint is to use biomass/biogas as part of the feedstock.

45 Carbon Capture and Storage Institute. The CCS Global Status report 2018.

46 IEAGHG, "Techno-Economic Evaluation of SMR Based Standalone (Merchant) Plant with CCS", 2017/02, February, 2017

The second alternative to "grey" hydrogen is "**green**" hydrogen obtained by electrolysis using energy with a minimum carbon footprint - primarily that from renewables energy sources.

Not all hydrogen produced by electrolysis can be called "green" - it all depends on the carbon footprint of electricity used for the process. For example, most of the known units in Germany use electricity from the electricity grid, and not exclusively from renewables, and because of its rather high carbon footprint, hydrogen produced is considered "grey." Connecting an electrolyzer solely to renewables can solve this problem - but in this case, the load factor of the electrolyzer drops by about half: it cannot be higher than the capacity factor of renewables utilization coefficient of the installed capacity of renewables. Another way of making the process of electrolysis "greener" is the decarbonization of the electricity sector, which is projected to reach 100% by 2050 in Germany, for example.

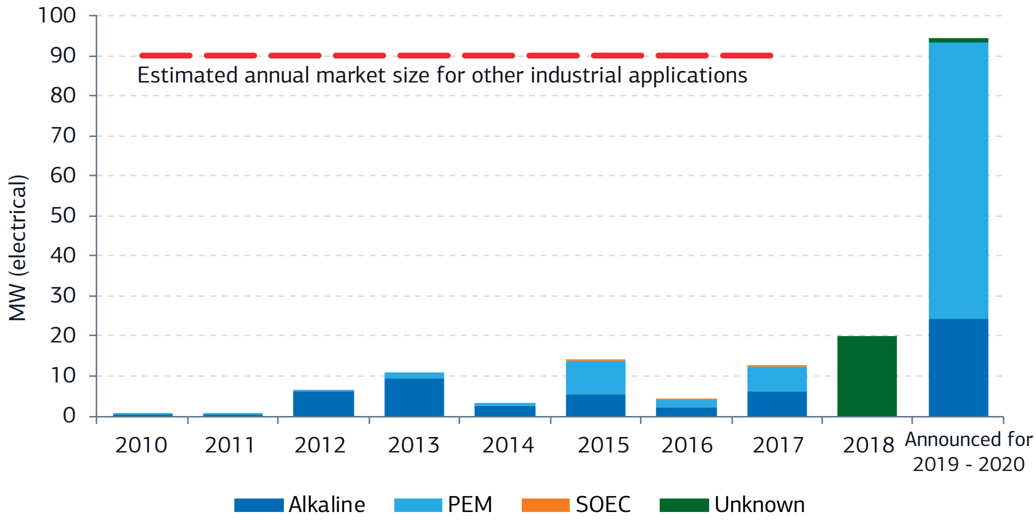
Only "green" hydrogen can be used for utilization from renewables in sectors other the electricity sector. - therefore, it is a cornerstone of the hydrogen economy as a whole, and research centres around it within most hydrogen programmes.

At the same time, energy companies with a significant portfolio of nuclear power plants are also claiming their place in the global hydrogen market. In April 2019, the French EDF, which owns 58 nuclear reactors, announced the launch of its subsidiary business, Hynamics, which will focus on the supply and maintenance of electrolyzers, as well as hydrogen vehicle fuelling. According to the company, its investments amounted to 16 million Euros, and it has announced 40 potential projects in France, Belgium, Germany and the UK. Hydrogen obtained on the basis of nuclear power will also have a minimum carbon footprint.

It is worth noting that the interest in "green" and "blue" hydrogen is clearly growing. According to the IEA, during the last seven years, around 10 MW of electrolyzers were put into operation in the world on average annually. In 2018, 20 MW were brought online, and by the end of 2020, another 100 MW are expected to be commissioned. Investments in electrolysers are growing – total installed capacity of units could almost triple in the next 2-3 years[47], reaching 150 MW. For complete commercialisation, it is necessary to break the threshold of 90 MW per year (Fig. 13).

47 https://www.iea.org/tcep/energyintegration/hydrogen/

Figure 13 Commissioning of new electrolysers of various types in the world in 2010-2018



Source: IEA[48]

According to estimates by NOW GmbH hydrogen association[49], to meet the need for electrolysers in Germany alone, this figure would have to increase 10-50 fold within a decade.

Electrolysers use various technologies. Polymer Electrolyte Membrane Electrolysers (PEM) have been in the lead in terms of their numbers being commissioned compared to Alkaline electrolysers and have already reached commercialisation, according to Frontier Economics[50]. Solid Oxide Electrolyser Cells (SOEC) are still in the demonstration phase but are, according to some assessments, likely to claim a breakthrough in the industry The challenge going forward is to scale up single (unit) capacity from single digits of MW to dozens and hundreds of MW.

Today, renewables based electrolysis remains the most expensive technology for hydrogen production - up to 3 times more costly than steam methane reforming, and the target objective of all national hydrogen programmes is to drastically reduce its cost. At the same time, it counts a virtually zero carbon footprint and the absence of the need to combine electrolysis with CO_2 capture and storage (CCS) among its important advantages.

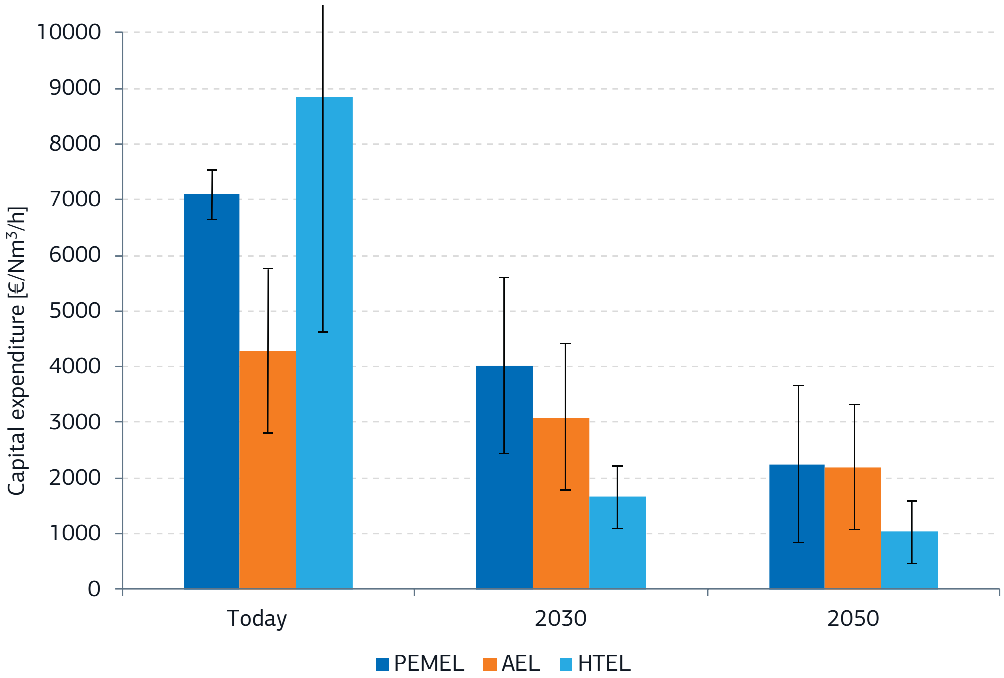
Electrolysers have a large cost reduction potential. This applies especially to Solid Oxide Electrolyser Cells and Polymer Electrolyte Membrane Electrolysers (Fig. 14). According to the UK Committee on Climate Change, there is also potential to increase efficiency (performance coefficient) from the current 67% to around 80% for Polymer Electrolyte Membrane Electrolysers and Alkaline Electrolysers and up to 92% for Solid Oxide Electrolyser Cells.

48 IEA World Energy Investments 2018, IEA World Energy Investments 2019

49 Brief Overview. Industrialisation of water electrolysis in Germany: Opportunities and challenges for sustainable hydrogen for transport, electricity and heat / National Organisation Hydrogen and Fuel Cell Technology – NOW GmbH. Berlin, October 2018

50 International aspects of a Power-to-X roadmap. A report prepared for the World Energy Council Germany / Frontier Economics Ltd, October 2018

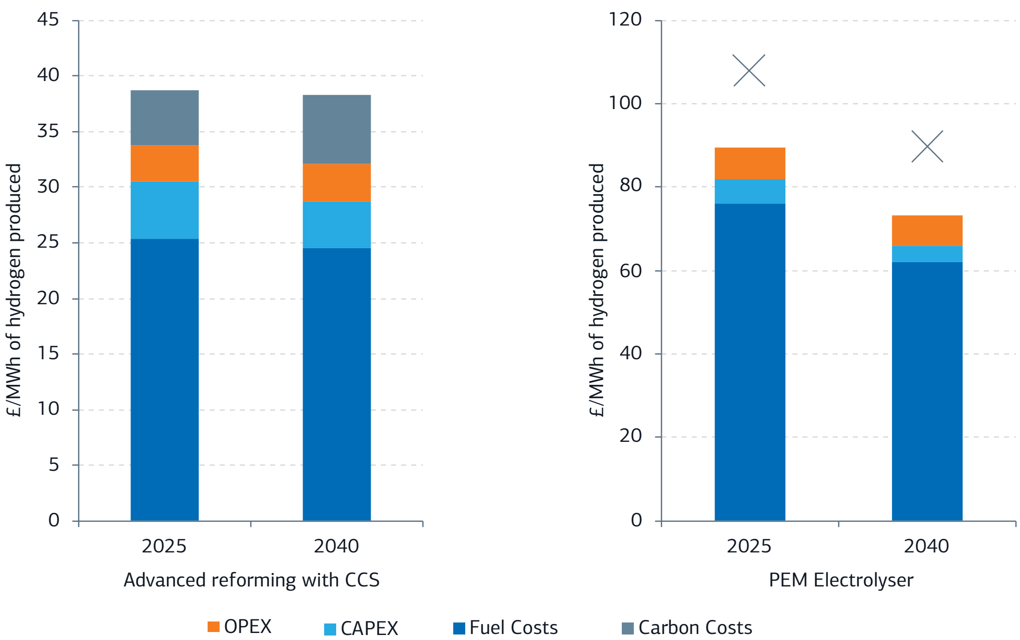
Figure 14 Projected changes in CAPEX for various types of electrolysers



Sources: NOW GmbH, Fraunhofer Institute, 2018[51]

This is assuming that by 2040 in the conditions of the UK, for example, steam methane reforming with CCS will still be more affordable at the reduced cost of hydrogen than electrolysis from renewables (Fig.15) - although there is quite a high degree of uncertainty within both estimates regarding the future efficiency of technologies, the cost of CO_2, fuel and electricity, the load factor of electrolysers, etc.

Figure 15 Present value of "blue" (left) and "green" (right) hydrogen for the conditions of the UK



Источник: UK Committee on Climate Change[53]

51 Hydrogen in a low-carbon economy / UK Committee on Climate Change, November 2018.

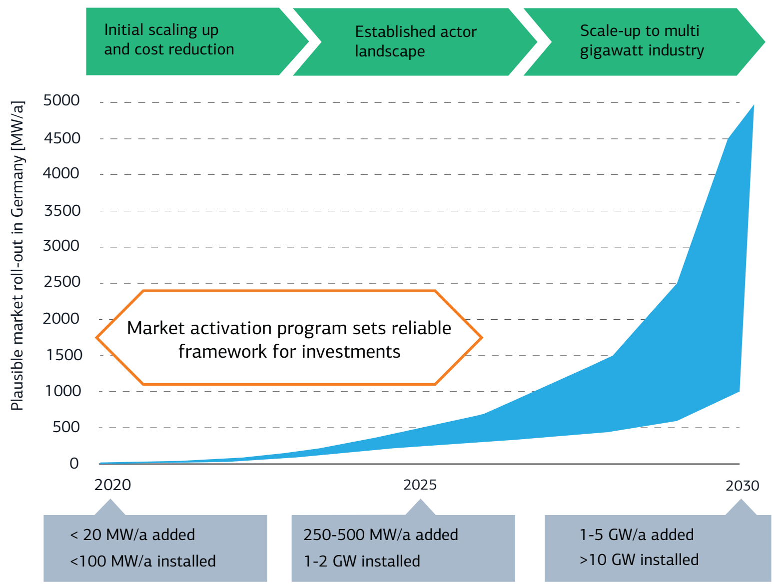
52 1 MWh = 30 kg hydrogen, 1 GBP = 1,13 EUR

53 Hydrogen in a low-carbon economy / UK Committee on Climate Change, November 2018.

According to the IEA, it is possible to create efficient hybrid systems based on electrolysers, solar and wind power plants in remote coastal areas. These would be able to produce "green" hydrogen at a price acceptable for export. For example, in Australia, it is possible to produce hydrogen with a total energy value of about 100 million toe (around 3% of the current global market) in areas within 50 km of the coastline, with the exception of deserts (as water is necessary for the process of electrolysis). The assessment was made based on electricity prices of 47 US Dollars/ MWh and the load factor of electrolysers of around 30–40%. The cost of hydrogen in this case could be under 3 US Dollars / kg, which is close to the price of steam methane reforming with CCS[54].

