Eurasian Development Bank

GLOBAL ENERGY

GREEN TECHNOLOGIES FOR EURASIA'S SUSTAINABLE FUTURE

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JOINT REPORT BY THE EURASIAN DEVELOPMENT BANK AND THE GLOBAL ENERGY ASSOCIATION

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The joint report of the EDB and the Global Energy Association is prepared by the key international industry experts and young scholars. It contains the results of technical research aimed at solving today's energy challenges and helping to reduce the carbon footprint in Eurasia. The focus is on hydrogen energy and energy storage systems, including those applied to the water and energy complex of Central Asia, offshore wind energy, hybrid materials for alternative energy technologies, CO_2 capture, storage and transportation technologies. The report popularizes and supports research and development of green energy technologies, as well as promoting the expansion of cooperation in energy sector among the EAEU member states.

Keywords: energy sector, alternative/renewable energy resources, climate, carbon neutrality, hybrid materials, energy storage systems, EAEU.

JEL: F15, O44, Q40, Q42, Q55, Q56.

The online version of the report is available at the websites of the Eurasian Development Bank and the Global Energy Association: https://eabr.org/en/analytics/special-reports/ and https://globalenergyprize.org/en/

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NIKOLAI PODGUZOV,

Chairman of the Management Board, Eurasian Development Bank (EDB)

The world energy system is on the verge of significant structural changes in which new clean energy sources are playing the leading role. Amidst rapid climate change and escalation of the global decarbonisation trend, the role of traditional sources of energy will be significantly redefined. Developing clean energy will significantly affect the structure of the Eurasian economies.

Introducing new energy technologies poses a number of complex issues of both a technological and an economic character. Applied research to advance energy technologies is a strategic element in addressing the challenge. We have to unlock the potential of green technologies, which will be able to promote the shift of the Eurasian countries to a new era. In this context, the EDB, as a key development institution of the EAEU, is seeking all-round cooperation with the leading think tank representing the intellectual core of the new energy industry in the region – the Global Energy Association.

The EDB has a key role to play in energy industry transformation. Our Bank is an active contributor to the formation of a green agenda and takes an active part in combating climate change and creating low-carbon energy in the Eurasian region. In 2019, the EDB Council enacted the Programme of financing renewable energy projects for 2020–2024. Such projects amount to 67% of the Bank's energy portfolio. In accordance with the Council-approved EDB strategy for 2022–2026, the Bank will significantly expand its presence in "green" financing. The complex issues of the water and energy balance in Central Asia are a strategic priority of the Bank for the next five years. The EDB is planning to embark on a course extending from applied economics research, regulation, and technologies, through technical assistance projects, to large investment projects in the Central Asian region.

In the context of the growing global trend for green energy, a window of opportunity is opening for the Eurasian countries, for rapid technological innovation in promising areas. For example, in the field of hydrogen energy, the wide range of potential developments includes many possibilities – from an energy storage function to a technical gas for hydroskimming petroleum products and the production of low-carbon steel. Amidst intense competition among energy powers, the Eurasian countries will require shared use of scientific and technical potential. This will ultimately create a broad synergetic effect for the development of the region's green energy.

SERGEY BRILEV,

President, Global Energy Association

You are reading the first joint outlook paper of its kind by the Global Energy Association and the Eurasian Development Bank (EDB).

Although world energy will mostly come from hydrocarbons over the coming decades, the role of renewables among primary sources is substantively increasing. The reason for that interest is primarily ecological. Climate change, depletion of natural resources, and environmental pollution concern not only scientists, policymakers, and economists, but also everyone involved: one has only to recall the global natural disasters of summer 2021. Hence a special emphasis on reevaluating the energy balance, shifting towards clean sources or environmental modernization of conventional energy.

The Eurasian Economic Community is now rolling out large-scale projects and research programmes. Due to its geopolitical and territorial features, especially the availability of isolated and inaccessible territories, development and implementation of renewable energy technologies has huge prospects for the future.

This report will describe the appeal of hydropower, challenges of offshore wind platforms and hydrogen production, and much more.

Looking ahead, we think of those who will conduct R&D, experiments, and wide implementation of new energy instruments. While developing our support for talented specialists, we offer the best of them the opportunity to have their say. That is why in this outlook paper an internationally authored chapter by young researchers holds a special place, reporting about hybrid materials of both natural and synthetic components, irreplaceable in developing highly efficient energy storage and transportation systems, including hydrogen. It is impossible to create clean and effective ways to use energy without searching for and developing new materials for alternative sources.

These issues are of concern to highly qualified researchers, and we hope also a wider audience of those who want "to be up on the latest" and receive information on modern trends in clean technologies and sustainable development.

Enjoy your reading!

WILLIAM BYUN,

Senior Partner, Oxford GAV Conservation Management LLC, Independent Director, International Green Technologies and Investment Centre of Kazakhstan

From civil society and policymakers to the business community, every enterprise and institution is having to determine its strategic positioning and performance expectations for sustainable development technology – renewable energy, climate change, and necessary investments. Globally, a paradigm shift is taking place with respect to energy, and Eurasia has long been planning ahead to adjust to the new reality.

UNREALIZED POTENTIAL

Eurasia has tremendous renewable energy resources, from hydropower, solar, and wind, to specific technologies based on developed petrochemicals infrastructure in the region, such as for the production of industrial hydrogen. Additionally, unlike so-called traditional developing economies, the countries of Eurasia have a foundational historic legacy of scientific education, research, and support, which make the adoption of leading science and technology an easier if not familiar process. With the tremendous renewables potential and the EAEU's crossroads geography, optimally located between Europe and Asia, such industries as data centres, which are very energy intensive, should become highly profitable.

Yet as in most countries, the actual implementation of renewables has lagged behind their potential. In the region, such hurdles arose from two significant factors. First, challenges from the major shifts in the underlying political-economic systems which swept the region over the past several decades. Interestingly, the other major hurdle arose from sources of economic strength, that of a robust and technically proficient fossil fuel sector, which has dominated and diverted policy focus, financing, and human resources away from the indigenous mobilization of green energy. As a result, the actual deployment of renewables and investment into the new energy technologies have been sporadic, scattered, and very small in scale.

A QUIET EVOLUTION

While the climate-related disruptions of this past year seem to have focused global attention on the challenges of climate change and new energy, the countries of the EAEU have actually been quietly preparing the groundwork for a shift to sustainable new energy technologies since the mid 2010s. From Uzbekistan to Kyrgyzstan, all of them, with their different national goals for their energy mix and carbon neutrality, and despite the centrality of traditional energy, have taken a forward-looking stance, which is manifesting itself in several respects through a layered "top-down" approach.

The updating and realignment of national legislation and regulations on environmental and other sectors of sustainable development is easily visible, including an emphasis on renewables and green energy and regulation of carbon emissions. The next layer down has been the building of cross-border cooperative frameworks among the countries of the region. Most fundamentally, the EAEU has been strengthening various environmental and civil society organizations and conducting regular capacity-building outreach programmes to businesses and local communities, not only on the technologies, but also on the overall framework for a new energy ecosystem. Kazakhstan, for example, has significantly upgraded and emphasized such framework organizations as the International Green Technologies and Investment Centre (IGTIC), the Astana International Financial Centre's Green Finance Centre, and the private Association of Environmental Organizations of Kazakhstan. These organizations are being developed with an emphasis not only on near-term projects or specific programmes, but also on deepening mobilization of the governance and financing of green technologies. An example of such a structural approach has been the IGTIC's focused cooperation with the Ministry of Ecology on developing a national Best Available Technology framework programme, within which businesses and companies receive guidance on the best international standards and practices within which they could evaluate and build their own individual strategies for sustainable technology. With such quiet structural building blocks and assessments of the practical technologies appropriate for the region, the uptake of renewables could then more broadly succeed, not project-by-project, but broadly across the entire region.

It is within this context that this report is examining various technological innovations, their possibilities, and the potential of renewable technologies for the EAEU. Like the quiet industrial policy approach now taking place in the region, we should also consider this report as one among many steps that are driving a great deal of research and innovation.

HYDROGEN ENERGY

Valery Bessel, Professor, Chair of Thermodynamics and Heat Engines
of the National University of Oil and Gas, Gubkin University

Hydrogen energy, involving the use of hydrogen as an energy carrier, has gained immense popularity in recent years, particularly due to growing environmental challenges and the climatic problems of modern global energy, depletion of proven fossil fuel reserves, and the low efficiency of thermal power plants (Bessel, 2021). The very concept of hydrogen energy emerged as a response to environmental pollution problems and the energy crisis (Polyakova, 2012). By 2050, hydrogen is forecasted (Hydrogen Council, 2017) to account for about 18% of total world energy consumption; hydrogen consumption will amount to 370 million tonnes per year by that time and up to 800 million tonnes by 2100. Transition to hydrogen energy by 2050 will result in a decrease of CO_2 emissions by 60%, while the demand for hydrogen might grow tenfold (Makaryan et al., 2020).

The concepts of renewable, carbon-free, and environmentally clean green energy used in expert discussions need clarification:

- Renewable energy comes from natural, permanent or intermittent energy flows: it is primarily solar energy, wind and geothermal energy, water-flow energy, and the energy from biomass and municipal solid waste (MSW) combustion; in the long run, it is expected that the energy of hydrogen isotopes will also be used – protium, deuterium, and tritium – which will contribute to industrial development of hydrogen and thermonuclear energy.

- Carbon-free energy means that there is no "carbon footprint" from power generation, and no emissions of greenhouse gases such as carbon oxides into the environment. Carbon-free energy involves nuclear energy and the energy generated from renewable energy sources: hydropower, the sun, and wind.

- Green, environmentally clean energy is generated from renewable energy sources (RES), but without geothermal energy, biomass energy, and the energy from MSW combustion.

Carbon-free and green energy can be used only for generation of electricity and heat, while fossil fuel can also be used for obtaining fuels and lubricants for internal combustion engines and products of oil, gas, and coal chemistry.