Accelerated development of the market for electrolysers and a reduction in renewable energy prices will help reduce the cost price of hydrogen. According to NOW GmbH, the electrolysis cells market (not only in Germany but also globally) is in a very early phase of development: annual production volumes are not sufficient for fast movement along the "learning curve" - there are few suppliers of parts, a small degree of automation, etc. The market will be able to achieve full-scale commercialization if it reaches gigawatt scale - that is, grows 500 to 1000 fold (Fig. 16). In a study by NOW GmbH, measures to stimulate demand for electrolysers are seen as much more important than investment in R&D and demonstration projects.

Figure 16. Growth rates of the electrolyser markets necessary for the industry to reach commercialisation



Sources: NOW GmbH, Fraunhofer Institute, 2018[55]

Therefore, "blue" and "green" hydrogen can complement each other: in the period up to 2040–2050 (when their prices will equalise on average across the world), "blue" hydrogen could become an effective "bridge" for the development of other elements of the technological chain.

54 IEA. World Energy Outlook 2018.

55 Hydrogen in a low-carbon economy / UK Committee on Climate Change, November 2018.

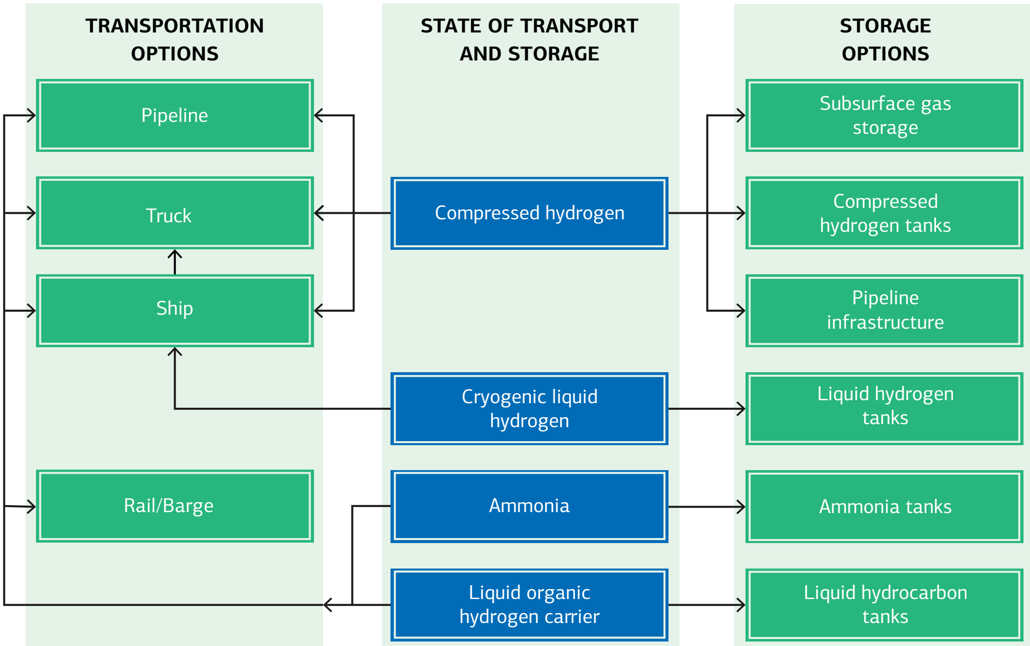
Steam methane reforming and electrolysis are the basic technologies around which, according to most researchers, hydrogen production sector will develop. Other methods include plasma reforming; reforming using ionic membranes; sorption-enhanced steam methane reforming; microchannel reactors[56]; decomposition (pyrolysis) of methane with the release of solid carbon[57]; high temperature gas cooled nuclear reactors, etc. These technologies are still in the earlier stages of commercialization.

Hydrogen transportation: tankers vs. pipes

Hydrogen has been transported for decades - for the current scale of the hydrogen market, these technologies are well developed and will certainly find their application in the future. At the same time, with the market growing multifold, there will be a call for new solutions - working with large volumes of hydrogen and long distances (including on an intercontinental scale).

In any case, the main feature of hydrogen transportation is the variety of its methods (Fig. 17), each of which has its own aspects in terms of energy consumption, safety and ease of use. It is possible to choose the optimum technologies from this set of criteria for any particular case and within each specific project, guided by the criterion of minimum costs for the entire logistics chain.

Figure 17 Possible means of transporting hydroge



Source: DNV GL[58]

56 Introduction to hydrogen production / R.Navarro, R. Guil, J.Fierro // Compendium of Hydrogen Energy. Volume 1: Hydrogen Production and Purification. Ed. by V. Subramani, A. Basile and T. N. Veziroglu. - Woodhead Publishing, 2015.

57 A group of researchers at the Karlsruhe Institute of Technology (KIT) и Institute of Advanced Sustainability Studies (IASS) are conducting methane pyrolysis tests, using a laboratory testing unit https://www.iass-potsdam.de/en/news/zero-emission-hydrogen-production-natural-gas-german-gas-industry-awards-prize-researchers

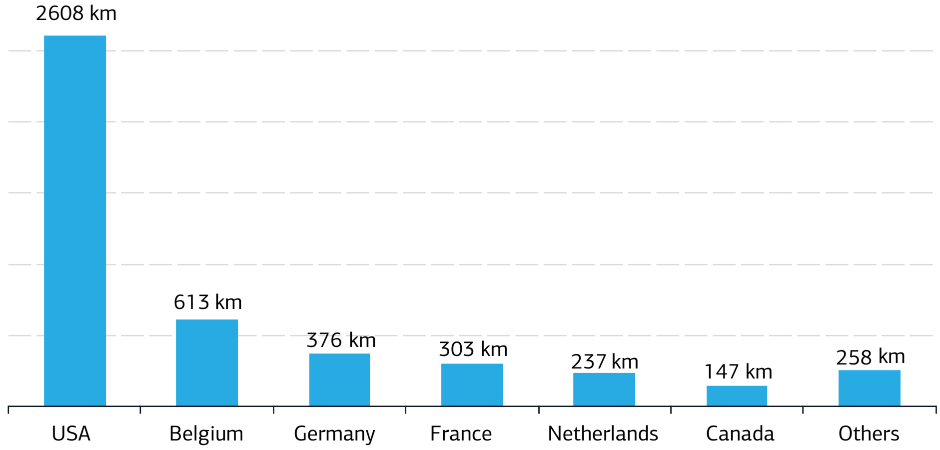
58 Hydrogen as an energy carrier. An evaluation of emerging hydrogen value chains / DNV GL, 2018.

Onshore transportation of hydrogen in compressed and liquefied form (road, rail and pipeline) has been a proven technology for decades, which is fundamental today and will remain so in the medium term.

For example, a standard **hydrogen tube trailer** transports a set of tubular tanks with a total capacity of about 20-25 m^3 of compressed hydrogen (pressure of 25 MPa), or around 0.5 - 1 tonnes. Tankers with a payload of up to 4 tonnes of hydrogen and capacity of up to 50 m^3 are used to carry shipments in a liquefied form. This is especially profitable for long distance transportation (up to 4,000 kilometres)[59]. In the future this direction could be developed further with a transition from steel to composite materials (which reduces the mass of the "container/tank" and eliminates the corresponding logistical constraints), an increase in pressure, etc.

Pipelines are suitable for transporting large and more consistent hydrogen volumes, although they require significant investment. As of 2016, there were over 4.5 thousand kilometres of hydrogen pipelines in the world - mainly in the US and in four European countries (Fig. 18).

Figure 18 Hydrogen pipelines in the world in 2016



Source: Shell[60]

It is not necessary to set up a specific pipeline system for hydrogen - it is possible to use the one for natural gas by blending hydrogen with gas up to a certain threshold. For many countries in Europe and the US, this technology is just "the well forgotten old" - in fact, from the 19th to the mid-20th century, many cities used to have a gas supply system for "city gas" (artificially produced from coal). Hydrogen content in such gas is usually around 50%.

Different countries allow different proportions of mixing hydrogen into natural gas, ranging from 0.1% (in Belgium, New Zealand, Great Britain and the US) to 10% in Germany and 12% in the Netherlands[61]. The upper threshold is determined by national technological standards linked to

59 Shell Hydrogen Study. Energy of the future? Sustainable Mobility through Fuel Cells and H_2 / Shell Deutschland Oil GmbH, Wuppertal Institut, 2017.

60 International aspects of a Power-to-X roadmap. A report prepared for the World Energy Council Germany / Frontier Economics Ltd, October 2018

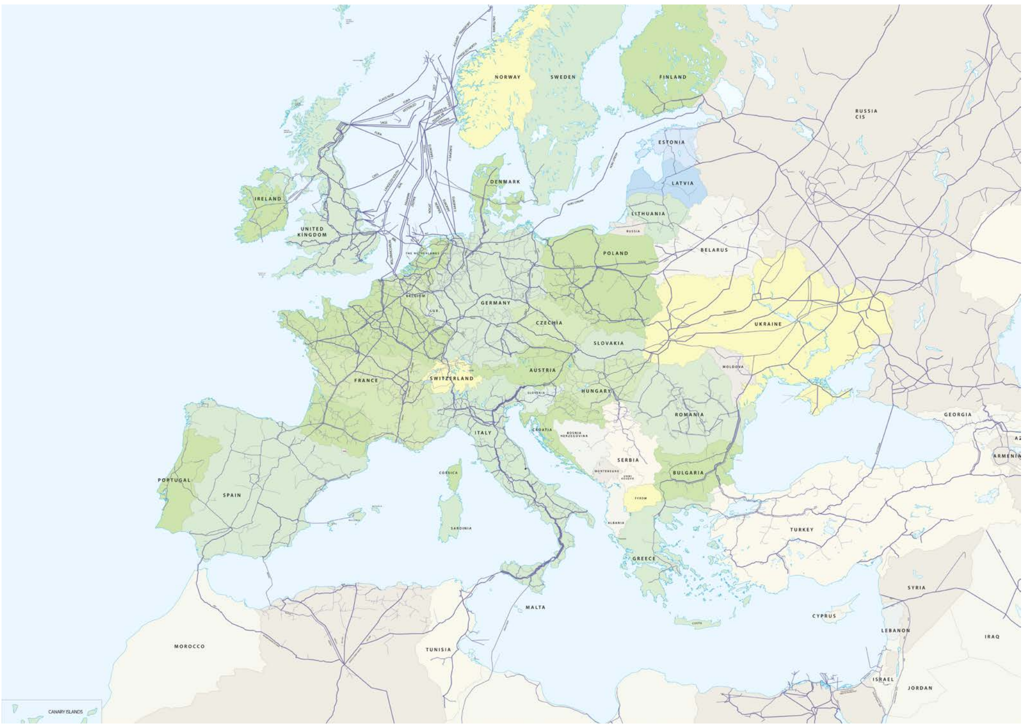
61 IEA. World Energy Outlook 2018.

pipeline safety and fuel (gas) burning equipment. NREL studies[62] show that an upper limit of 15% can be achieved and in some cases exceeded significantly in existing gas transmission systems without any major design changes. According to Gazprom Export, modern gas pipelines of the "Nord Stream" type allow an achievable limit of 70%[63].

The H21 North of England project[64], which is being developed by a local gas company in partnership with Equinor, involves converting transmission networks and equipment on the consumer side of northern England to hydrogen and building new hydrogen pipelines. As a result, 3.7 million homes and businesses will switch to using hydrogen for heating. The total cost of the project is estimated at 28 billion US Dollars - while CO_2 emissions will decrease by 20 million tonnes per year.

For the large-scale European gas transmission system (Fig. 19), blending in 20% of hydrogen, according to IEA, will reduce[65] CO_2 emissions by 60 million tonnes per year (by 7%). At the same time, according to Navigant, setting up hydrogen pipelines stretching from neighbouring regions (for example, from North Africa)[66] may be preferable for Europe at the initial stage.

Figure 19 The existing gas pipeline network in Europe



Source: Frontier Economics[67]

62 Blending Hydrogen into Natural Gas Pipeline Networks: A Review of Key Issues. Technical Report / National Renewable Energy Laboratory, March 2013.

63 Blue Fuel - Gazprom Export Global Newsletter / 2018, Issue 48.

64 H21 North of England Report 2018 / D. Sandler, H. Anderson. – November 2018, 544 p.

65 IEA. World Energy Outlook 2018.

66 Gas for Climate. The optimal role for gas in a net-zero emissions energy system / Navigant Netherlands B.V., reviewed by Kees van der Leun and Prof. Dr. Kornelis Blok. March 2019.