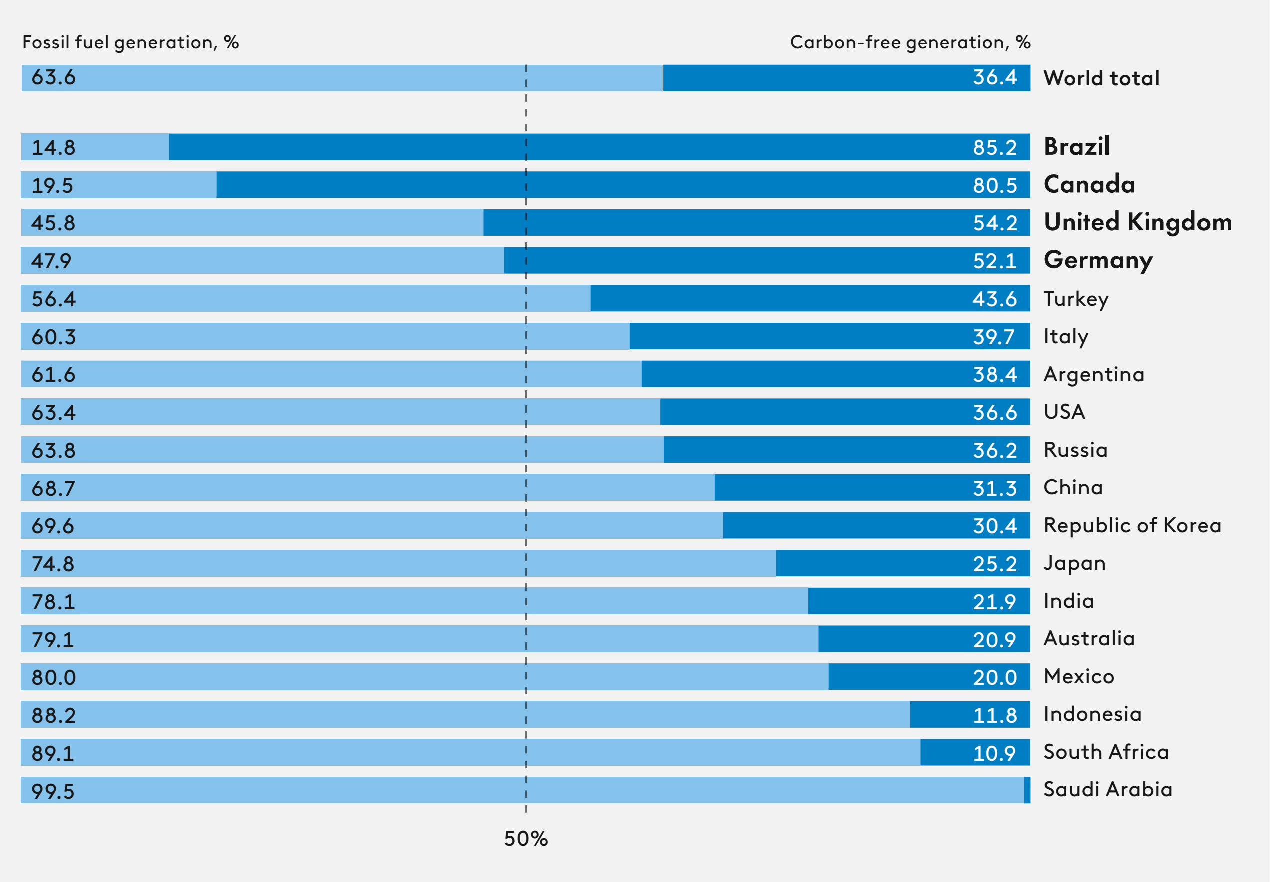
The distribution of fossil fuels and other types of energy in global electricity generation is as follows: coal 36.4%, natural gas 23.3%, hydropower 15.6%, nuclear energy and RES 10.4% each, oil and petroleum products 3.1%, biomass, MSW, etc. 0.9% (BP, 2020). The dominant sources of thermal power generation are currently combustion of fossil fuels, biomass, and municipal solid waste, as well as geothermal energy, all of which release carbon oxide emissions into the atmosphere at 63.7% of the total, while the share of carbon-free energy using NPPs and RES (hydro, sun, wind) accounts for only 36.3% of electricity generation.

The G20 countries making a decisive impact on world economic development determine the current trends in the global energy development. Figure 1 shows the structure of electricity generation by thermal power plants burning fossil fuels and municipal solid waste, and by geothermal power plants and carbon-free energy sources based on NPPs and RES in the G20 countries (the top/bottom ranked in terms of energy consumption) in 2019 (BP, 2020).

The share of carbon-free generation exceeds thermal generation only in four G20 countries: Brazil (85.2%), Canada (80.5%), United Kingdom (54.2%), and Germany (52.1%).

The accelerating growth of power generation from renewable energy sources (RES) can be explained by their potential and technical availability (Bessel, Lopatin, Kucherov, 2014); they are gaining support for political, environmental, and climatic reasons, as a result of state investment decisions and resulting significant technological development, and the decrease in the cost of power generation from RES, which is comparable to or even lower than the cost of power generation from fossil fuels in many countries of the Organization for Economic Cooperation and Development (OECD) (IRENA, 2020).

Figure 1. The share of thermal and carbon-free generation in the G20 countries and the world in 2019, %

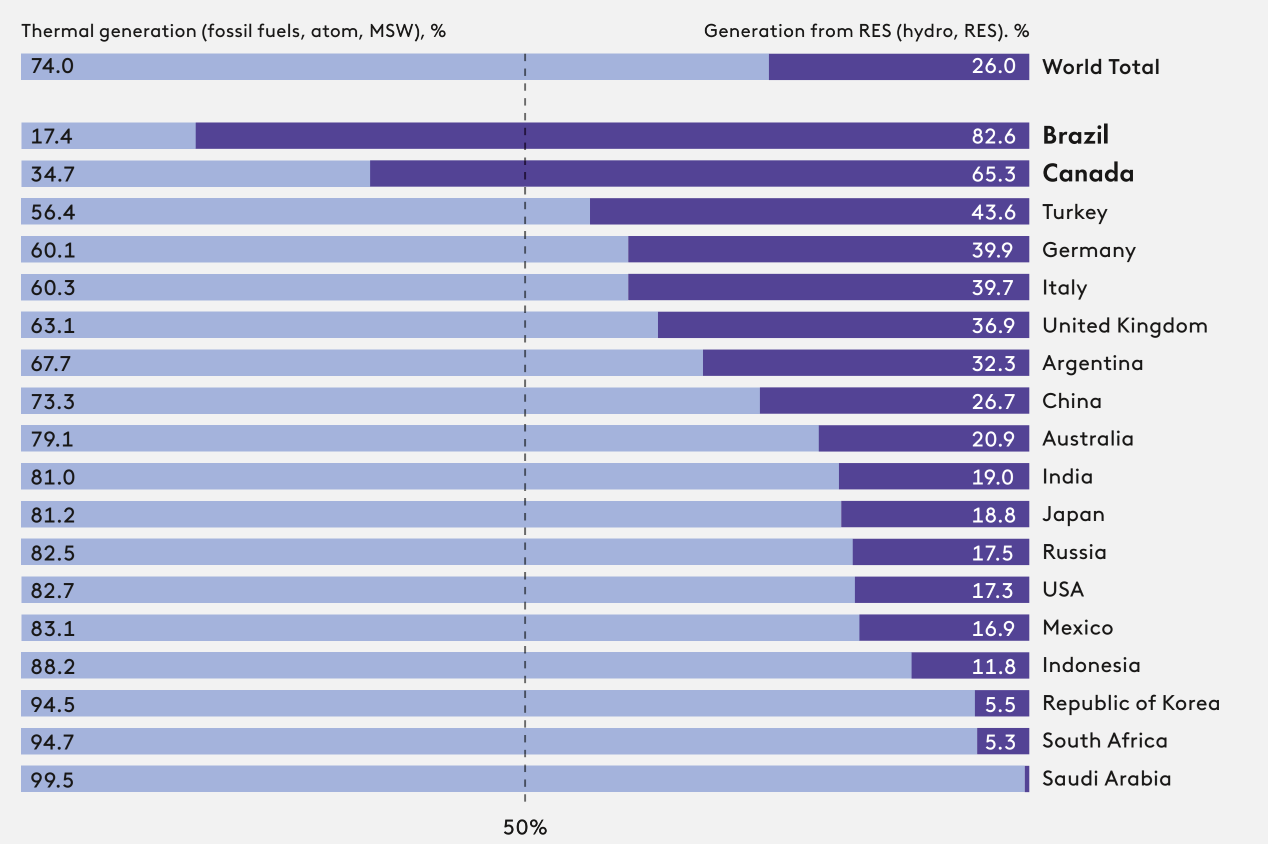


Source: BP, 2020.

Figure 2 shows the share of thermal generation using fossil fuels, MSW, nuclear and geothermal energy, and green, environmentally clean energy from RES in the G20 countries (the top/bottom ranked in terms of energy consumption) in 2019.

The share of green energy from RES in global electricity generation is steadily growing: it was 26.0% in 2019 but only 18.5% in 2000 (BP, 2020). Among the G20 countries, Brazil (82.6%) and Canada (65.3%) are the leaders in green energy share – they are the only ones in the G20 where green energy prevails over thermal energy in electricity generation.

Figure 2. The share of thermal energy generation from fossil fuels, MSW, nuclear and geothermal energy and green energy generation from RES in the G20 countries and the world in 2019, %



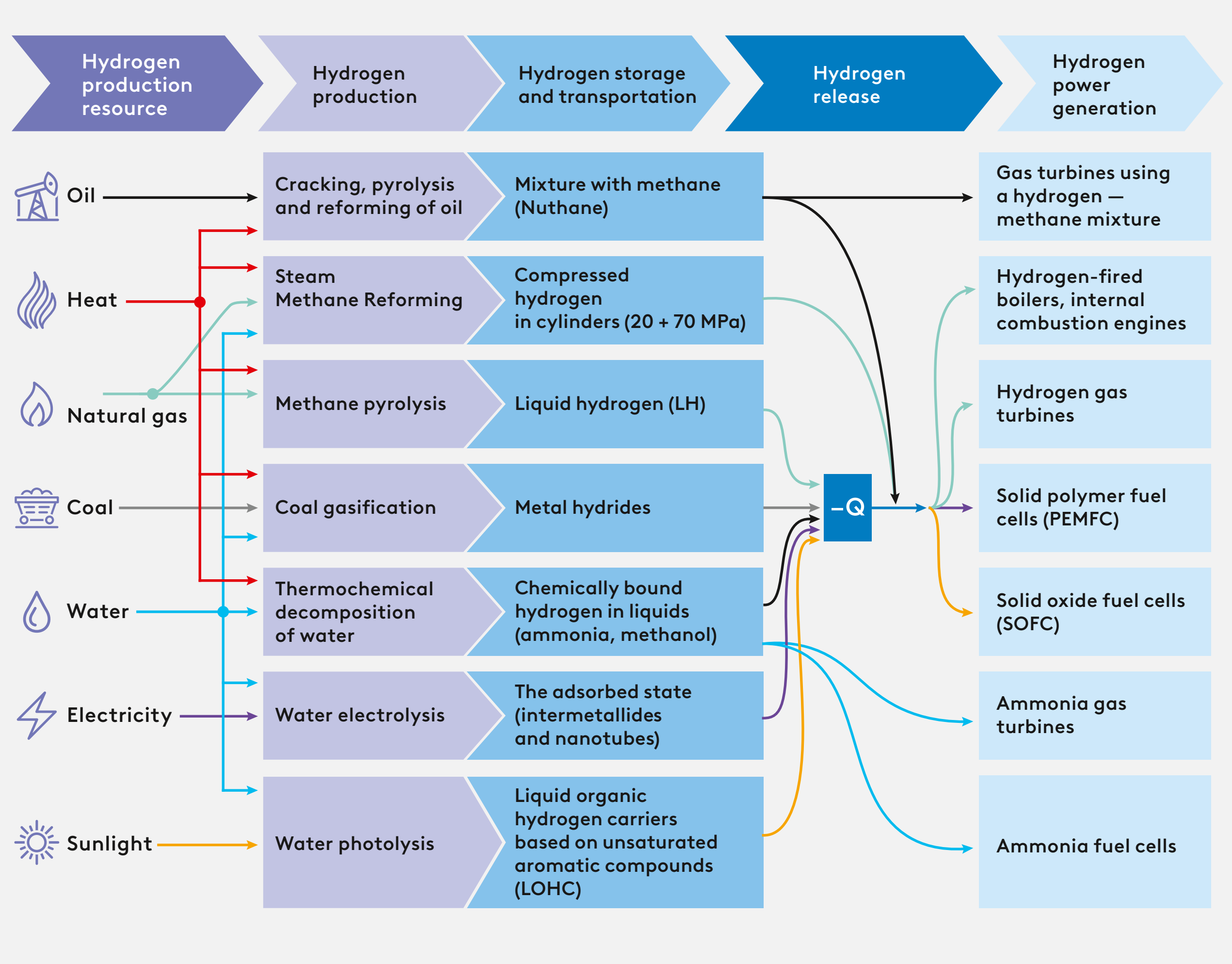
Source: BP, 2020.