67 International aspects of a Power-to-X roadmap. A report prepared for the World Energy Council Germany / Frontier Economics Ltd, October 2018

Transportation by sea and river is possible for various types of hydrogen - compressed, liquefied and chemically bound. River transport is being used now on a small scale (via auto tankers able to carry compressed hydrogen with the involvement of ferries), but does not play a significant role. Creating a global market for hydrogen as an energy carrier will require other technologies comparable to the liquefied natural gas (LNG) industry - for example, large-capacity tank ships with liquefied hydrogen with total volumes of 150–200 thousand cubic metres, which would use boil-off gas (generated from hydrogen heating) for the ships' engines. The development of such vessels began in the 1980-1990s in Europe and Japan, but complete vessels have yet to be produced. Most likely, the first hydrogen tankers will appear within the above-mentioned Japanese-Australian project Hydrogen Energy Supply Chain or a similar Japanese-Norwegian project. Kawasaki Heavy Industries, which once built the first LNG tanker in Japan[68], is responsible for the supply chains in these projects. A small demonstration tanker is already under evelopment, and large ships are projected to be built in the 2020s.

Transportation of liquefied hydrogen is generally more expensive than LNG transportation, due to the higher cost of ships, energy required for liquefaction and the need to maintain a much lower temperature. Therefore, in addition to liquefaction, two other potential hydrogen carriers are considered within the export projects:

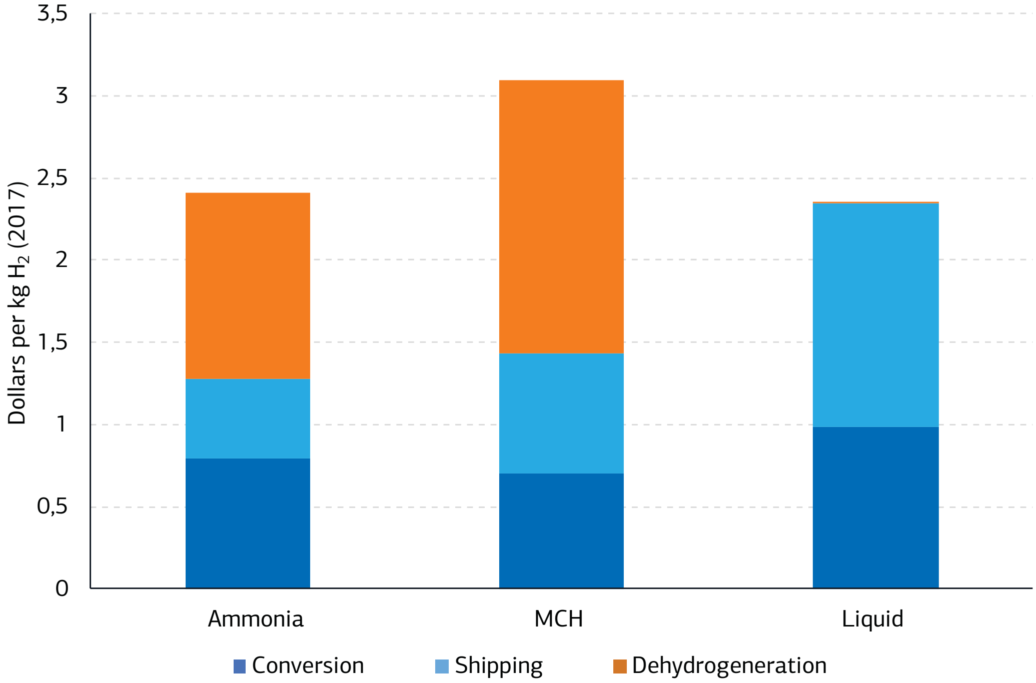
- hydrogen bonding in ammonia - followed by liquefaction and transportation of ammonia. After this ammonia can either be sold as an independent product (the global market of ammonia is valued at 80 billion US Dollars) - or separated into hydrogen and nitrogen;
- hydrogen bonding in hydrocarbons, for example, in methylcyclohexane by hydrogenating toluene[69] - after which methylcyclohexane can be transported in a straightforward manner and hydrogen can be recovered from it.

According to the IEA, the cost of all three methods is not substantially different - in the range of 2.6-2.8 US Dollars / kg for the purposes of the hydrogen export project in Australia in 2040. Within the method of hydrogen production from ammonia, it is possible to reduce the cost to 1.5 US Dollars / kg, if the option of pulling hydrogen from ammonia is foregone.

68 Kawasaki Hydrogen Road / Access mode: https://global.kawasaki.com/en/hydrogen/index.html

69 The chemical reaction of adding hydrogen to organic matter

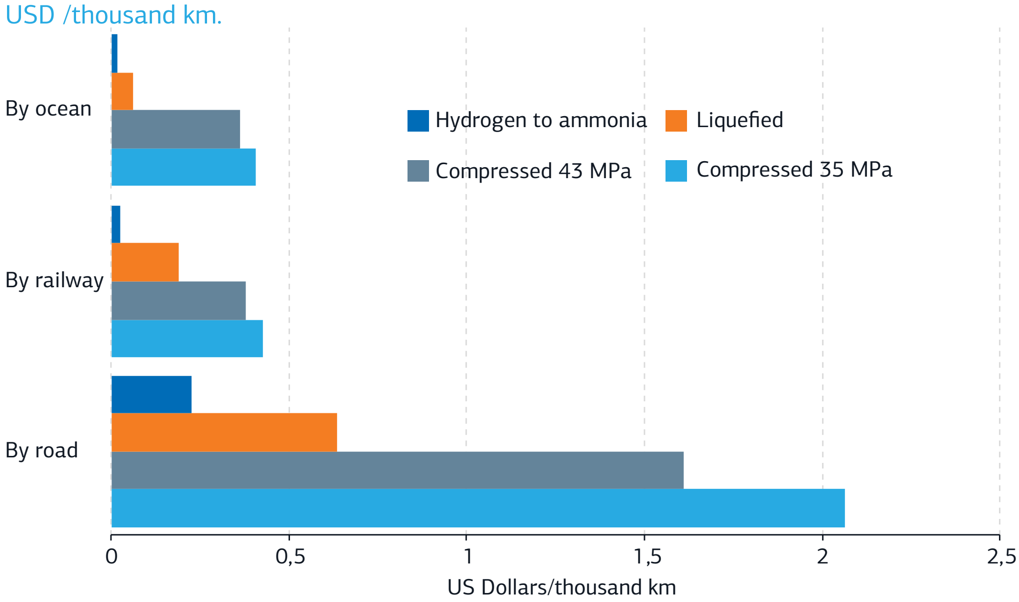
Figure 20 The cost of transporting hydrogen from Australia in 2040



Source: IEA[70]

According to Australian companies, liquefying hydrogen reduces transportation costs 2-5 fold, and converting it to ammonia by up to 20 fold (Fig. 21) compared to the option of compressed hydrogen. In this case, the cost of separating ammonia from hydrogen is not taken into account.

Figure 21 Present value of transporting hydrogen in various ways and forms, USD /thousand km.



Source: ARENA[71]

70 IEA. World Energy Outlook 2018.

71 Opportunities for Australia from Hydrogen Exports, ACIL Allen Consulting for ARENA, August 2018.

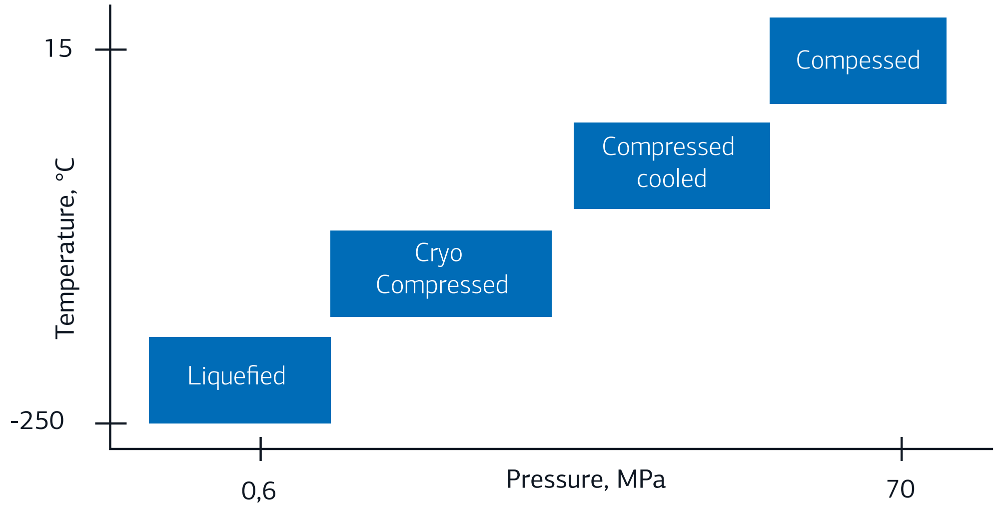
As in the case of hydrogen production, transportation costs will depend on the pace of technological development and cost reduction. Marine transport of hydrogen is still at the very beginning of this journey: the first symbolic shipment of a small amount of hydrogen in a bound form from Australia to Japan took place at the end of April 2019 as part of a joint research project of the universities of Queensland and Tokyo.[72]

Hydrogen storage – from tanks to salt caverns

The possibility of short-term and long-term storage is the basic advantage of hydrogen as an energy carrier over electricity.

Technologies of **physical storage** of hydrogen are already well developed - in a compressed form, in a cooled form, or in a combination of these two. Depending on the type of physical storage (fig. 22), hydrogen pressure in the tank can vary from 0.6 to 70 MPa (nearly 120 - fold), and the temperature can drop from our usual 15-25 °C to almost absolute zero (- 250 °C).

Figure 22 The state of hydrogen during its storage

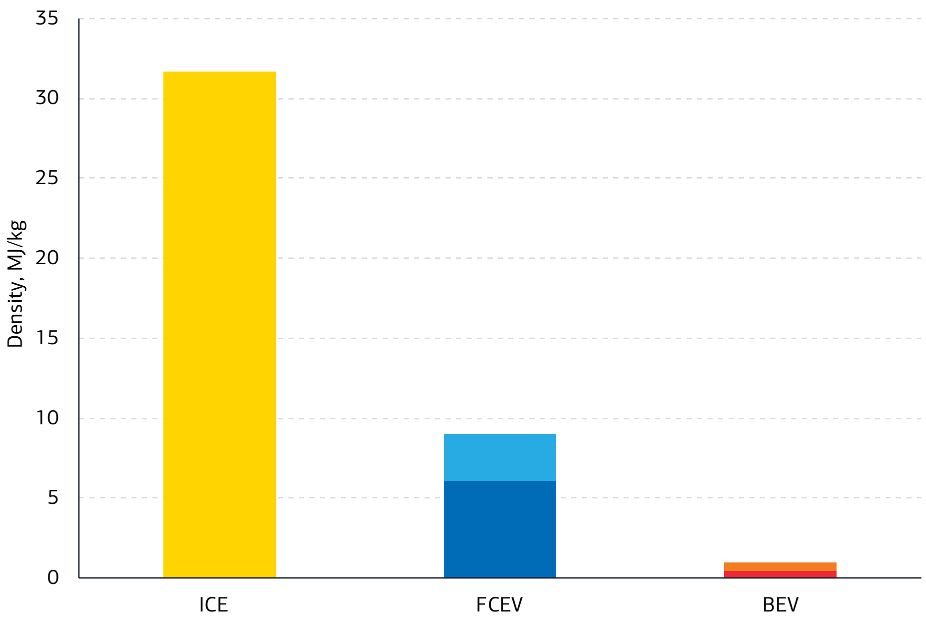


Source: SKOLKOVO Energy Centre

Hydrogen in a **compressed form** is stored, for example, in the tanks of "hydrogen" electric vehicles (fuel cell electric vehicles, FCEV). This is a well - developed technology. The key challenge in this segment is the fact that high pressure in tanks leads to necessary increases in their mass (because of thick metal walls) and their cost. The use of new materials (for example, carbon fiber) is one of possible solutions. As of now, the energy content of a tank with gasoline or kerosene is several times higher than that of the hydrogen system (in terms of fuel and equipment mass) – at the same time, performance of battery electric vehicles is 6 - 8 times below hydrogen-operated ones (Fig. 23)

72 https://www.redlandcitybulletin.com.au/story/5979927/locally-produced-hydrogen-exported-to-japan/

Figure 23 Density of various hydrogen storage systems in transport, MJ/kg



Source: Shell[73]

Compressing hydrogen allows you to store it not only in the tanks of cars, but also on an industrial scale underground - in salt caverns, depleted oil and gas fields, aquifers. Underground natural gas storage has been in place for decades and, although hydrogen underground storage is still at an early stage of development, the technology is already being used at several sites in the US and Europe, primarily in old gas storage facilities. Salt caves are the most promising segment, as their volume reaches from 50-100 to 1000 thousand cubic meters. However, this technology has yet to be mastered, and several pilot projects in Europe are focused on this. One small cavern, for example, is capable of storing hydrogen with total energy capacity of 50 GWh (approximately 5% of annual electricity consumption in Russia).

Storage in **a cooled compressed form** is a relatively new concept for the transportation sector, aimed at reducing the volume of storage tanks and, consequently, reducing their cost. This is achieved by cooling hydrogen to the temperature of liquid nitrogen (about -180 ° C), followed by compression at the station, and then refueling. In the process of refueling electric vehicle tanks, the temperature of hydrogen increases by about 100°C. This technology reduces the mass of storage tanks by up to 50% with a corresponding price reduction, but the total cost of the storage system remains significant due to energy costs.

Even in **a liquefied form**, at a temperature of about - 250 ° C, hydrogen continues to have very "low density": one litre of liquid contains only 71 grams of hydrogen (10 times less than gasoline). For example, a 140-liter hydrogen tank for a BMW passenger car, developed in the 1970s by Linde, contained only up to 12 kg of hydrogen with the total weight of

73 Shell Hydrogen Study. Energy of the future? Sustainable Mobility through Fuel Cells and H_2 / Shell Deutschland Oil GmbH, Wuppertal Institut, 2017.

tank of around 100 kg. The temperature difference with the environment is so great that the loss of hydrogen due to the heating of the container is almost inevitable even with the use of complex multi-layer (including vacuum) insulation — reaching from 0.2 to 3% per day. In addition, liquefaction requires energy consumption of up to 20-30% of the energy intensity of liquefied hydrogen. At the same time, this technology has long been used in astronautics (Fig. 24).

Figure 24 Liquified hydrogen storage, 3200 m^3 in the Kennedy Space Centre, USA

Another direction of hydrogen storage, other than changing its temperature and pressure, is based **on the use of materials (materials-based)**. These technologies are still in the initial stage of development - achieved storage density, time of "charging / discharging" and the total cost of these storage methods are not yet sufficient to compete with physical methods. Among these methods, we can differentiate hydride compounds (for example, metal hydride materials - interstitial hydrogen compounds with metals in which the metal absorbs hydrogen up to 900 times its own volume), as well as liquid storage and storage on surfaces.

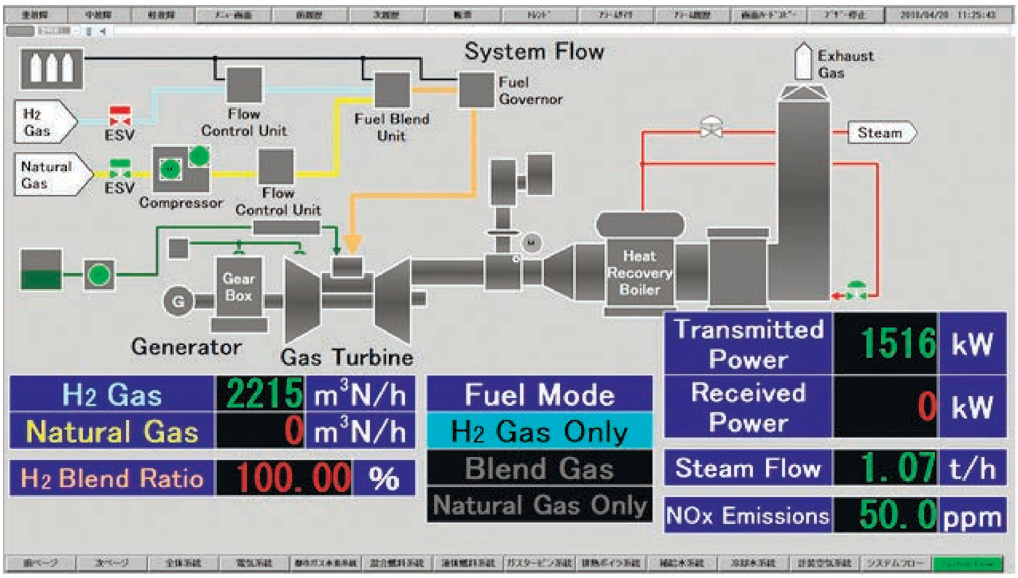
Hydrogen in the energy sector – into every household?

Hydrogen can be used in the same processes as natural gas in power generation — both at powerful gas turbine-fired power plants, and in small boilers or in household mini-power fuel cell generators.

A "hydrogen" gas turbine is a key technology critical for the large-scale application of hydrogen energy in gas-fired power generation. According to the IEA, almost 25% of electricity in the world is produced at thermal power plants from natural gas - and in Russia this figure reaches 47%. According to Mitsubishi Hitachi Power Systems (MHPS), one of the world leaders in the gas turbine market, it is possible to increase the proportion of hydrogen up to 20% in its mixture with natural gas without making any significant changes to the design of existing turbines. MHPS is taking part in a pilot project between Nuon / Vattenfall, Statoil and Gasunie to switch the existing 440 MW power unit based on a gas turbine to burning 100% hydrogen by 2025 - this is the Magnum power plant in Groningen (Netherlands). This project will require advanced infrastructure development - Statoil is responsible for producing "blue" hydrogen, while Gasunie is in charge of transporting it to the station.

Another Japanese company, Kawasaki, in April 2018 brought the share of hydrogen in the fuel mix of a gas turbine power station in Kobe to 100% during testing (Fig. 25).

Figure 25 A screenshot of a control management system workflow at the first hydrogen gas turbine in the world during its testing, April 2018 (Kobe, Japan)



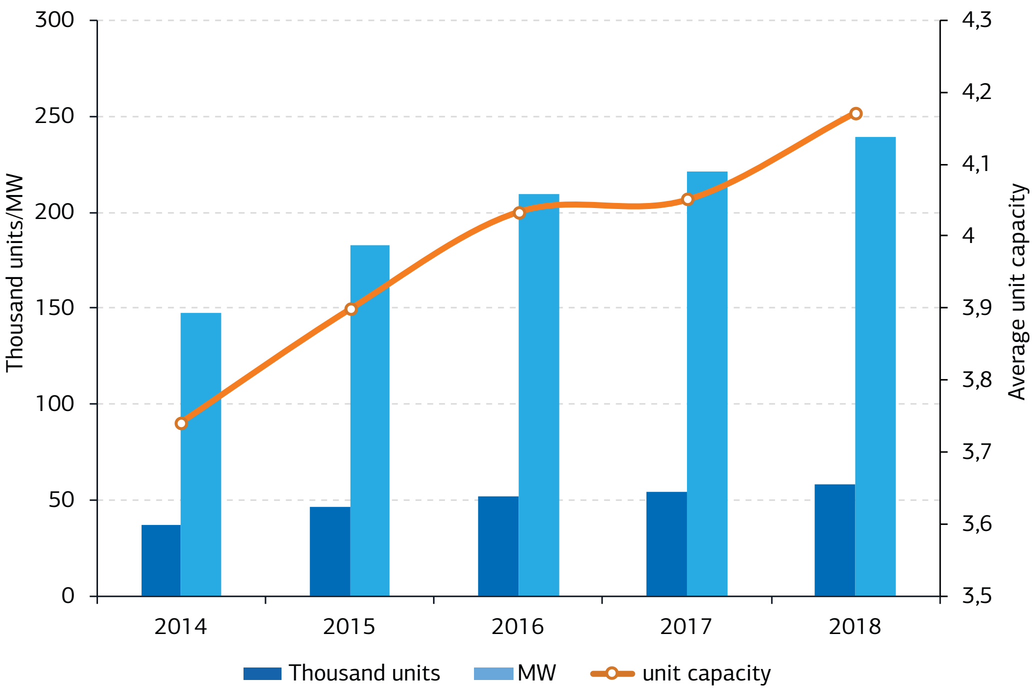
Source: Kawasaki

Fuel cell mini-power plants (fuel cell CHPs) are fundamentally different from thermal power plants in that they convert chemical energy directly into electrical energy (the reverse electrolysis process). Therefore the need for turbines disappears altogether, and the efficiency of this conversion already exceeds 50-65 % (that is, it is at the same level or slightly higher than that of the most powerful thermal power plants operating on natural gas). Such plants are environmentally friendly (unlike gas turbines, which, even when burning 100% hydrogen, pollute the atmosphere with nitrogen oxides), noise-free and also produce heat. They are also called "co-generation power plants" and can be used in households on a mass scale. In addition, they are compact: such a power unit is similar to a fridge in size.

Solid oxide (Solid Oxide Fuel Cell, SOFC) and phosphoric acid (Phosphoric Acid Fuel Cell, PAFC) fuel cells (FC) play a major role in the market of powerful electrochemical energy sources. They can serve as the basis for creating power plants with a capacity of several kilowatts to dozens of megawatts, using not only pure hydrogen, but also natural gas, bio-gas and synthetic gas. Flexibility in terms of fuel allows to spread in time the implementation of FC in households and the development of hydrogen infrastructure - this, in particular, is specified in the Japanese hydrogen program. Fuel cells with a proton exchange membrane (Proton-Exchange Membrane Fuel Cell, PEMFC), molten carbonate (Molten Carbonate Fuel Cell, MCFC) and other FC are also among promising technologies.

The market of stationary fuel cells is on the rise (Fig. 26) , shipments are growing, although not as fast as in the transportation segment, where fuel cells are used in hydrogen electric vehicles. In 2016, Navigant Research predicted[74] the growth of the market for stationary fuel cells to 1 GW annually in the period up to 2020, but it is highly likely that this forecast will not be fully met.

Figure 26 Annual shipments of stationary fuel cells in the world



Source: SKOLKOVO Energy Centre, based on E4Tech[75] data

Japan is in the front-runner in terms of stationary FC technology. In 2018 50,000 household power units based on stationary FC were installed within the Ene-Farm project alone (by the end of 2018, almost 300,000 units were installed within this project). As part of the Ene-farm project, households receive subsidies for installing FC powered cogeneration power units. In total in 2018 around 70 million US Dollars of such subsidies are allocated for the residential and commercial sectors. This market is also developing in South Korea, the United States and Germany, bolstered by regulatory support measures. BloomEnergy (California, US), founded in 2001 to develop technologies for obtaining oxygen from the atmosphere (as part of the NASA

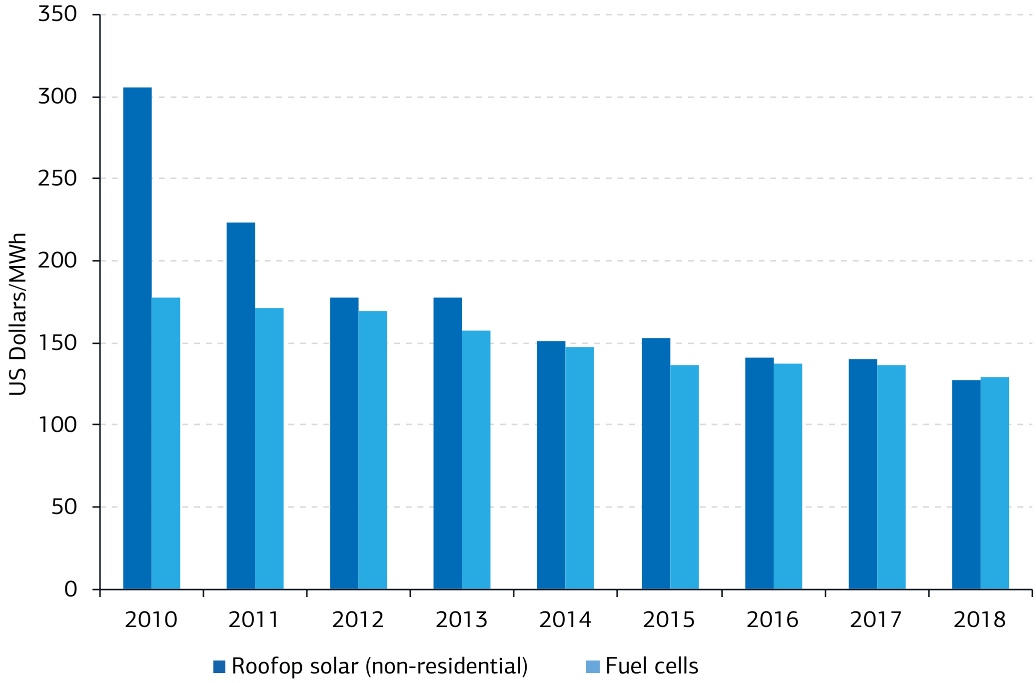
74 Navigant Research. Stationary Fuel Cells / 3Q 2016.

75 E4Tech. The Fuel Cell Industry Review 2018 / December 2018.

Mars Program) entered the New York Stock Exchange in 2018 with 1500 employees and 740 million US Dollars in revenues and has already become a leader in the FC market for households and the commercial sector.