The fastest way to tackle the problem of green energy dominance in electricity generation in the G20 countries is considered to be industrial application of hydrogen energy, in the medium term, to optimize the satisfaction of steadily growing human needs for renewable and clean energy, along with other types of energy (Polyakova, 2012). The USA, the EU countries, United Kingdom, Japan, China, South Korea, and Australia already have their own national strategies and programmes for creation and development of hydrogen energy. In the United States, budget allocations for hydrogen projects currently amount to USD 1.7 billion for a five-year period (funding from private companies is several times this amount), in the European Union EUR 2 billion, in Japan USD 4 billion for 20 years (Makaryan et al., 2020).

The hydrogen energy concept involves solution of a range of issues (Kozlov, Fateev, 2009):

- Hydrogen production from non-renewable and renewable energy sources (fossil fuel, NPP power, hydropower, solar, wind and biomass);
- Hydrogen storage and transportation;
- Hydrogen use in the power industry, production sector, transport, and domestic use;
- Reliability and safety of hydrogen power systems.

Figure 3. The main technological chains of hydrogen energy



Source: developed by the author.

Figure 3 shows the main technological chains of hydrogen energy: from production to the use of hydrogen as an energy carrier.

The main resources for hydrogen production currently are fossil fuels (oil, gas, and coal), water, sunlight, electricity, and heat.

The main methods for hydrogen production and the resources required for the production process are currently:

- Steam Methane Reforming (methane, water, and heat);
- Methane pyrolysis (methane, heat);
- Cracking, pyrolysis, and reforming of oil (oil and heat);
- Coal gasification (coal, water, and heat);

- Water electrolysis (water, electricity);
- Water photolysis (water, sunlight);
- Thermochemical decomposition of water (water, heat).

Figure 4 shows an approximate distribution of raw materials for hydrogen production in the world (%), by sources.

At present, the global hydrogen production structure is dominated by fossil fuels (natural gas, coal, and oil) ~ 96% and only ~ 4% of hydrogen is produced by water electrolysis, which currently makes it difficult to refer to hydrogen energy as renewable and environmentally clean.

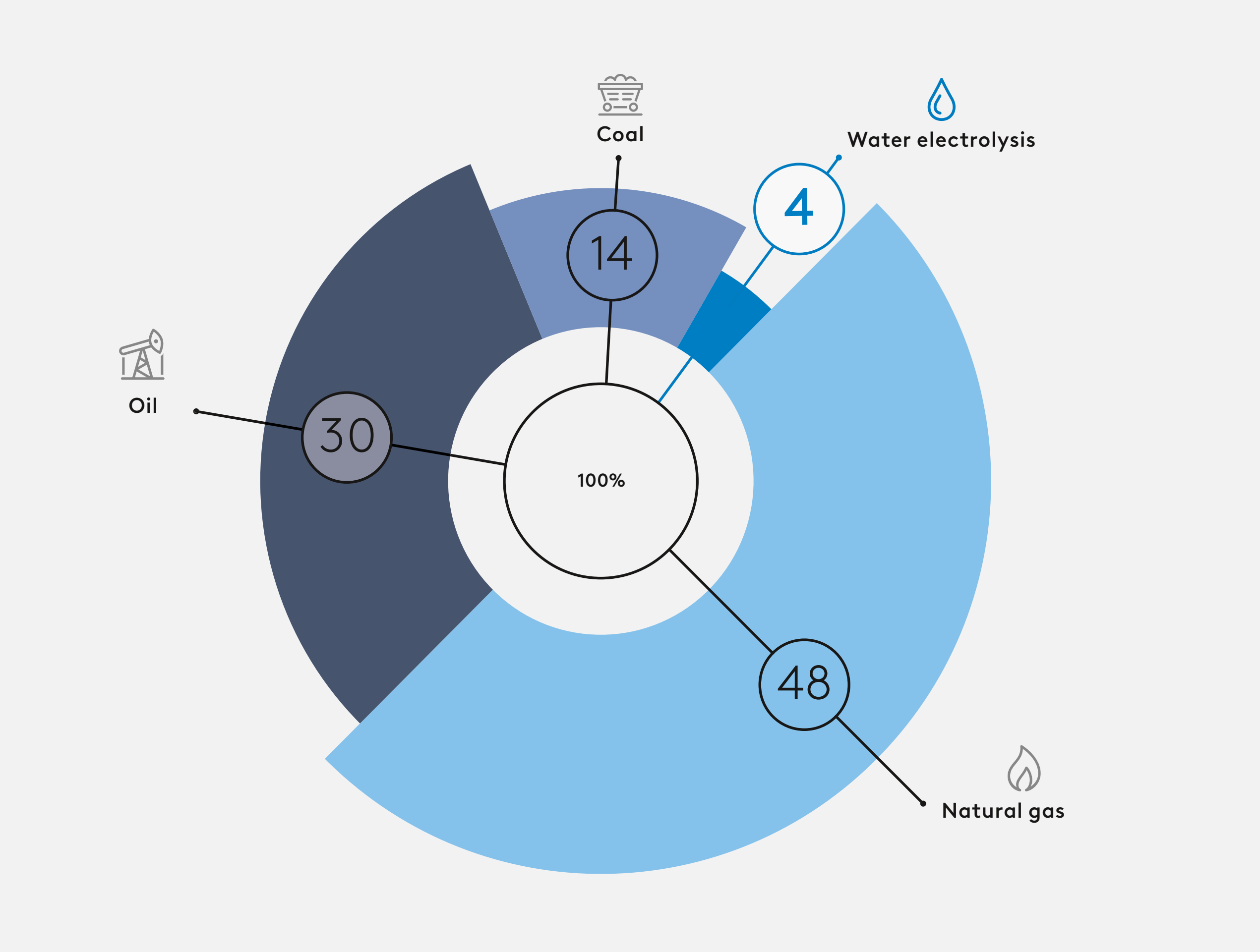
Depending on the hydrogen production methods, the EU Hydrogen Strategy (European Commission, 2020) divides hydrogen into:

- Renewable (clean) hydrogen — green, obtained as a result of water electrolysis using electricity produced from RES;
- Electricity-based hydrogen — obtained from electrolysis of water, regardless of electricity source;
- Fossil fuel hydrogen — turquoise, obtained from various processes using fossil fuels as a raw material, mainly by reforming natural gas (Steam Methane Reforming, SMR);
- Fossil fuel hydrogen with CO_2 capture – blue, produced from fossil fuels using carbon capture and storage technologies to capture up to 90% of CO_2 (Carbon Capture, Utilization and Storage, CCUS);
- Low-carbon hydrogen — consists of "fossil fuel hydrogen with CO_2 capture and electrically based hydrogen".

After the produced hydrogen has been treated, the following methods are used for its storage and transportation:

- Compressed hydrogen in steel or composite cylinders under pressure of 200 to 700 atm;
- In a liquefied state at a temperature of -253°C (20°K);
- Mixed with methane (hydrogen and methane — hythane) under pressure, in a gaseous state, transported through pipelines or in process vessels;
- In the form of transition metal hydrides (in fact, they are a solid solution of hydrogen in metal; hydrogen atoms are incorporated into the crystal lattice of the metal);
- In a sorbed state in intermetallic compounds (chemical compounds of two or more metals) or in carbon nanotubes;

Figure 4. The structure of global hydrogen production by sources of raw materials, %



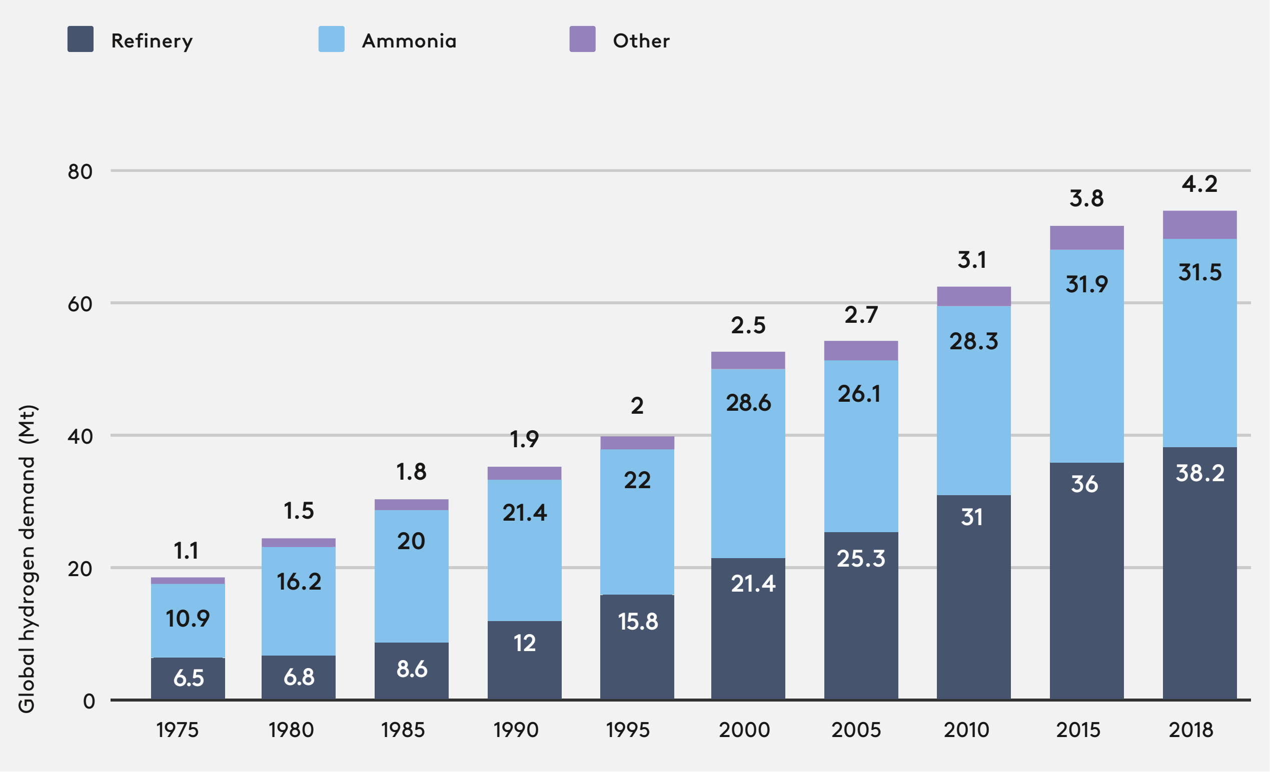
Source: Makaryan et al., 2020.

- In liquid organic hydrogen carriers based on unsaturated aromatic carriers (Liquid Organic Hydrogen Carrier — LOHC);
- Chemically bound hydrogen in liquids (ammonia, methanol).

Power is generated from hydrogen mainly with the use of:

- Gas turbine plants operating on a hythane mixture;
- Gas turbine plants operating on hydrogen;
- Gas turbine plants operating on ammonia;
- Combustion of hydrogen or hythane mixture at boiler plants;
- Solid polymer (Proton Exchange Membrane Fuel Cell – PEMFC) or solid oxide (Solid Oxide Fuel Cell – SOFC) fuel cells;

Figure 5. Global dynamics of hydrogen consumption (million tonnes) in various sectors of economy during 1975–2018



Source: IEA.

- High temperature ammonia fuel cells (ShipFC);
- Direct Methanol Fuel Cell (DMFC).

Hydrogen is actively used not only as an energy source but also as a valuable chemical raw material in various sectors of the economy, including oil refining, especially in the hydrogenation processes. Global hydrogen consumption is steadily growing; Figure 5, based on International Energy Agency data, shows the dynamics and structure of global hydrogen consumption from 1975 to 2018.

During the period under review, hydrogen consumption increased fourfold, from 18.5 million tonnes in 1975 to 73.9 million tonnes in 2018, and hydrogen consumption in oil refining grew even faster, almost 5.9-fold, which can be explained by the steady growth in global consumption of petroleum products (BP, 2020).

HYDROGEN AS AN ENERGY SOURCE

The specific heat of hydrogen combustion (gravimetric energy density) is ~ 121 MJ/kg, which is 2.4 times higher than that of methane (~ 50 MJ/kg) or 2.9 times higher than liquid hydrocarbon fuel (~ 42 MJ/kg). But the use of hydrogen as an energy source depends directly on its volumetric heat (volumetric energy density – MJ/l), since any liquid or gaseous fuel is stored, transported, and consumed in bulk.

Figure 6 shows the dependence of gravimetric energy density (MJ/kg or KW*h/kg) and volumetric energy density (MJ/l or KW*h/l) of various types of fuel.

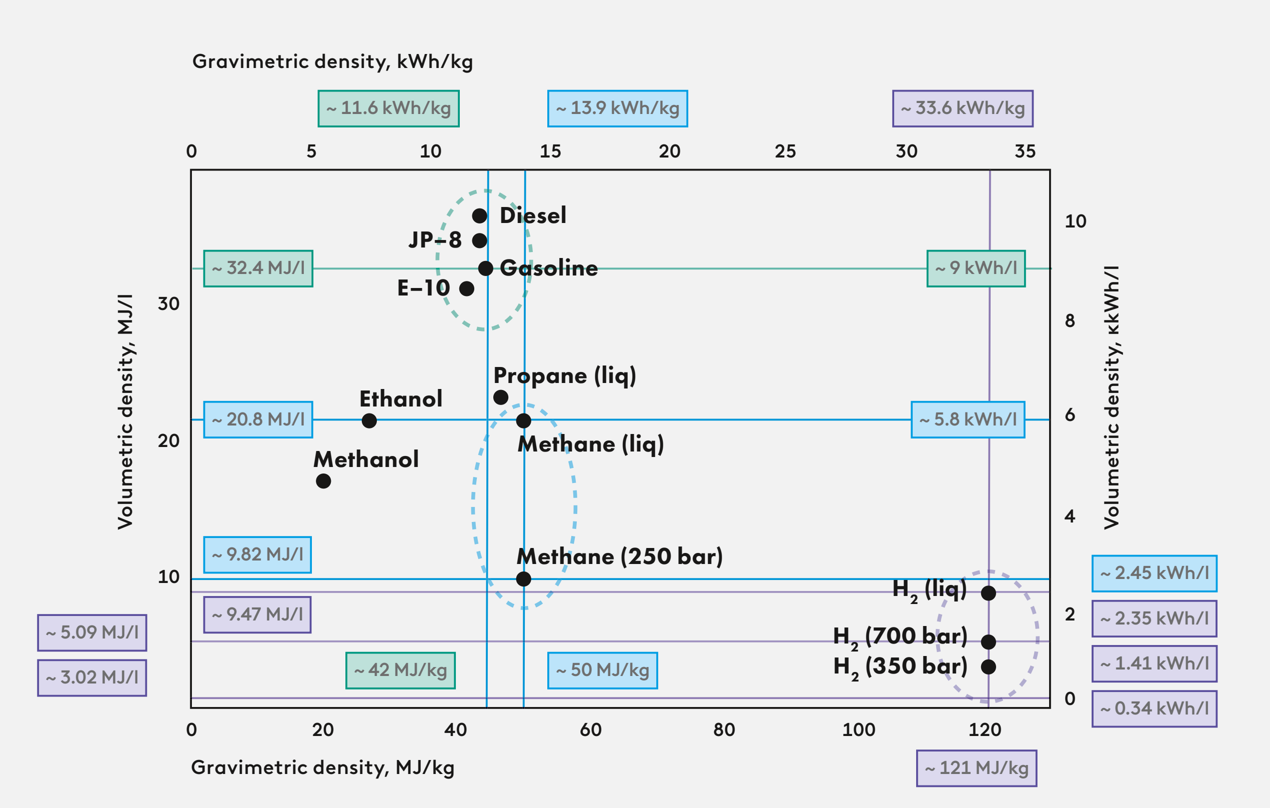
Due to its significantly lower density, liquefied hydrogen has a lower volumetric energy density (~ 8.47 MJ/l) than gaseous methane compressed to 250 atmospheres (~ 8.82 MJ/l).

If we compare the volumetric energy density of liquid hydrogen with that of other types of fuel, we can see that the heating value of a unit volume of liquid hydrogen is less than that of the following fuels:

- Methane compressed up to 25 MPa – 1.04 times;
- Liquid methane – 2.47 times;
- Gasoline – 3.83 times.

A substantially lower volumetric energy density of hydrogen compared to hydrocarbon analogues makes its current use problematic as an energy source in real energy projects. Nevertheless, the world's leading energy companies are making great efforts to develop hydrogen energy projects due to the stringent environmental and climatic requirements for modern global energy (European Commission, 2020).

Figure 6. Dependence of gravimetric (MJ/kg) and volumetric (MJ/l) energy density of various fuels



Source: Naccarella, 2017.

DEVELOPMENT OF HYDROGEN ENERGY IN RUSSIA AT THE PRESENT STAGE

Hydrogen technologies will inevitably develop on a global scale, primarily because without them it is impossible to achieve the goals of combating global climate change set by the governments of dozens of countries. There are proven hydrogen production technologies in Russia used at oil and gas refining plants to improve the hydrocarbon processing quality, and at power plants to cool their generator sets. Russia not only has huge untapped resources for being integrated in a new global market, but also has its own theoretical and technological designs (albeit still far from commercialization) and promising domestic demand (Mitrova, Mel'nikov, Chugunov, 2019).

The Ministry of Energy of the Russian Federation has developed a "roadmap" called Hydrogen Energy Development in Russia for 2020–2024, which formed the basis of the Action Plan approved by RF Government Decree of 12.10.2020 (No. 2634-r). Russia plans to produce and export hydrogen in line with the global trend of phasing out hydrocarbon energy. Starting from 2021, the Government wants Russia to gain a reputation as a supplier of hydrogen as an alternative to traditional energy sources. The plan (Ministry of Energy of the Russian Federation, 2020) includes solution of such clusters of problems as:

1. Strategic development and monitoring of renewable energy development.
2. Measures to promote renewable energy development and provide for its state support.
3. Formation of production potential.
4. Implementation of priority projects in renewable energy.
5. Scientific and technical development and design of high-tech solutions.
6. Improvement of the regulatory framework and the national standards system.
7. Human resource development.
8. Development of international cooperation.

The plan foresees hydrogen energy in Russia by 2025–2035. Hydrogen can be produced at the most powerful HPPs in the southeast as well as at the Leningrad and Kola NPPs, in the northwest of Russia. Shipping of hydrogen to the APR countries can be arranged from the southeast sites in Russia, and to Europe from the Leningrad and Kola NPPs. Russia's competitive advantages are its reserves of generating capacities, proximity to potential consumers (EU countries, China, Japan), and functioning transportation infrastructure (Energynet, 2018).

The largest Russian energy companies – Gazprom, NOVATEK, and Rosatom – are working on technologies for production of hydrogen with a minimum carbon footprint, with the use of adiabatic methane conversion and high-temperature nuclear reactors. The technologies are at the stage of preliminary scientific development or testing at a pilot laboratory setup (Mitrova, Mel'nikov, Chugunov, 2019).

Technologies at the laboratory testing stage:

- Hydrogen production by aluminium oxidation in water (Joint Institute for High Temperatures of RAS);

- Fuel processors for conversion of natural gas and diesel fuel into a hydrogen-rich fuel mixture and separation of pure hydrogen from it (Branch Central Research Institute of Marine Electrical Engineering and Technology of FSUE Krylov State Scientific Centre).

Scientific research in electrolysis is being carried out by the Kurchatov Institute and the research centres of the Russian Academy of Sciences, such as the Institute of High Temperature Electrochemistry of the Ural Branch of the Russian Academy of Sciences (Mitrova, Mel'nikov, Chugunov, 2019).

We cannot omit the extremely significant role of Kazakhstan and the other countries in the region that are potential exporters of various types of hydrogen and the potential of these states for promotion of their own development strategies for this industry, which will meet all the requirements of the emerging hydrogen infrastructure.

We can summarise some of the hydrogen energy development results at the present stage:

- The main goals of hydrogen energy are reduction of environmentally harmful emissions and transition to renewable energy. However, the current technologies dominant in hydrogen production from fossil fuels prevent classification of hydrogen energy as environmentally clean and renewable. In the future, the industrial and economically justified scale of hydrogen production from water will make possible classification of hydrogen energy as a renewable and environmentally clean green energy.

- Hydrogen energy is designed to solve the problem of increasing energy efficiency since thermal power systems based on combustion of fossil fuels have low efficiency. Currently the main converter of hydrogen energy into low-power electricity is fuel cells whose efficiency reaches 60–80% which is more than twice as much as the efficiency of thermal power systems.

- In such high-tech industries as aviation, aerospace, shipbuilding, and nuclear power, elements of hydrogen energy are used everywhere, which raises hopes that technological solutions will be used in the future if there is no technological breakthrough in development of other types of energy.

- At the present stage, hydrogen energy is at the level of intensive scientific and technological research in all developed countries, but the industrially required results are still insufficient.

- The world hydrogen market is under active development, and all global fuel and energy companies are investing huge sums in development of hydrogen energy projects. Russia has unique opportunities to occupy a dominant position in the hydrogen markets of Europe and the APR countries due to its huge reserves of natural gas and coal, the surplus generating capacities at its NPPs and HPPs, especially in the northwest and southeast of the country, its practically inexhaustible resources of freshwater, and the logistical accessibility of the main consumers of hydrogen.