The market for stationary fuel cells is part of a growing global distributed energy resources market[76]. Fuel cells compete with other types of distributed generation in this market — thermal power plants operating on natural gas, diesel fuel, biomass, solar, wind power plants, etc. Fuel cells, like traditional thermal power plants, can adjust the load within a wide range in response to consumer demand for electricity. At the same time, they need regular fuel supplies. They are environmentally friendly and are almost carbon neutral (in the case of operating on hydrogen), similarly to solar and wind power plants. In the end, the cost factor is the decisive one - and here FC are lagging behind renewables: over the past 8 years, renewables have managed to "close" the almost twofold gap in the levelized cost of electricity (LCOE) with the fuel cell (Fig. 27).

Figure 27 Average levelized value of electricity (LCOE) generated from rooftop solar panels and fuel cells in the US, US Dollars / MWh



Source: SKOLKOVO Energy Centre based on Lazard[77] data

The rate at which the stationary fuel cell market is developing is still insufficient for the implementation of ambitious plans, for example, of the Japanese hydrogen programme (1.4 million units of installed fuel cells by 2020, 5.3 million by 2030). So far the annual sales of stationary fuel cells in the world total only slightly over 50 thousand units per year. For comparison, sales of solar mini-power plants only for operation in an off-grid mode reached 25-30 million units per year in 2014-2017.

76 For more details on distributed energy please refer to: Distributed energy in Russia: development potential / SKOLKOVO Energy Centre, etc. // February 2018

77 E4Tech. The Fuel Cell Industry Review 2018 / December 2018.

Hydrogen in transport – in competition with Musk

The application of hydrogen in the transport sector is possible with the use of internal combustion engines (ICE) or turbines, and with the use of fuel cells. Hydrogen buses, cars and ICE operated vans appeared in the middle of last century. However, fuel cells eventually received better distribution globally because of the absence of noise, emissions, and high theoretical efficiency of energy conversion that they offer[78].

Potential for the application of hydrogen energy in transport and possible alternatives are summarized in Table 2.

At this point hydrogen transport is not limited to just pilot projects and prototypes. There is also small-scale production (of passenger cars). Below are some descriptions and specifications of demonstration projects along with manufacturing companies that have already presented their products to the market.

In addition to compressed hydrogen and fuel cells, passenger electric cars have a buffer battery in their system. It is used for starting the vehicle in cold weather and supporting peak loads and accelerations. The output power of serial models is 70-130 kW, maximum speed is 160 km / h (limited by the motor controller system), hydrogen consumption is 0.76-1 kg H_2 / 100km, hydrogen under pressure is 700 bar, the range is 385-750 km. At the moment, Honda Clarity holds the record for its estimated maximum travelling range of 750 km on one charge and is in mass production. In March 2019, a prototype of a fuel cell electric vehicle with a range of 1000 km was presented in China, and the vehicle is being prepared for mass production.

For comparison, the "longest-range" model of the battery electric vehicle (BEV) Tesla, according to the company, can travel up to 590 km[79] on a single charge.

The most common models on the market cost as follows: Honda Clarity - 51000 Euros, Toyota Mirai - 78600 Euros, Hyundai ix35 Fuel Cell - 65400 Euros. Audi, BMW, Daimler, Ford, GM, Mercedes-Benz are also on the list of manufacturers of such cars. Potential users include private owners, taxi services, car rentals and car sharing companies. Nevertheless, for further development of the industry, it is necessary to develop infrastructure and further reduce costs, requiring significant investments from both private companies and the state.

78 Energy of the future? Sustainable mobility through Fuel Cells and H_2. Shell Hydrogen Study. Hamburg, 2017

79 https://www.tesla.com/models

Table 2. Hydrogen use for various types of transport

Type of transport	Supply in the market	Objectives	Advantages	Disadvantages	Alternatives	Technical readiness ***
Motor transport	prototypes	Low purchase and maintenance costs, ease of storage, travelling range	Noise and emission – free, a long travelling range	High costs, infrastructure	ICE vehicles, hydrogen fuel cell (HFC) vehicles	2-3
Cars	Proven technology, small scale production	Maintenance, travelling range and performance comparable to ICE, a large number of filling stations	Noise and emission – free, travelling range comparable to ICE	High costs, infrastructure	ICE vehicles, electric vehicles (EV)	4
Carsharing/taxi	Pilot projects *	Maintenance, travelling range and performance comparable to ICE, inter-city filling stations	Noise and emission – free, government and city subsidies, company image	A high purchase price and underdeveloped service mechanisms	ICE vehicles, electric vehicles (EV)	2-3
Small cargo transportation	Primarily in the US (50) and Germany, prototypes	Hydrogen storage which save space, reliable in exploitation, decreasing costs	High performance, noise- and emission-free	A smaller travelling range compared to ICE, high costs	Diesel transport, fuel cells	2-3
Buses	Proven and tested technology (Europe, North America, Asia)	Reliable use with a short filling time, absence of restrictions on weight and number of people for public transport	300-450 km travelling range, no need for city infrastructure	The travelling range is still insufficient for inter-city transfers	Buses operating on diesel, gas, fuel cells	3-4
Commercial freight trucks	Over 11 thousand vehicles** (North America), demonstration projects in Europe and Japan	Filling stations for large volumes, long usage time within several shifts	High performance and efficiency, emission-free	Small tonnage, sometimes has to be increased additionally	Fuel cells (inside), gas, petrol, diesel (outside)	4-5
Railway transport	Pilot projects	Necessary and reliable hydrogen production	The absence of electricity transmission lines and railway lines; noise-free	need a lot of space for fuel, high cost	Diesel, hybrid, electric trains	2-3
Marine transport	the use of fuel cells to generate electricity on board, pilots for small ships	Emission and pollution-free, affordable system and fuel costs	High efficiency, emission and pollution-free	High cost of systems and fuel	Diesel, gas turbines	1-2
Aviation	the use of fuel cells to generate electricity on board, first small capacity airships	Reliability, a compact size, light weight	An effective energy converter, multi-functional	High volumes of fuel storage, high cost	Aviation fuel	1-2
Space	A technology established in the 1950-60s, high reliability, a small part of commercial flights	Reliability, high performance	The technology has been used for a long time, reliability, high performance	A need for cooling systems, high volumes of fuel storage, pumps	Rocket fuel	5

* HYPE taxi project in France, 600 cars by 2020
** loading machines
*** 1-2 – prototypes are tested in an appropriate environment
3 – the prototype is used
4 – the product and the final system have proven the functional possibility of utilisation
5 – the products and the final system are used in the environmen

According to the Hydrogen Council, the almost two-fold gap in the cost of ownership of FCEV compared to owning an internal combustion engine car can be reduced to 10% between 2025 and 2030. Such a significant drop in cost (80%) can be achieved with economies of scale - both in car manufacturing and in the filling station infrastructure. Other researchers make similar assessments[80]. Since hydrogen electric cars are at the beginning of the "learning curve", one can expect that their market will grow at a rate similar to the battery electric car market

80 Low-carbon cars in Europe: A socioeconomic assessment / Cambridge Econometrics, July 2018.

- where the number of electric cars on the roads increased from 12 thousand to 5 million in 8 years from 2010 to 2018 (for comparison, in 2018 there were around 11 thousand FCEV on the roads in the world).

Figure 28 Examples of hydrogen powered cars

Sources: websites of car manufacturers - Toyota, Hyundai, Honda, Mercedes-Benz

A number of countries have stated their intention to develop fleets of hydrogen electric vehicles up to 1 million by 2030 - in total, these plans approach the level of 4.6 million (Table 3). This is still a small indicator given the existing fleet of ICE vehicles (over 1 billion), but it is comparable to the number of electric vehicles in 2018 (about 5 million).

Table 3. National goals for the use of hydrogen filling stations, thousand units

	2020	2022	2023	2025	2028	2030
US	13	40				
California						1 000
Japan	40			200		800
France		5			20 – 50	
China	5			50		1 000
The Netherlands	2					
Korea			81			1 800

Источник: IEA[81]

Buses are an important example of the application of hydrogen energy in public transport. Standard chassis with an electric motor as a drive system are used to manufacture "hydrogen" buses. Electric power for their operation is produced by fuel cells (the hybrid version the

81 https://www.iea.org/tcep/energyintegration/hydrogen/

bus is also equipped with an electric power storage device). Capacity is over 100 kW, specific hydrogen consumption is 8-14 kg / 100 km. With the efficiency coefficient of 51-58% average travelling distance is 250-450 km. Compressed hydrogen is stored in cylinders with pressure of 350 bar. Existing modifications of hydrogen buses can carry 75-105 people, and the average cost is 625 thousand Euros. The leaders in this market include Daimler EvoBus, Van Hool, VDL, Solaris, Toyota, Writghtbus, Ballard, Hydrogenics, etc.

There are also examples of hydrogen use in **railway transport.** For example, in Germany a diesel-powered train was replaced by a hydrogen one manufactured by Alstom. The output power of this train is 400 kW, the system works in a hybrid with electric batteries. Maximum speed is 140 km / h, hydrogen consumption is 0.25-0.3 kg / km, travelling range is 600-800 km, hydrogen is under the pressure of 350 bar. The capacity of the train is 300 people, of which 150 are seated. The cost of one train is around 5.1-5.6 million Euros, excluding infrastructure. Alstom not only supplies the train and services it, but also installs gas stations and builds infrastructure jointly with the company which places the order. In the near future potential users of this service can include government agencies, regional railway service providers, and railway companies (private and public).

The category of **small freight transport**, including garbage trucks, light delivery trucks, forklifts, etc., is a promising area for the application of hydrogen energy. Capacity can vary from 2.5 - 4.5 kW for loaders, up to 30 - 80 kW for trucks and garbage trucks. Light-duty trucks can reach speeds of 100-130 km / h and have the travelling range of 200-300 km. Average duration of operation in case of powerful loaders is 8 hours. CAT, Linde, Renault / Symbio Fcell, E-Trucks Europe, FAUN Kirchoff, ULEMCo and other companies operate in this market. Customers include logistics and warehousing companies, municipal services, delivery services and postal services.

Scooters (mopeds) on hydrogen fuel can reach speeds of 50-70 km / h, maximum range is 350 km at an average speed of 30 km / h. Output power 3-4 kW, fuel cell efficiency of 53% (at a nominal power of 3.9 kW). APFCT and Suzuki operate in this market. Customers include both private users and city services. The average cost of such a scooter is 3,100 Euros.

Hydrogen **bikes** use fuel cells, compressed hydrogen and an electric motor to assist pedaling. Their speed is about 25-35 km / h, the range is over 100 km, output power is 0.1 - 0.25 kW, and hydrogen is under pressure of 200-350 bar. Such bikes weigh 24-35 kg. The market is led by Linde, Gernweit, Clean Air mobility, Pragma Industries, Atawey (infrastructure).

Buyers include both private users and delivery services, bicycle rental services in the city.

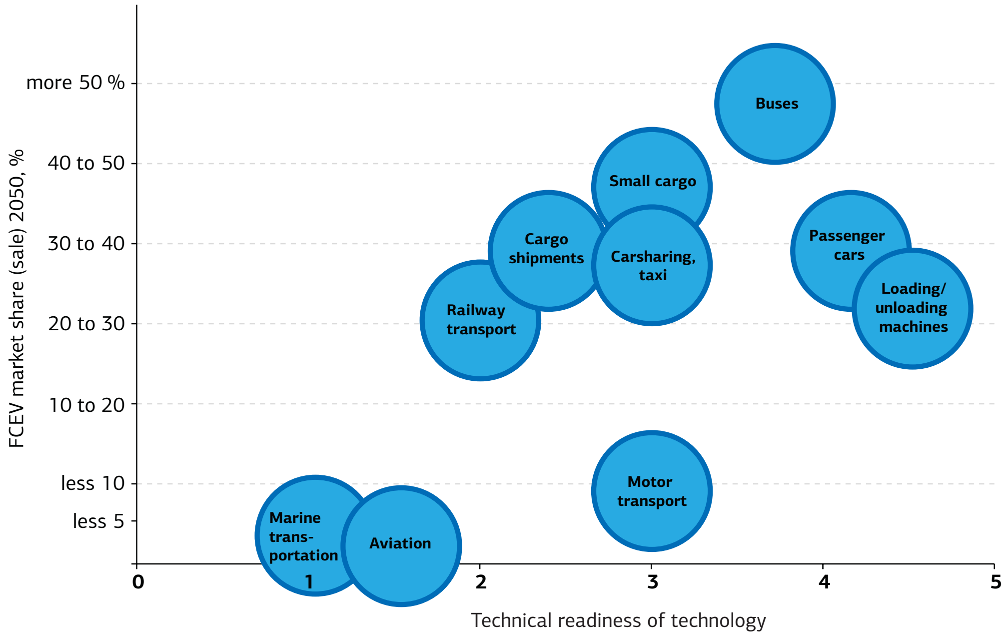
Developed concepts and pilot projects also exist in **freight transport** for use in regional logistics and delivery projects. In this segment, the retail sector stands out, for example, grocery delivery to stores, as transport often moves along the same route within a region / city. Output power of freight transport is currently 250-750 kW, hydrogen consumption is 7.5 - 15.7 kg H_2 / 100 km, travelling range - 320 - 1200 km, hydrogen is under a pressure of 350 bar.