CO_2 CAPTURE, STORAGE, AND TRANSPORTATION TECHNOLOGIES

Sergey Khan, Professor, National University of Oil and Gas Gubkin University

In connection with the global trend towards decarbonisation of economies, launched by the Paris Agreement on December 12, 2015 at the 21st session of the Conference of the Parties to the United Nations Framework Convention on Climate Change (COP 21), many countries have in recent years been developing their own programmes for reducing the environmental impact of greenhouse gas emissions. Most countries are striving to achieve carbon neutrality across all sectors of the economy. CO_2 emissions estimates over the past decade are equivalent to 31–34 $GtCO_2$/year. To solve major issues of reducing carbon dioxide emissions, the scientific and engineering community is constantly developing new technologies, including those that made CO_2 emissions go down to about 2.1 $GtCO_2$ over the past year (BP, 2021).

CAPTURE TECHNOLOGIES

There are now 65 commercial CO_2-capture projects worldwide (Global CCS Institute, 2020; Khan et al., 2012), with varying degrees of implementation and using such CO_2-capture technologies as:

- CO_2 capture from point sources
- Direct Air Carbon Capture and Storage (DACCS)
- Bioenergy with Carbon Capture and Storage technology (BECCS)

CO_2 capture from point sources is used in such industries as production of cement and steel, hydrogen or fossil fuel power generation, and waste incineration. The CO_2 is captured before reaching the atmosphere.

Among these industries, it is worth highlighting hydrogen generation, 98% of which is currently produced from coal (through gasification) and natural gas (through steam methane reforming). Both processes generate significant CO_2 emissions. Given the active rise of hydrogen's share in the prospective balance of energy consumption despite the availability of technologies without CO_2 emissions, capture technologies will undoubtedly be widely used.

There are several technologies for capturing CO_2 from point sources, including:

- post-combustion CO_2 capture
- pre-combustion CO_2 capture
- oxy fuel combustion CO_2 capture

Each process deals with the separation of CO_2 from a gas stream. To accomplish this, five technologies have been developed, each selected according to the technical state of the CO_2 emissions to be captured (concentration, pressure, volume):

- chemical solvent cleaning
- physical solvent cleaning
- adsorption/desorption
- membrane separation
- cryogenic separation.

Post-combustion CO_2 capture

In traditional combustion, the air is used as an oxidizing agent, and flue gases form under ambient pressure. Therefore, CO_2 separation from flue gases is quite difficult due to the very low pressure and low concentration of CO_2 in these gases, which are mainly nitrogen. Combustion of 1 m^3 of natural gas produces 10.52 m^3 of exhaust gas and about 8.8 kWh of energy.

Another problem is excess oxygen (O_2) remaining in the flue gas. Post-combustion CO_2 separation requires that chemical dissolving/absorbing/desorbing systems, usually involving amine reactions, and special chemical inhibitors, work with O_2. Back recovery of amine requires steam, and the requirements are quite high – about 1.5 tonnes of steam per tonne of CO_2 captured. In addition, the flue gas must have low levels of nitrogen dioxide (NO_2) and sulphur dioxide (SO_2) at the inlet to the absorber to avoid binding reactions with the recycled amine.

Additional NO_X reduction and SO_2 removal systems may be required, depending on the flue gas composition after conventional emission controls have been applied.

The main challenge in post-combustion CO_2 capture is meeting the high heat and energy requirements, amine desorption and compression, and dehumidification of the fatty (water-saturated) CO_2 that leaves the stripper. These requirements can significantly reduce overall (net) performance and energy efficiency. In addition, CO_2 absorbers have to be very large due to the low pressure and low CO_2 concentration in the flue gas. The actual volume of the gas treated in the absorber after combustion is approximately 60 to 100 times greater than the actual volume of the gas treated in the absorber before combustion, for the same amount of CO_2 captured.

The key advantage of post-combustion CO_2 capture is the ability to extract it from any existing flue gas stream. This allows it to be used for retrofitting of the existing installations without major process changes and renovations.

Pre-combustion CO_2 capture

In the pre-combustion CO_2-capture systems, the primary fuel is treated in a reactor with an air- or oxygen-saturated stream, to create a mixture consisting primarily of carbon monoxide and hydrogen (syngas). Additional hydrogen, along with CO_2, is generated by a carbon monoxide reaction with the stream in a secondary reactor (a shift reactor). The resulting mixture of hydrogen and CO_2 can then be separated into a CO_2 gas stream and a hydrogen stream. If the CO_2 is recycled, then the hydrogen is a carbon-free energy carrier that can be burned for electricity and/or heat generation. Although the initial fuel conversion stages are more complicated and costly than post-combustion systems, high CO_2 concentrations (typically 15–60% by volume on a dry basis) and high pressures formed by the shift reactor create more favourable conditions for CO_2 separation.

The key benefit of pre-combustion CO_2 is the use of H_2 as an intermediate energy carrier. H_2 has many potential strategic long-term advantages over vapor and heat stream, with CO_2 capture after the combustion process or oxygen combustion.

The challenge of pre-combustion CO_2 capture is a complex chemical treatment associated with the first gasification stage to convert fuels to syngas CO and H_2 under pressure. The expertise and experience required are usually limited to the chemical and oil industries. There is also a demand for significant investment in equipment to convert feedstock to syngas. High energy consumption during the syngas production stage can also affect total energy per unit of CO_2 captured, which is higher with pre-combustion CO_2 capture than with post-combustion CO_2 capture.

Pre-combustion CO_2 capture is worth considering only for new construction or major refurbishment of the available process equipment.

CO_2 capture in oxy fuel combustion

Oxy fuel combustion is one variation used at post-combustion capture. The fuel is burned in oxygen, not in the air. Thus, the exhaust gas contains mainly carbon dioxide and water vapor.

In this case, the flue gas is characterized by high CO_2 concentrations (over 80% by volume). Then the water vapor is removed by cooling and compressing the gas stream. Combustion of fuel with oxygen enrichment requires oxygen production from the air at the beginning of the technological chain, while the latest designs assume that oxygen with 95–99% purity is used.

Oxy fuel combustion has several advantages: 1) oxy fuel combustion to capture CO_2 is suitable for retrofitting existing combustion systems. This is especially attractive for such systems as existing cement kilns or fluid catalytic cracking units at oil refineries, where conversion of the air to oxygen raises productivity; 2) prevention of complex chemical processes associated with the pre-combustion and post- combustion CO_2-capture systems, and elimination of the need for SO_2 and NO_X controls; 3) oxygen combustion requires less energy, in total, than post-combustion CO_2 capture.

The main disadvantage of oxy fuel combustion is the high demand and capital and energy costs for production of oxygen. Compared to pre-combustion CO_2 capture, oxy fuel combustion requires two to three times more oxygen for the same amount of CO_2 captured. High energy consumption for such a supply of oxygen can significantly reduce overall (net) performance and thermal efficiency.

DACCS/BECCS

Negative emissions technologies (DACCS / BECCS) are capable of recovering the carbon emitted to the atmosphere as CO_2.

BECCS technology involves removing CO_2 from the atmosphere by plants, and then its extraction from the combustion products when the biomass is burned. With DACCS technology, CO_2 is captured directly from the air.

BECCS and DACCS can actually capture CO_2 from the air at any source of fossil fuel combustion anywhere in the world. The BECCS method is expected to be less costly (perhaps USD 50 to USD 200 per tonne of CO_2 removed and stored), while DACCS could be about twice as expensive. However, DACCS can remove large volumes of CO_2 from the atmosphere without any impact on the natural systems required to grow the biomass (Figure 7).

TRANSPORTATION TECHNOLOGIES

Unless a CO_2 capture facility is located directly above the disposal site, the captured CO_2 must be transported from the capture point to the storage site.

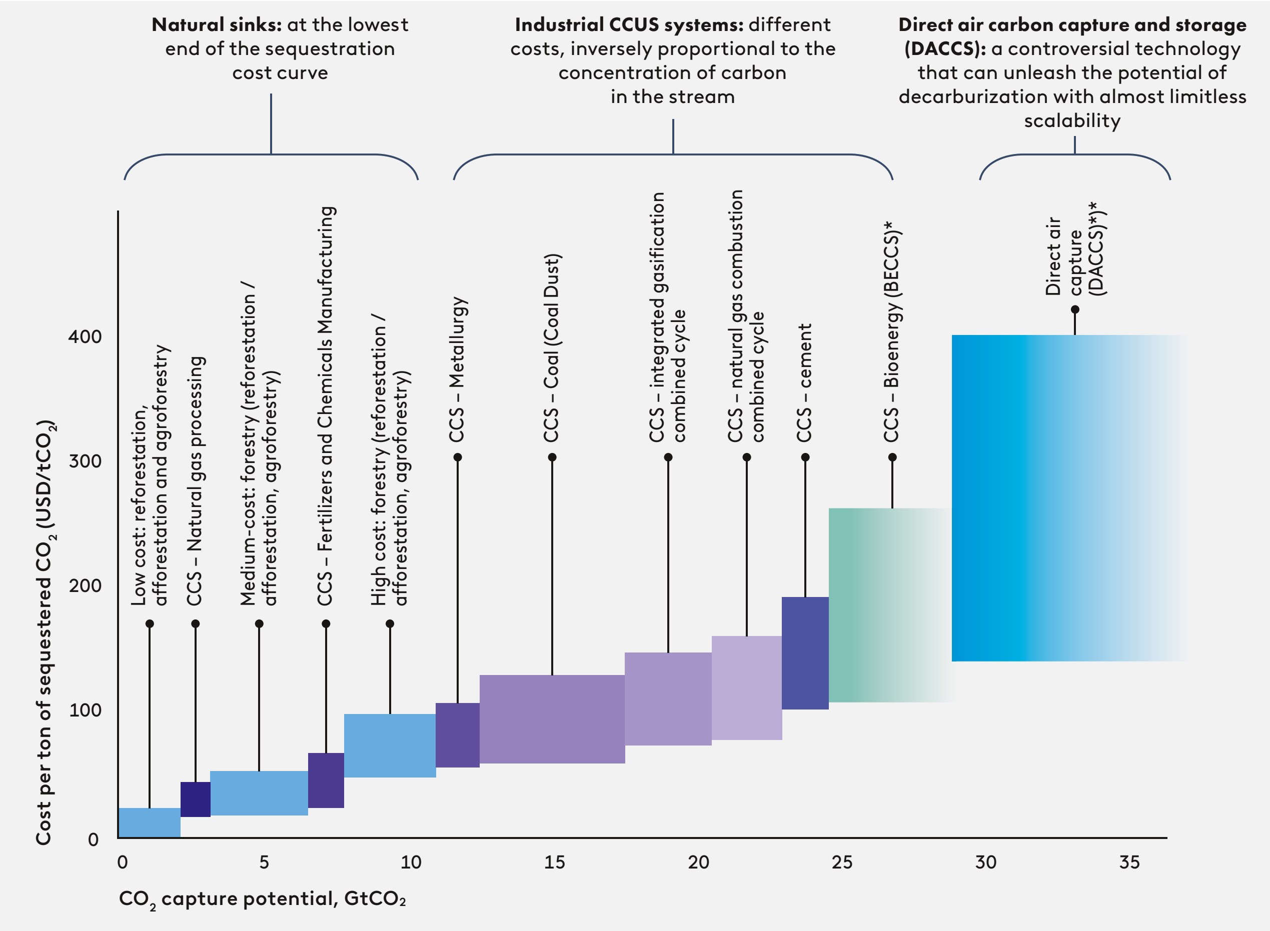
Pipelines today operate as a perfect market technology and are the most common way of transporting CO_2. Carbon dioxide in pipelines is preferably transported under pressure above 7.39 MPa and low temperatures, to prevent two-phase flow regimes and increase its density, due to which it is in a so-called "supercritical" state, and its density becomes close to the density of the liquid. CO_2 can also be transported as liquid by ships, road, or rail, in insulated tanks at temperatures well below the ambient temperature and at much lower pressures.

The first long-distance CO_2 pipeline went into operation in the early 1970s. In the United States, over 2,500 km of pipeline delivers more than 40 $MtCO_2$ per year from natural and anthropogenic sources, mainly to locations in Texas where CO_2 is used to improve the oil recovery factor. These pipelines operate in a "dense phase" mode (in which there is a constant progression from gas to liquid without a pronounced phase change), and at ambient temperatures and high pressures. In most of these pipelines, the stream is driven by compressors at the pipeline upstream end, although some pipelines have intermediate (auxiliary) compressor stations. The total length of the extensive network of carbon dioxide pipelines in the United States is 7,200 km, which is comparable to the length of the Druzhba pipeline network with a length of 8,900 km (Parsegov, 2017).

In some situations or locations, CO_2 transportation by ship may be more cost effective, especially when CO_2 needs to be transported over long distances or across the sea. The characteristics of liquefied CO_2 are similar to those of methane, and the technology can be scaled up to the size of large CO_2 carriers if the demand for such systems is to be met.

Transportation by road and rail tank cars is also a technically feasible option. These systems transport CO_2 at the temperature of -20°C and the pressure of 2 MPa. However, they are less cost effective than pipelines and ships, except for very small volumes, and they are unlikely to be suitable for large-scale projects (IPCC, 2005).

Figure 7. Carbon sequestration cost curve and potential to reduce greenhouse gas emissions



* Technologies that are still at an early (pilot) stage of development

Source: UNECE, 2021a.

STORAGE TECHNOLOGIES

The most promising CO_2 storage technology is its injection into geological structures (Khan et al., 2012). With this method, after the capture process, the CO_2 is compressed and injected into porous rock layers to the depth of one kilometre or more, beneath impermeable rocks. For these purposes, mainly four options for geological sites are considered: depleted oil and gas fields, deep aquifers, coal seams, and replacement of the buffer gas volume in underground gas storage (UGS).

Depleted hydrocarbon deposits

Several factors make depleted oil and gas reservoirs good candidates for CO_2 storage. First, the presence of an effective overburden is what allowed oil and gas to accumulate over geological periods. Second, since the porosity and permeability of their reservoirs were sufficient to produce fluids, they would provide CO_2 injection capability. The third aspect is that detailed knowledge of the geological structure and physical properties of these reservoirs is accumulated during exploration and production; therefore, there is a lower risk that the injected CO_2 will behave in an unexpected way.

CO_2 storage in depleted fields can be divided into two categories.

The first, Enhanced Oil Recovery (EOR), is a widely used process in which CO_2 is injected into the depleted oil fields as part of operating activity to produce oil that would otherwise be impossible: when CO_2 is injected, it dissolves in oil, significantly reducing its viscosity, which makes possible an increase in its fluidity. At the end of the field operation, almost all the injected CO_2 remains in the formation. Perhaps most importantly, CO_2 injection into depleted oil fields offers commercial benefits: in fact, it is already common practice in some regions to inject CO_2 solely to extract oil that would otherwise be impossible to get.

The second category is direct disposal of CO_2 in the depleted fields, without attempting to increase the hydrocarbon recovery factor, but exclusively using the reservoir layer as a free reservoir.

1. Sufficient porosity, permeability, formation thickness, and structural shape
Porosity and permeability ensure that a geological structure can store CO_2; significant thickness, along with lateral distribution of the aquifer, are critical for retaining a significant volume. The most obvious thing is to use the anticlinal structures of aquifers.

2. Sufficient depth
Ideally, the aquifer should have a minimum depth of ~ 800 m. While CO_2 is a gas on the earth's surface, at depth it can go into a liquid or "supercritical" state, with a high mass density convenient for storage.

3. Impermeable overburden
An impermeable barrier must overlap the aquifer to prevent CO_2 vertical migration, where it could be released into the atmosphere.

Coal seams

Coal deposits have been found in many sedimentary basins. Typically, coal seams are only mined down to ~ 1,500 m. In principle, deeper coal seams may be suitable as CO_2 underground reservoirs. The mechanism for CO_2 storage in coal seams differs from the one in aquifers. After CO_2 injection, it is strongly bound to the surfaces of the carbon matrix as a result of adsorption. By analogy with enhanced oil recovery in oil fields, this may have an economic incentive. Rather often, coal seams contain coalbed methane adsorbed onto the coal matrix. As CO_2 is adsorbed on the surface of the carbon matrix, the initially bound methane is desorbed and released, and it can be recovered from production wells. This process is known as Enhanced Coal Bed Methane Recovery with CO_2 and is used in the San Juan Basin in the United States. The most important feasibility criterion of this storage option is permeability of the coal seams, which determines whether the injected CO_2 can reach large areas of the coal matrix. Coal that is too deep to be mined is often highly compacted, and the permeability is too low to allow effective injection of CO_2. In addition, many coal seams swell when CO_2 is injected, which significantly reduces their permeability. In general, CO_2 storage in deep, low permeability coal seams continues to pose unresolved geoengineering problems (UNECE, 2021b).

Replacement of the buffer gas volume in the UGS

Currently, there are about 700 UGS facilities around the world (Makar'ev et al., 2020; Mikhalenko, 2018). To ensure the required daily capacity of the UGS at the stage of building a facility, a buffer gas volume is injected, which acts as a "cushion" and is not used during the period of operation. To optimize costs and improve the environmental friendliness of production, the possibility is under consideration of replacing the buffer of methane gas with non-hydrocarbon gases, in particular CO_2 (Dmitrievskiy et al., 2009).

This method was first tested in practice by Gaz De France at the Saint-Clair-Sur-Epte underground storage created in the Rauracian aquifer (Tek, 1989; Laille, Molinard, Wents, 1988). The Gaz De France specialists decided to replace 20% of the natural gas buffer volume with non-hydrocarbon gasses consisting mainly of nitrogen (87.4%) and CO_2 (11.2%), and others. Non-hydrocarbon gas injection began in 1979, and over the entire period, 60.2 mmcm of non-hydrocarbon gas has been injected.

When replacing the UGS buffer gas volume, it is advisable to select thermobaric reservoir conditions under which carbon dioxide is in a "supercritical" state, since in that case it is possible to reduce the mixing zone between carbon dioxide and methane (Khan, Dorokhin, Bondarenko, 2016; Khan et al., 2017; Dmitrievskiy et al., 2009).

It is also necessary to take into account a number of challenges when considering the issues of CO_2 injection into the reservoir, including:

- precipitation of secondary carbonates, which can lead to a decrease in the reservoir layer's permeability;
- equipment corrosion;
- interaction with formation water, which leads to CO_2 dissolution in water or interaction with the dissolved cations of divalent and trivalent metals, with further precipitation of carbonates;
- interaction with the rocks of the reservoir layer, which leads to changes in mineral composition;
- overflows and leaks of carbon dioxide;
- filtration-convective diffusion and mixing with the active gas volume (with partial replacement of the buffer gas) (Khan, Dorokhin, Bondarenko, 2016; Khan et al., 2017; Dmitrievskiy et al., 2009).

Partial neutralization of these problems is possible when carbon dioxide is injected into the fields with a high CO_2 content in the initial gas composition (Dmitrievskiy et al., 2009).

Gazprom is carrying out a number of studies to solve these challenges. Experiments were done to assess the impact of various mixtures of non-hydrocarbon gases (N_2, CO_2, O_2, CO) on the corrosion rate of the metal of underground equipment at the Severo-Stavropol UGS, as a result of which the following conclusions were drawn.

The temperature of the medium is of great importance for development of corrosive processes in a gas mixture containing aggressive components.

In the Severo-Stavropol UGS conditions, the corrosion rate in mixtures (N_2 + CO_2) in the absence of oxygen is minimal and amounts to 0.0028–0.0048 mm/year.

Addition of oxygen (O_2) to the mixture of non-hydrocarbon gases (N_2 + CO_2) dramatically changes the metal corrosion rate. The corrosion rate in the presence of O2 in a mixture of non-hydrocarbon gases in a moisture-saturated environment increases by an order of magnitude, and at a constant concentration of O_2 (2% vol.) with a changing concentration of N_2 and CO_2, constitutes 0.021–0.055 mm/year. Moreover, the higher the CO_2 concentration in a mixture with N_2 and O_2 in a moisture-saturated environment, the higher the metal corrosion rate. At the same time, in the absence of CO, an increase in the corrosion rate with an increase in the CO_2 concentration can be explained by the rapid diffusion of O_2 to the metal surface as a more aggressive gas, especially in the presence of water. A subsequent increase in the CO_2 concentration probably promotes loosening of the oxide film and better penetration of aggressive gases to the metal surface and its further oxidation.

Quite the opposite picture is observed when adding carbon monoxide (CO), in a mixture of non-hydrocarbon gases containing nitrogen, carbon dioxide, and oxygen. When there is carbon monoxide (CO) in the mixture, at a constant concentration of O_2 (2% vol.) and CO (0.5% vol.), with an increase in the concentration of carbon dioxide (CO_2) in the mixture, a decrease in the rate of deep corrosion of the metal is observed due to the formation of a more stable continuous oxide film on the metal surface, and in this, partial pressures (the ratio of concentrations in the mixture) of CO_2 and CO play an important role under certain thermobaric conditions.

Resistance of the metal to aggressive components (O_2, CO_2, H_2O) will depend on the properties of the films formed (continuous or not, thin or thick), the mechanism and rate of their growth, and the impact of various factors under certain thermobaric conditions.

In the absence of a continuous dense layer or a sufficiently porous layer of the film, the oxidizing gas freely penetrates through it to the metal surface, is adsorbed and enters into a chemical reaction with the metal. The limiting stage in the growth of the film's thickness is oxygen diffusion to the metal surface.

Another option for CO_2 storage is to inject it, after it is captured, directly into a deep ocean (to the depth of over 1,000 m), where most of it will be isolated from the atmosphere for centuries. This can be achieved by transporting CO_2 through pipelines or by ship to an ocean storage site where it is injected into the ocean's water column or onto the seabed. Ocean storage has not been used or demonstrated yet; it is still in the research phase. However, small field experiments have been done, and theoretical, laboratory, and model studies have been performed for 25 years, for the purpose of storing CO_2 in the ocean.

Oceans, whose average depth is 3,800 m, cover over 70% of the Earth's surface. Since carbon dioxide can dissolve in water, natural exchanges of CO_2 between the atmosphere and the water at the ocean's surface occur until equilibrium is reached. As the atmospheric concentration of CO_2 rises, additional CO_2 is gradually absorbed by the ocean. Thus, oceans have absorbed about 500 $GtCO_2$ (140 GtC) out of the total amount of anthropogenic emissions of 1,300 $GtCO_2$ (350 GtC) emitted into the atmosphere over the past 200 years. Due to an increase in atmospheric CO_2 concentrations resulting from human activities compared to pre-industrial levels, oceans are currently absorbing about 7 $GtCO_2 \cdot year^{-1}$ of CO_2 ($2\ GtC \cdot year^{-1}$).