In these configurations, there also exists a battery with capacity from 30 to 320 kWh. This segment is developed by Esoro, Kenworth, Nikola, Navistar, Toyota, Scania / ASKO. Developments are made based on fuel cells produced by PowerCell, Hydrogenics, Ballard, US Hybrid, Toyota, NuCellSys.

Other transportation sector segments include construction, cleaning equipment, light aircraft, boats, small ships, ferries, and others. These are also developing, although to a lesser extent.

Comparing forecasts of market share development by 2050 and current technical readiness (Fig. 29), we can see that even now there is a good potential for growth in relation to small trucks, cars and loading equipment.

Figure 29 Projected market share of hydrogen transport depending on the technical readiness of its segments



Source: an analysis by A. Glagoleva (Skoltech) based on the Hydrogen Council и Shell's data

Filling stations are the basic infrastructure for hydrogen transport, without which it will not develop. In this sense, the situation is similar to electric transport - the only difference is that it is easier to place electric charging stations in public places; however, charging time can vary tenfold (hydrogen electric cars refuel within a few minutes, while battery operated ones can take from 1-2 hours using ultrafast charges, of which there are few, to several hours on fast ones). As of 2019, there are more than 300 filling stations in the world and 5 thousand units of hydrogen powered vehicles, primarily in the United States, Western Europe, and Japan. By 2030, there are plans to increase the number of charging stations several-fold (Table 4). The approximate cost of a filling station is around 1 million US Dollars.[82]

Table 4. National goals for the use of hydrogen fuel cell vehicles, units.

	2020	2022	2023	2025	2028	2030
US	80	100				
California				200		1 000
Japan	160			320		
France		100			400-1000	
China	100			300		500
The Netherlands	100			400		1000
Korea			310			
Germany			400			

Sources: IEA[83], H_2Mobility[84]

Filling stations include a hydrogen storage system, a cooling facility, a compressor, and a dispensing device for refueling vehicles. The stations are designed to international standards, and the modular structure enables to adapt performance and the size of stations to projected consumption. It is important to observe uniform standards among manufacturers of filling stations and hydrogen transport to ensure their compatibility.

As in other segments of the hydrogen technology market, the role of practical international cooperation is important in the transportation sector. For example, the JIVE 2017 project (Joint Initiative for Hydrogen Vehicles Across Europe) involves introduction of more than 140 buses in 9 selected locations in Europe and is sponsored by the European Union in the amount of 106 million Euros. The project solves the problem of "chicken or egg" for the selected region - filling infrastructure or vehicles. In 2015, a similar project (3EMOTION) for manufacturing 21 new buses received funding of 41 million Euros, while demonstration projects (HIGH V.LO-CITY) - were allocated 29.2 million Euros in 2012. General Motors and Honda are working jointly to reduce the cost of vehicles and infrastructure.

82 Hydrogen: the next wave for electric vehicles? McKinsey & Company. November 2017.

83 https://www.iea.org/tcep/energyintegration/hydrogen/

84 CEP 2019 https://cleanenergypartnership.de

Hydrogen fuel cell transport is growing and developing most in Germany, the US (California), South Korea and Japan. In each of these countries, there are various programmes supporting the development of hydrogen transport, sponsored both by the governments and industry consortia. These programmes include H_2 Mobility in Germany, H2US and CaFCP in the US and HySUT in Japan. Support for research and development, technology deployment and infrastructure development is essential for the development of hydrogen transport. It is also necessary to quickly achieve the ability of hydrogen transport to compete in value with hydrocarbon-fueled vehicles and battery electric vehicles.

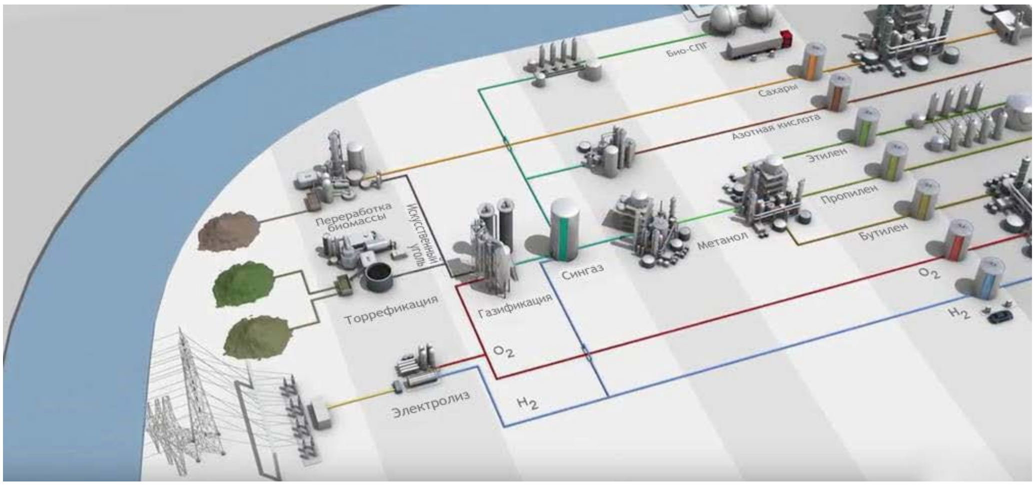
Hydrogen in industry – the new oil and coal

The chemical industry and metallurgy have used coal, oil and gas in technological processes for decades - both as a source of energy and as chemical raw materials. The possibilities of electrification in this sector of the economy are limited - it is as impossible to completely "electrify" the blast furnace and coke oven as it is to produce ethylene from electricity. It is necessary to deploy fundamentally new technological processes which would use "green" or "blue" hydrogen and carbon produced from biomass among other resources. In this case, it would be possible to achieve deep decarbonisation of the industry.

Hydrogen is becoming the basis for the production of synthetic gases that can be used as raw materials in the chemical industry - within the overall concept of power-to-X conversion: power-to-ammonia, power-to-chemicals and power-to-methane.

For example, the Chemport Europe project in the north of the Netherlands is being implemented with the goal of creating a fully-fledged gas-chemical cluster operating exclusively on local bio-resources and renewable energy with zero carbon footprint by 2050. The vision for this project is represented below (Fig. 30):

Figure 30. Vision for the Chemport Europe project (the Netherlands)



Source: Chemport Europe

- woody biomass is processed, carbohydrates obtained in the process are used as feedstock for a diverse range of chemicals;
- electricity from offshore wind power plants is converted by electrolysers into hydrogen and oxygen;
- oxygen and hydrogen are used in chemistry (hydrogen is used to produce green methanol), while oxygen acts as a gasifying agent in the gasification of recycled biomass from local fields of over one million hectares in size;
- gasification of biomass produces synthetic gas - a pure mixture of hydrogen, CO_2 and CO. “Green” hydrogen from electrolysers is also added;
- nitric acid, methanol, ethylene, propylene, butylene are the substances that could completely displace oil and natural gas from their stable positions as feedstock for the chemical industry;
- Syngas can be sent for liquefaction (bio-LNG) and used to refill cars and for other classic needs.

The project initiators would like to bring the cost of syngas to the cost of natural gas. Initial project investment is 50 million Euros, of which 15 million Euros is provided by EU grants.

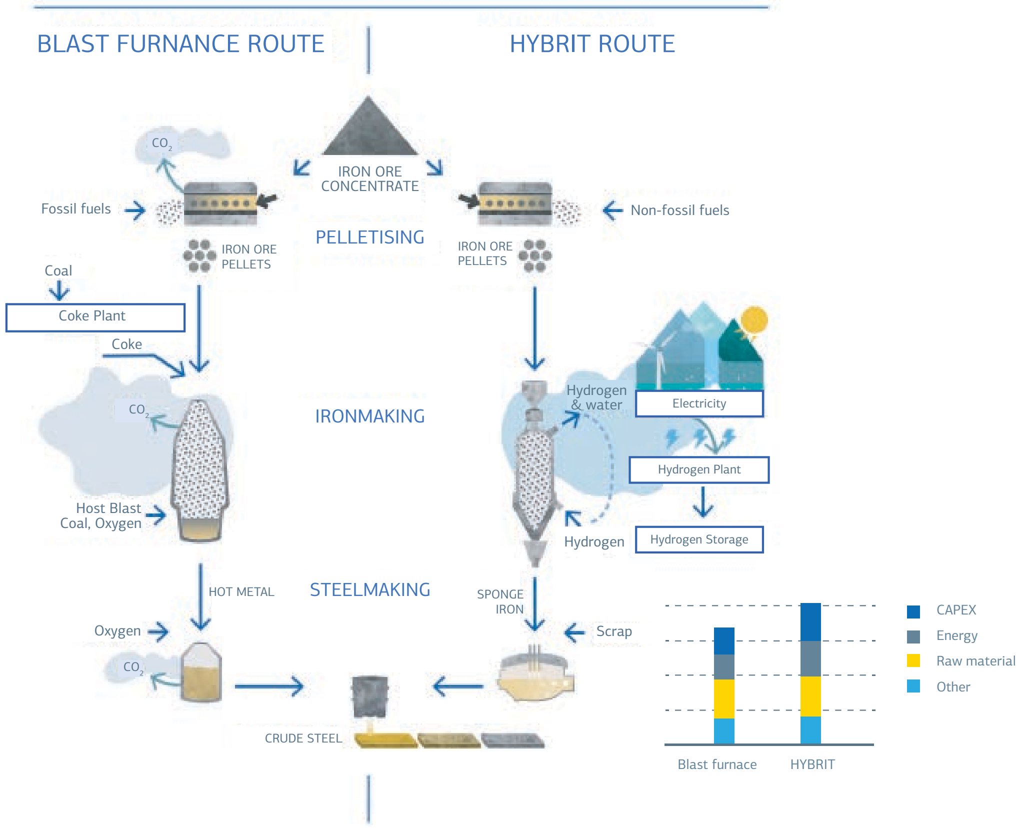
Within this large concept, companies are starting to develop individual projects. In February 2019, the chemical company Nouryon and Gasuine started considering a project for the production of "green" hydrogen (3,000 tonnes per year) for the chemical cluster in Delfzijl - for biomethanol production. Investment decision on the project is expected in 2019[85].

Decarbonization in metallurgy is associated with a transition to direct reduction of iron ore (with the abandonment of coke-chemical and blast-furnace processes that consume coal and natural gas). The HYBRIT project in Sweden focuses on this, and hydrogen will play a key role in the new process (Fig. 31). In 2018, construction of a pilot site began in Luleå, and the project’s goal is to commercialize the technology by 2035.

The cost of steel using a technology based on the results of a feasibility study is still 20-30% higher than with traditional technology - although much will be determined by the movement of coke, electricity and CO_2 prices.

85 https://www.chemport.eu/news/article/green-hydrogen-as-feedstock/

Figure 31 HYBRIT project in Sweden: the technological chain and a comparison of the cost structure of steel production compared to the conventional method



Source: HYBRIT[86]

Safety and technical regulation

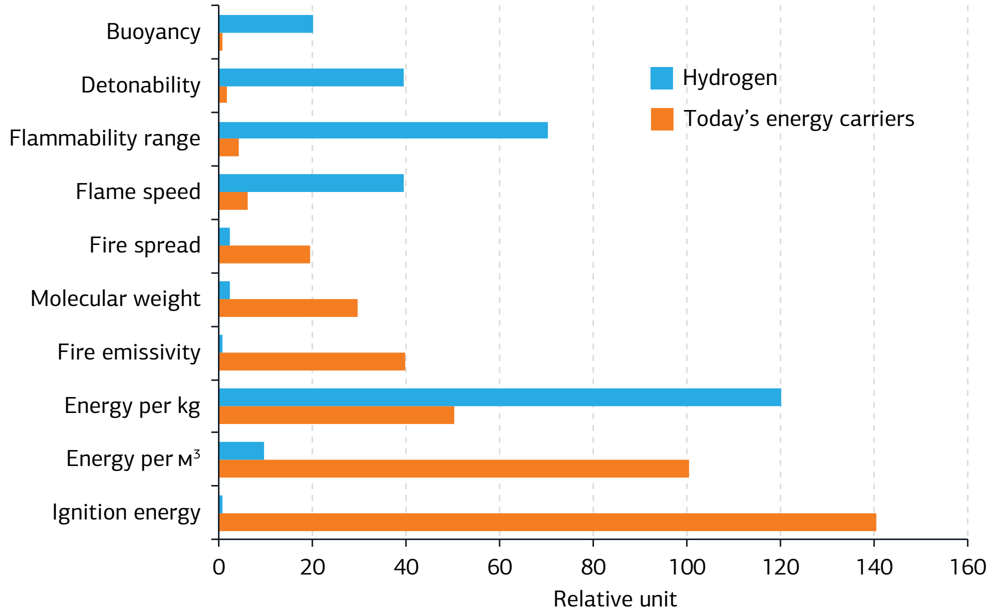
The safety of hydrogen technologies has been an important subject of debate for decades. In the public arena, it is customary to recall the Hindenburg airship crash in 1937 or even the Chernobyl nuclear power plant catastrophe in 1986. Over 80 years have passed since the first accident, there are hundreds of hydrogen buses operating, hydrogen fueling stations are located in the immediate vicinity of residential buildings. The Chernobyl reactor may have been destroyed by an explosion of a mixture of hydrogen and oxygen — but this mixture formed as a result of a whole chain of erroneous actions by the plant personnel and, probably, the design features of the reactor — so it is hardly possible to "blame" hydrogen for this catastrophe as well.

Hydrogen has been used in industry for decades - perhaps it is a new energy source, but certainly not a new gas. Its properties have been well studied for a long time - they differ significantly from those methane, propane, and gasoline (Fig. 32).

Hydrogen is a less hazardous energy carrier in terms of fire safety and thermal effects, but may be responsible for the more significant effects associated with changes in pressure.

86 HYBRIT: fossil-free steel. Summary of findings from HYBRIT Pre-Feasibility Study 2016–2017.

Figure 32 Safety characteristics of hydrogen in a qualitative comparison with current energy carriers



Source: John H.S. Lee, McGill University[87]

Hydrogen differs from hydrocarbons in the following ways:

- wider limits of detonability and flammability;
- low ignition and detonation energy values;
- a colorless flame;
- fast dispersion, diffusivity.

The answer to these challenges is clearly the use of appropriate technologies:

- Hydrogen is explosive only in a mixture with air in certain conditions (especially in enclosed spaces)- unlike, for example, acetylene which is explosive without air. A tank of compressed hydrogen is no more dangerous than a tank with gasoline or kerosene — in fact, it is more difficult to restrict air access to the latter (this caused TWA800 flight crash in 1996, killing 230 people);
- The flame from the combustion of hydrogen is often invisible, but special sensors are already being used to detect it;
- Hydrogen embrittlement due to the absorption of hydrogen atoms or molecules by the metal can indeed occur, especially in areas of plastic deformation of metals (dents, cracks). Therefore, it is important to correctly select structural materials able to withstand the load. In addition, composites are generally not susceptible to embrittlement;

87 John H.S. Lee. The Detonation Phenomenon / Cambridge University Press, 2008. – 402 p.

- Hydrogen is an all-pervasive gas, and can "leak” through any material with time. However, this does not mean that it cannot be stored: leaks through storage valves have no practical significance, etc.

Safety of hydrogen technologies is an important component of national hydrogen programmes. For example, there is an initiative of the European Hydrogen Safety Panel in the framework of the European FCH JU programme. The global nature of the hydrogen economy of the future requires increased international cooperation - including the harmonization of national standards across the entire process chain with the active participation of suppliers of hydrogen, equipment for its production, storage, transportation, hydrogen users, independent experts, product safety regulatory authorities, etc. Therefore, technical regulation has a key role in ensuring the safety of hydrogen technologies. ISO/TC 197[88] is the technical committee responsible for developing international standards on hydrogen energy technologies.

88 https://www.iso.org/committee/54560.html

RUSSIA'S POSITION IN THE GLOBAL HYDROGEN ECONOMY

Incentives

Up until now Russia has, with the exception of a few standalone projects, stood apart from the international communities and partnerships which develop hydrogen technologies. This is the case even though the universities and institutes of the Russian Academy of Sciences have significant relationships with colleagues in many countries.

Firstly, the reason for this is that until now, the climate agenda and decarbonisation have played a minor role in the country's energy strategy. National regulation of greenhouse gas emissions is in its formative stage, the earliest federal acts or presidential decree are expected in 2019–2020, and the national low-carbon development strategy is under development. Among stakeholders, there is predominantly a cautious, conservative attitude both on the whole in relation to the anthropogenic nature of global climate change, and to whether it makes sense for Russia to make serious commitments to reduce greenhouse gas emissions. All this together significantly hinders the development of not just hydrogen, but in general any low-carbon technologies (renewables, energy efficiency, electric transport, etc.)

In Russia, not only is there no national hydrogen programme, but there is not even any apparent coordination of various research groups and interested parties. Nevertheless, there is design work and scientific developments in the fields of production, storage and transportation of hydrogen, as well as its use in mobile transport. In addition, Russia has enormous potential hydrogen production and its export on a global scale. Therefore, hydrogen technologies are being spoken about in a positive way both at the largest Russian forums[89], and in the course of discussing the innovation strategies of the largest Russian companies. This section focuses on the analysis of these aspects.

Technologies and stakeholders

On the **production** side, there are proven technologies for producing "grey" hydrogen in Russia, as well as in the world. They are deployed at oil and gas processing plants (methane conversion) and power plants (electrolysis). All hydrogen produced is used onsite - for example, to improve the quality of hydrocarbon processing or in the cooling systems of power generators. The largest producer of electrolysers, PJSC Uralkhimmash (Yekaterinburg), manufactures units with capacity of 4 to 300 cubic meters of hydrogen per hour.

The largest Russian energy companies, Gazprom and Rosatom, are working on the technologies for producing hydrogen with a minimum carbon footprint by using adiabatic conversion of methane[90] and high-

89 President of Russia Vladimir Putin said during the Russian energy week 2017: "We are certainly thinking of hydrogen projects and we will be implementing (these) in practical terms."

90 O.E. Aksyutin et al. The contribution of the gas industry to the formation of an energy model based on hydrogen. / Vesti gas science - scientific and technical collection. Environmental protection, energy saving and labor protection in the oil and gas complex. Special edition - 2017, p. 12.

temperature nuclear reactors[91]. These technologies are at the stage of preliminary scientific research or (in the case of adiabatic methane conversion) - testing at an experimental laboratory unit.

Russian developers have the following technologies at the stage of laboratory testing:

- Hydrogen generation by aluminum-water reaction (Joint Institute for High Temperatures of the Russian Academy of Sciences, JIHT RAS);
- fuel processors for the conversion of natural gas and diesel into a hydrogen-rich fuel mixture and the release of pure hydrogen from it ("Central Research Institute of Ship Electrical Engineering and Technology" ("Central Research Institute SET"), Krylov State Research Centre")[92].

The Kurchatov Institute and research centres of the Russian Academy of Sciences, for example, the Institute of High-Temperature Electrochemistry of the Ural Branch of the Russian Academy of Sciences, are engaged in scientific developments in the field of electrolysis.

Transportation and storage of hydrogen is less developed because it is consumed at the place of production. Gazprom, the owner and operator of the gas transmission system of Russia, conducted studies showing the possibility of adding hydrogen to transported natural gas in the range of 20–70%[93] - but real experiments have yet to be conducted. Scientific and experimental developments in the field of liquefying and transporting hydrogen in a liquefied state were carried out by the NPO Geliymash[94] for the space programme of Russia and by PJSC Cryogenmash[95].

Scientific research concerning hydrogen storage based on metal hydrides is available at the Institute for the Problems of Chemical Physics Institute at the Russian Academy of Sciences.

Several research centres and companies are developing fuel cell technologies for hydrogen **use:**

- The Institute for the Problems of Chemical Physics Institute at the Russian Academy of Sciences (hydrogen-oxygen proton exchange membrane fuel cells);
- Autonomous Energy Centre of the Moscow Institute of Physics and Technology (solid oxide fuel cells);
- Institute of High-Temperature Electrochemistry of the Ural Branch of the Academy of Sciences (solid oxide fuel cells);

91 N.N. Ponomarev – Stepnoi et al. Nuclear energy technological complex with high temperature gas cooled reactors for large scale environmentally friendly hydrogen production from water and natural gas. / Gas Industry, №11 – 2018.

92 http://www.niiset.ru/index.php/vodedprod

93 Blue Fuel - Gazprom Export Global Newsletter / 2018, Issue 48.

94 http://geliymash.ru/production/vodorodnye-ozhizhiteli/

95 http://www.cryogenmash.ru/catalog/vodorodnoe-oborudovanie/

- Rosatom TVEL fuel company (including the Electrochemical Converters Plant, NPO Centrotech, Sverdlovsk Region) - solid oxide fuel cells for the autonomous power supply of facilities located away from the infrastructure.

Electric buses and passenger cars with batteries (BEV) have already appeared in Russian cities - but hydrogen fuel cell electric vehicles are not yet in use. Prototypes of the Gazelle light truck with internal combustion engines operating on a mixture of gasoline and hydrogen (converted from the original gasoline version) made a rally along the route of Moscow-Nizhny Novgorod-Kazan-Nizhnekamsk-Cheboksary-Moscow in 2006. The main objective of the project was to attract public attention to the issue of hydrogen transport.

In 2018, the Russian Venture Company, Skolkovo Foundation and the Agency for Strategic Initiatives organised the First Element technological projects competition, which aimed to overcome global technological barriers in the promising segment of hydrogen energy and fuel cell technology by Russian scientists, developers and manufacturers of power plants. Two prototypes of power units operating on hydrogen fuel cells for vehicles are being created within this project (small air and onshore units with capacity of around 2 and 50 kW, respectively). These would be comparable with traditional energy sources used to power vehicles in efficiency. The winners of the competition will receive grants in the amount of up to 140 million Roubles (around 2 million Euros)[96].

Non-Profit National Association of Hydrogen Energy (NAVE)[97] works in the area of hydrogen technology standardization. This is the organisation which created and implemented over 20 Russian equivalents of international standards in the field of hydrogen technologies.

Resources

Russia is one of the world's largest suppliers of hydrocarbons, ranking second in on oil exports, first in gas exports and third in coal exports in the world[98] and is one of the leaders in hydrocarbon reserves.

The existing gas transportation infrastructure (taking into account new gas pipeline projects) and the growing natural gas (LNG) industry create long-term prerequisites for the development of "blue" hydrogen production (Fig. 33) with minimum costs of raw materials and hydrogen export via pipelines and in a liquefied form. According to Gazprom estimates, transporting hydrogen via export gas pipelines entails some risks of violating long-term contractual obligations related to gas quality, and necessitates additional investments in the gas transmission system. Therefore, the company is considering an alternative - production of hydrogen from natural gas after the latter has been

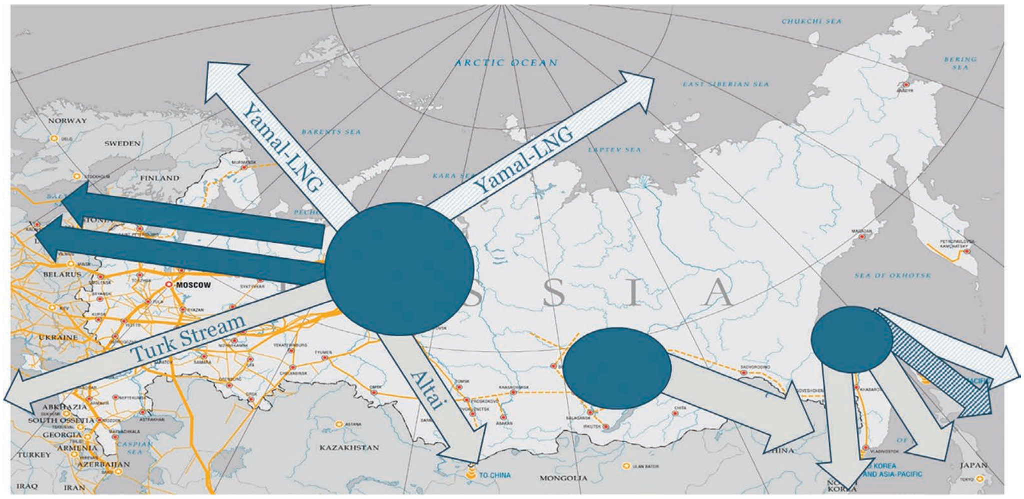
96 http://1element.upgreat.one

97 http://h2org.ru

98 IEA and BP data for 2017

transported through the trunk pipelines[99]. At the same time, Gazprom valued the European market for hydrogen produced in this way at 153 billion euros by 2050, according to Bloomberg.[100] It is important to note that suppliers of "green" or "blue" hydrogen will have a high chance of operating in this market. Given the available technology, this leaves one alternative: steam methane reforming with CCS.

Figure 33 Natural gas export flows from Russia



Source: SKOLKOVO Energy Centre

Russia ranks fourth in the world in electricity production, while its generation has one of the lowest carbon footprints in the world. Gas-fired thermal power plants dominate in the generation structure (around 48%), while nuclear power plants (18%) and hydroelectric power plants (17%) exceed the share of coal-fired power plants (16%). As a result, electricity carbon content in Russia is less than in the US, China, Australia, India, Japan, Germany and other countries (Fig. 34).