Most of this carbon dioxide now remains in the upper layers of the oceans and has so far reduced the pH on the order of 0.1 on the ocean's surface due to the acidic nature of CO_2 in water. Now, however, there is little or no change in pH in the ocean depths. Models predict that over the next several centuries, the oceans will eventually absorb most of the CO_2 released into the atmosphere as CO_2 dissolves on the ocean's surface, and then mixes with deep ocean waters (IPCC, 2005).

AN EXAMPLE OF IMPLEMENTATION

Among actively developing CCS (carbon capture and storage) projects, we can single out the Porthos project (Netherlands), in which CO_2 from the port of Rotterdam will be transported and stored in a depleted gas field at the bottom of the North Sea. The companies participating in the project will supply CO_2 to a common pipeline running through the port region of Rotterdam. Then the CO_2 will be compressed at a compressor station and transported via an offshore pipeline to a platform in the North Sea, about 20 km offshore. From that platform, CO_2 will be injected into a depleted gas field. It is expected that in the early years of its existence, the depleted field will be able to receive about 2.5 million tonnes of CO_2 per year.

Onshore transport

The collective pipeline running through the Rotterdam port is approximately 30 km long and extends from the eastern end of Oude Maas in the Botlek area, through the Europoort area to the compressor station at Maasvlakte. The CO_2 collected will flow in a gaseous state at the pressure of 35 bar through a pipeline with a diameter of approximately 108 cm (42 inches).

A compressor station

The compressor site in Maasvlakt covers an area of about 2 hectares. The compressor station includes three compressors that compress the CO_2 up to a maximum pressure of 130 bar, for its subsequent transfer to an offshore platform.

Offshore transport

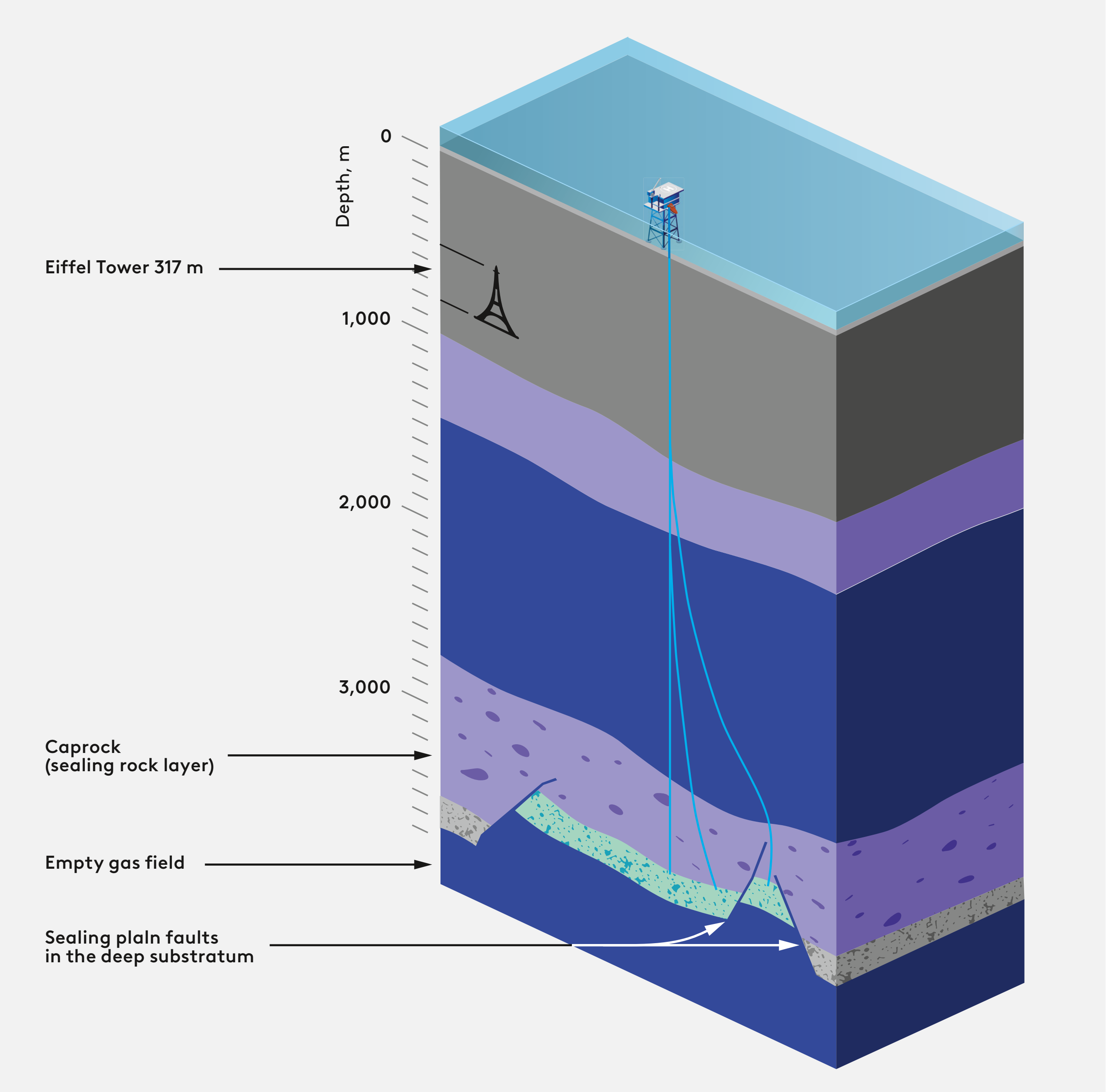
A 22 km pipeline with a diameter of approximately 40 cm (16 inches) transports CO_2 from the compressor station to the P18-A platform in the North Sea. The maximum pressure in the pipeline is 130 bar and the CO_2 is in a "supercritical" state. The former P18-A gas platform will be reused for CO_2 storage. The platform will be fitted with the equipment necessary to transport the collected CO_2 to injection wells. In addition, various technical systems will be installed for monitoring and remote control over the system.

Storage

The collected CO_2 will be stored in the pores of a sandstone substratum that early contained natural gas. For millions of years, that gas was hermetically trapped under high pressure, between the impermeable layer of caprock and sealing faults. The local pressure in this field, which gradually decreased during gas production, will rise again as a result of CO_2 injection. The reservoir layer will be constantly checked to make sure that the pressure does not exceed that at the start of the field development. The CO_2 from the pipeline will be injected into the depleted gas field below the P18-A platform, through a well (Figure 8).

This well is a metal casing anchored to the rock all the way down to the reservoir in the substratum. To make the available equipment suitable for CO_2 injection, a new tubing string is to be installed in the well. The wells will also have monitoring equipment used for checking the local pressure and temperature during CO_2 injection. Upon completion of the CO_2 injection – when the reservoir becomes full and at the correct ultimate pressure – the wells will be sealed with plugs.

Figure 8. Schematic of CO$_2$ storage in the Porthos project



Source: Porthos project.

CONCLUSION

Development of technologies for CO$_2$ capture and storage is currently at an early stage, and the potential for development of new cost-effective technologies is really great. Regulatory control requires early development and international synchronization. Under the current conditions, an extremely important component is exchange of experience and best practices. The next step will be movement from demonstration projects to formation of a full-fledged CCS market. CO$_2$ capture and storage technologies open the door to a decarbonised energy sector, if funding is available.

OFFSHORE WIND ENERGY: CHALLENGES AND PERSPECTIVES

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INTRODUCTION

Climate change is one of the biggest challenges of our time. Temperatures have been rising at 0.03°C per year over more than two decades (IRENA, 2017). Carbon dioxide (CO_2) and other air pollutants are accumulated in the atmosphere, absorbing sunlight and solar radiation. A large part of the greenhouse gas emissions is attributed to the supply and use of energy from fossil fuels. A transition from fossil fuels to renewable energy is the way to reduce energy-related carbon dioxide emissions.

In order to realise a transition to renewable energy and limit greenhouse gas emissions, strategic decisions to reduce greenhouse gas pollution have been made by leading players around the world. The Paris Agreement, which seeks to limit temperature rise to well below 2°C, was signed by 196 parties in 2015 and entered into force in 2016. In 2020, the European Parliament voted to approve the European Green Deal, a set of policy initiatives by the European Union with the goal of making Europe climate neutral by 2050. The European Green Deal Investment Plan was presented in 2020. The USA announced a new target to achieve a 50–52 % reduction from 2005 levels in economy-wide net greenhouse gas pollution by 2030. China aims to achieve carbon neutrality by 2060.

These policies include expansion of wind energy generation. Wind energy is one of the fastest-growing renewable energy technologies. An increasingly important role in the global market is played by offshore wind energy. An example of an offshore wind farm, the Rampion Offshore Wind Farm in the United Kingdom, is shown in Figure 9. In this paper, the perspectives of offshore wind energy are reviewed. Advantages and challenges of the development of offshore wind energy are discussed.

EARLY DEVELOPMENT OF OFFSHORE WIND ENERGY AND REGIONAL DIFFERENCES

The advantages of offshore wind energy compared to onshore wind energy include availability of new large areas for installation of wind turbines, the possibility of building larger and taller turbines, stronger and steadier winds at sea, easier maritime transportation, much less negative visual and noise impact (Mishnaevsky et al., 2017). Further, coastal areas often have high energy needs, since a large part of the population in many countries, such as the USA, China, and Northern Europe, lives in coastal areas, with a high concentration of industry there. Prominent examples of highly populated coastal regions include the East Coast of the United States (with New York, Boston), Eastern China (with Shanghai, Tianjin, Beijing), Northern Europe, and Scandinavia.

History of offshore wind energy development. The first offshore wind park was constructed in 1991 in Vindeby off the coast of Denmark, with eleven 450 kW turbines, placed in shallow waters. During the next 10 years, the growth of offshore wind energy was quite slow, and only a few wind farms were built in Europe. In 1998, the Danish and British governments announced plans to build several more wind farms (Ørsted, 2019). The total market volume of offshore energy was 0.25 GW, with a typical project size of 20 MW. In 2002, Hornns Rev 1 offshore wind farm, with 160 MW, was built by

Figure 9. Rampion Offshore Wind Farm, United Kingdom

Source: Photo by Nicholas Doherty/Unsplash.