The carbon footprint is several times lower than on average across Russia in some Russian regions, for example, in Karelia (where nuclear power plants dominate) or in the Magadan region (where hydroelectric power stations dominate).

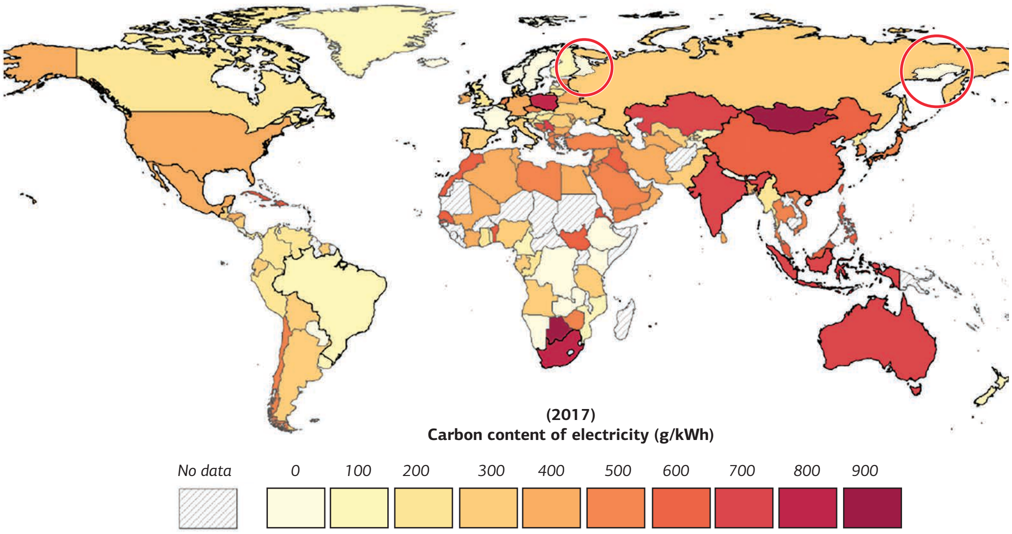
This opens up opportunities for the production of hydrogen by electrolysis with electricity from the regional electricity grid - and hydrogen will be actually be "green" even without the development of solar and wind power.

99 General and Contractual Risks of Hydrogen Decarbonization – presentation for EU-Russia Gas Advisory Council's Work Stream on Internal Market Issues (GAC WS2)/ Gazprom, Brussels, March 2019.

100 https://www.bloomberg.com/news/articles/2018-11-08/russia-looks-to-hydrogen-as-way-to-make-gas-greener-for-europe

This has prompted interest from international players: for example, according to an agreement signed at the Eastern Economic Forum in the autumn of 2017, Kawasaki Heavy Industries should revisit a feasibility study on the export of hydrogen produced in the Magadan region to Japan. This project has not yet received development, but as the infrastructure develops in the Far East and the cost of hydrogen electrolysis and logistics technologies goes down, interest in such initiatives will clearly only increase. On the other hand, their development is hindered by the imperfection of the regulatory framework, including "green certificates" in the electicity.

Figure 34 Electricity carbon content in the world, by country



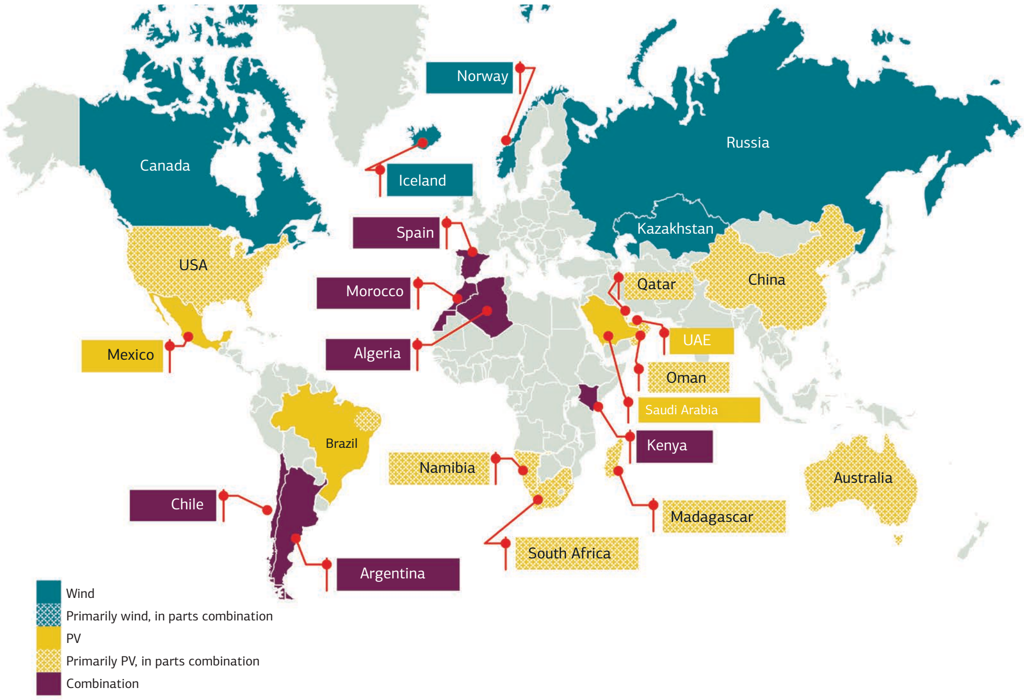
Sources: Staffell[101], SKOLKOVO Energy Centre

Even greater opportunities are opening up for Russia in the event that its renewable energy potential is realized - primarily, wind energy. Although the share of wind power in Russia's energy balance in the coming years will be insignificant (less than 1%), total potential in this sector is valued at 17.1 thousand TWh[102] which is 16 times higher than total generation in Russia in 2018. That is why the studies of the global potential of power-to-x technology (Fig. 35) refer to Russia as one of the "hidden champions" whose huge potential is combined with a lack of interest from the state and the stakeholders.

101 I. Staffell, M. Jansen, A. Chase, E. Cotton and C. Lewis (2018). Energy Revolution: Global Outlook. Drax: Selby.

102 Russian Wind Energy Market Review for 2018 / Russian Wind Industry Association (RAVI), March 2019

Figure 35 Energy supplying countries with the largest PtX potential, according to the power to x technology (Ptx) chart



Source: Frontier Economics[103]

Domestic hydrogen demand

Until decarbonisation has become mainstream in the Russian energy policy, the transport sector can drive the development of hydrogen demand. In major Russian cities, motor transport is the main air pollutant with nitrogen oxides, sulfur, benzo (a) pyrene and other hazardous substances - therefore cities are starting to seriously consider electric transport as a solution to environmental problems. For example, by the end of 2019, Moscow will purchase 300 electric buses and plans to buy as many annually until 2021, after which this number may increase.

Hydrogen electric transport (FCEV) may be preferable to battery (BEV) in Russian conditions, since in this case the negative impact of low outdoor air temperatures on the power reserve is excluded. In addition, there are companies, universities and research centres in Russia which are involved in the development of fuel cell technologies and hydrogen storage systems (unfortunately, electrical storage systems for electric buses are still being purchased in China). For example, in 2015, a project to create a pilot hydrogen fueling station and a bus route was proposed for Yekaterinburg - given the proximity of the city to main technology developers[104].

103 International aspects of a Power-to-X roadmap. A report prepared for the World Energy Council Germany / Frontier Economics Ltd, October 2018

104 http://h2org.ru/images/stories/rauvtek2015.pdf

Autonomous (island mode) power supply powered by fuel cells for hard-to-reach facilities is the second possible development direction. These facilities would include cell phone towers, equipment which serves gas and oil pipelines, remote villages, etc. As in other countries, this trend may initially develop locally using fuel cell technology and natural gas (if available).

Competitiveness of hydrogen technologies with gas engine vehicles, battery electric vehicles, wind turbines or solar power plants, powerplants operated on LNG or liquefied hydrocarbon gases has to be analysed in each particular case, taking into account possible changes in Russia's low carbon development strategy.

The Russian hydrogen programme as a response to global challenges

The above qualitative analysis shows that hydrogen technologies will inevitably continue to develop on a global scale - primarily because it is impossible to achieve the goals of combating global climate change, which the governments of many dozens of states have already set for themselves, without them.

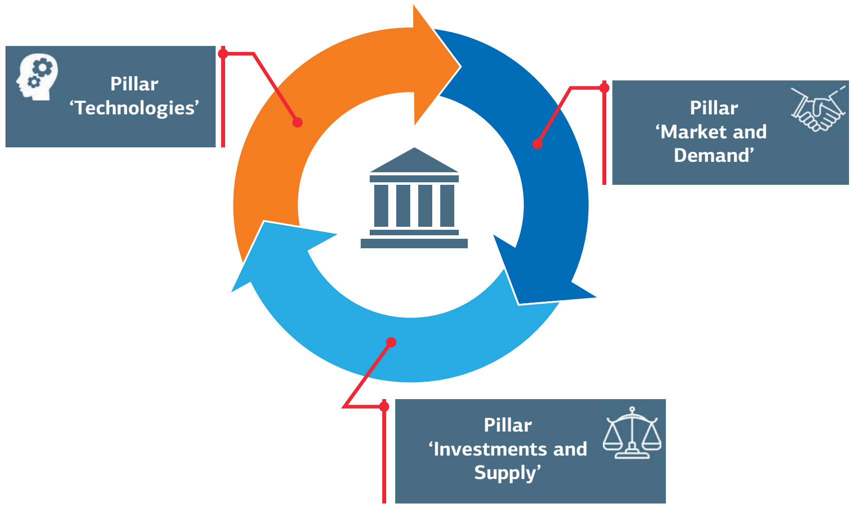
At the same time, Russia has got not only enormous resources to bring to a new global market, but also its own technological developments (which are, however, for the most part far from commercialization at this point) and promising domestic demand.

The emerging hydrogen market will likely compete with hydrocarbon markets, where Russia's position now seems unshakable - and in this sense, a strategy of ignoring or even opposing the new may seem attractive in the short term. But in the long run, such a strategy will place the national economy at the risk of a slowdown - not only because of falling demand for hydrocarbons, but also as a result of holding back the development of the innovation sector in industry.

Incorporating hydrogen technologies in the Russian energy strategy and the low carbon development strategy — or the adoption of a separate national hydrogen programme is a possible response to these challenges.

Frontier Economics identifies three main pillars for the sustainable development of the global hydrogen market (Fig. 36). These principles can be useful for the creation of the Russian hydrogen programme.

Picture 36 Three pillars for the global hydrogen market



Источник: Frontier Economics[105]

Firstly, it is important to ensure **technological development** - mastering and reducing the cost of all elements of the monetization chain of "green" hydrogen, as well as complementary technologies - CO_2 capture and storage, steam methane reforming, etc.

Secondly, there is a need for **market support and sustainable demand** for hydrogen - first of all, for consumers who are interested in buying "green" hydrogen and its derivatives.

Thirdly, the key to success is to **attract international investment**, creating mechanisms to compensate for commercial, currency, inter-cultural and national risks.

The Russian programme, based on these three pillars, may also include the following elements:

- **Development of pilot projects for hydrogen exports:**
  - ◊ Exports of grey / blue / orange hydrogen to Japan, Europe
  - ◊ Launch of international projects with the participation of Russia
- **Development of hydrogen clusters in the domestic market:**
  - ◊ creation of several supporting "hydrogen clusters"
    - with a focus on the markets and centres of competence,
    - Moscow, St. Petersburg, Novosibirsk, Krasnoyarsk, Yekaterinburg, etc.
- **Development of fundamental and applied research on hydrogen:**
  - ◊ inventory of available reserves and coordination of research and development;
  - ◊ specialization in the areas in which Russia already has

105 International aspects of a Power-to-X roadmap. A report prepared for the World Energy Council Germany / Frontier Economics Ltd, October 2018

developments, and those that receive less focus in other national programmes;

- ◊ focus on the future markets, avoiding "reinventing the wheel"- based on a preliminary analysis of the status of hydrogen technologies and forecasting their development abroad;

- **Education in the field of hydrogen technology**
- **Popularization**
- **Standardization and certification**
- **State coordination:**
  - ◊ management and coordination at a high political level, with the federal ministry playing the leading role (with the creation of a separate department within the Energy Ministry);
  - ◊ key performance indicators for restructuring and a breakdown by year of programme implementation, with mechanisms for their adjustment;
  - ◊ creation of a unified information platform;
  - ◊ creating a system of incentive measures for large and small businesses (taxes, benefits, orders) and technology localization.
- **International cooperation:**
  - ◊ Technological partnerships
  - ◊ Entry into international hydrogen organisations and platforms.

Determining the government's position on this issue will largely determine the attitude of large companies to it. Many of these already have plans and developments in the field of hydrogen technologies; however, are not yet giving them priority.

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