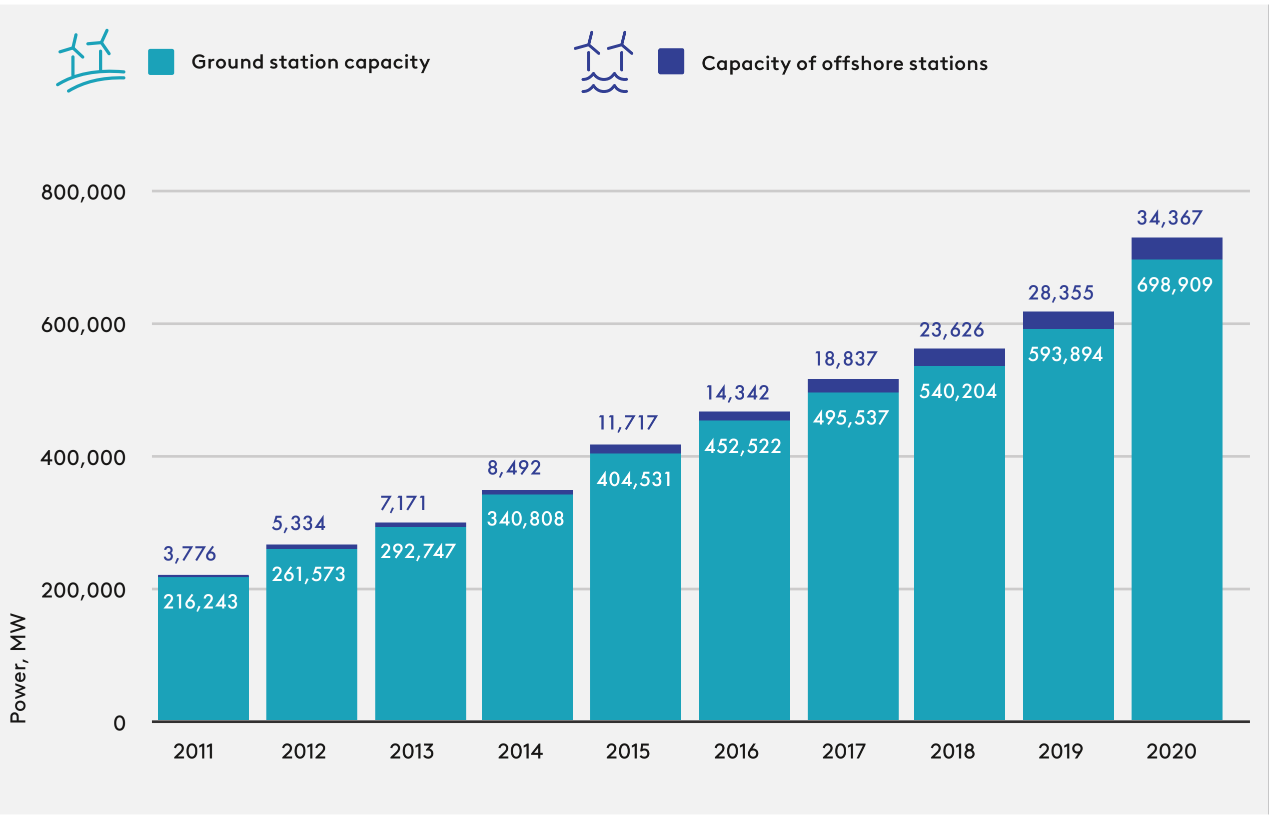
the Danish energy company Elsam (now Ørsted) to the west of Denmark. In 2001, the British property management company Crown Estate initiated a leasing round for the first UK offshore wind farm. Two further leasing rounds were initiated in 2003 and 2008. At this time, the market volume was 6.4 GW, with a typical project size of 100 MW (Ørsted, 2019). At the next stage, 2012–2017, efforts to reduce the costs of offshore wind energy were intensified, with a view to the austerity policies, setting the target at EUR 100/MWh by 2020.

In the last decades, global installed wind energy generation capacity increased drastically: from 7.5 GW in 1997 to some 564 GW by 2018. Further, wind generation capacity expanded by 10% in 2019, with 58.4 GW of new capacity added. In 2020, the wind sector installed 111 GW, and global installed offshore wind capacity reached around 34.4 GW (28.4 GW in 2019) or 5% of total wind capacity (Buljan, 2021). Total installed offshore wind capacity is expected to reach 228 GW in 2030 and near 1,000 GW in 2050, representing nearly 17% of total global installed wind capacity in 2050 (IRENA, 2019).

The global offshore energy market has grown and is still growing very fast, at a compound annual growth rate (CAGR) of 14.21%, in 2020–2024 (PR Newswire, 2021), while the market for wind power in general is expected to grow at a CAGR of 7.9% in 2020–2025 (Businesswire, 2020). For comparison, the global automotive industry will expand at a CAGR of 2.78% until 2024.

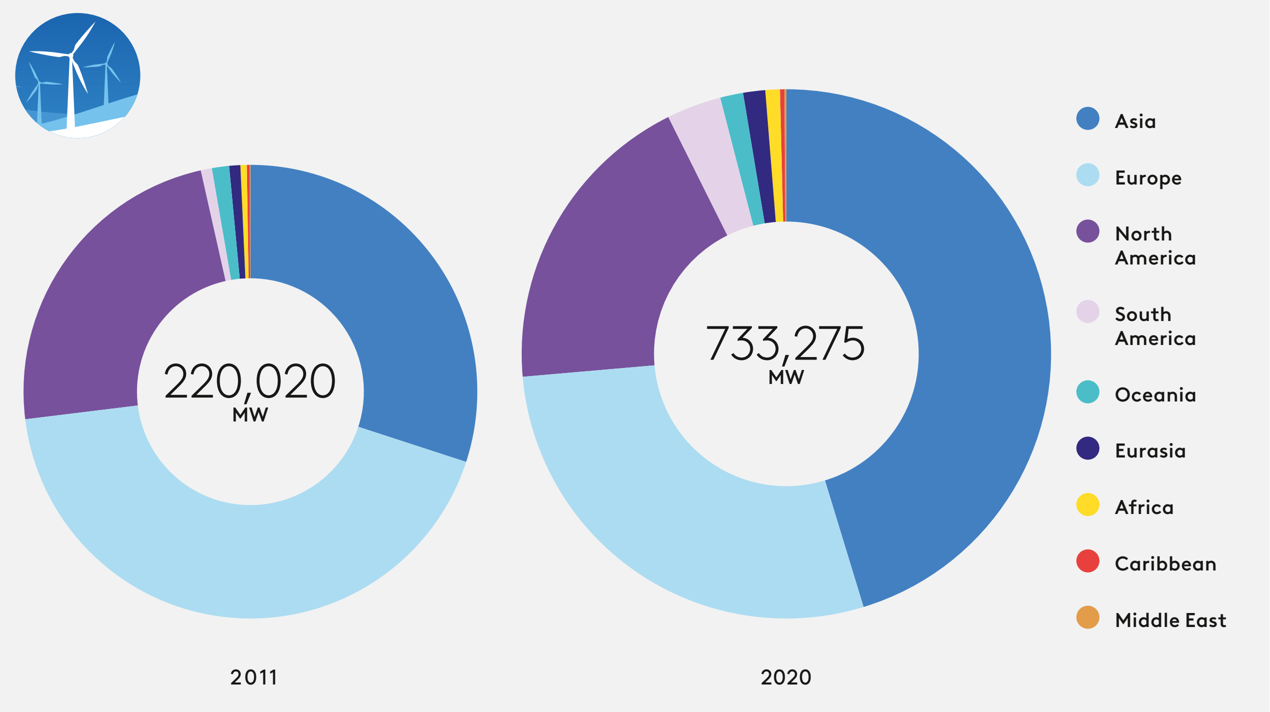
There are significant regional differences in the development of offshore wind energy.

Figure 10. Total installed capacity of wind power plants (worldwide), MW



Source: IRENA, 2021.

Figure 11. Total installed capacity of wind power plants (by region), MW



Source: IRENA, 2021.

Europe: Europe is the leading region in offshore wind development. European companies represent 90% of the global market for offshore wind energy. Three out of the top five global offshore wind turbine manufacturers are based in Europe (Statista, 2021). Most of the offshore wind capacity is located in Europe, 24.9 GW. In 2019, 502 new offshore wind turbines were connected to the grid in Europe. Among European countries, the highest installed capacity is in the United Kingdom (44% of all offshore wind energy installations in MW), followed by Germany (34%), Denmark (7%), Belgium (6.4%) and the Netherlands (6%).

Asia: In 2019, China had 40% of global added offshore wind capacity in 2019, with a record 2.5 GW (Baiyu, 2020). In 2020, China become the third-largest offshore wind energy country, after the UK and Germany (Evwind, 2021). By 2030, China will add a further 52 GW of offshore wind capacity, for a total of 58.7 GW. China is expected to become the global leader in offshore wind energy, holding the highest offshore wind power market share (Shenvekar, 2021).

In India, the development of offshore wind energy is still in an early stage. The country has a large potential for offshore wind, with its 7,600 km of coastline and well-developed onshore wind energy, which is currently the second-largest renewable energy source in India. The Government of India has set two ambitious offshore wind targets, 5 GW by 2022 (this target will probably be missed) and 30 GW by 2030.

North America: Twenty-nine MW of offshore wind are installed in the United States. The Block Island Wind Farm (30 MW) has been in operation since 2016. The Coastal Virginia Offshore Wind pilot project will be fully constructed in 2026. The U.S. Department of Energy expects the installation of 22 GW offshore wind power plants by 2030, and 86 GW by 2050 (U.S. Department of Energy, 2015).

Russian Federation: While Russia has the largest offshore wind energy potential in the world (~23 PWh/year), its power generation from wind farms is currently only 148 GWh, and no offshore wind farms have been built (Kudelin, Kutcherov, 2021; Lu, McElroy, 2017). Several years ago, there were reports that the Chinese company Sinomec was planning to build the first offshore wind park in Russia, in Kemsky District, with a capacity of 60 MWh (Asia Times, 2018). These plans were connected to the Chinese vision of a "Polar Silk Road".

It should be noted that while northern regions have a large wind energy potential, a number of challenges have to be overcome to install offshore wind turbines in areas that are covered by ice in the winter. These challenges include additional loads (due to the ice), sea icing, additional strength requirements, and the additional weight of the structures (Maier, 2015).

CHALLENGES TO THE DEVELOPMENT OF OFFSHORE WIND ENERGY

While offshore wind energy is a promising and efficient way of generating energy, its development faces some challenges.

Maintenance of offshore wind turbines. Stronger winds in offshore locations also mean a higher load on the wind turbines, leading to higher failure rates. The failure rate per turbine per year is four times higher for offshore than for onshore wind turbines, for the blades and hub (Dao, Kazemtabrizi, Crabtree, 2019). The average failure rate of an offshore wind turbine is 8.3 failures per turbine per year. That includes 6.2 minor repairs (costs below EUR 1,000), 1.1 major repairs (103–104 EUR), 0.43 major replacements, and 0.7 failures where no cost data can be categorised (Carroll, McDonald, McMillan, 2016). Figure 14 shows a micrograph of eroded blades, which is the mechanism most often damaged, leading to drastic reduction of energy generation of wind turbines (Mishnaevsky et al., 2020, 2021). An average blade repair (offshore) can cost up to USD 30,000 (for onshore blades, it can be two times less) (Stephenson, 2011). With four times more frequent failure and two times higher repair costs, maintenance of wind turbines becomes an important factor for offshore wind energy costs. This also sets much higher requirements for the wind turbine design, materials for offshore wind turbines, and repair quality.

Environment protection. There are constraints on the development of wind energy related to the necessity to protect marine ecosystems and biodiversity. In Europe, the EC guidance document "Wind energy developments and Natura2000" provides recommendations on wind farm developments in or adjacent to Natura2000 sites (nature protection areas in the European Union). Measures to minimise the effect of wind turbines on wildlife are based on the "mitigation hierarchy": avoid — reduce — compensate — offset. Strategic impact assessments form the basis for Environmental Impact Assessments (EIAs), which determine the necessary mitigation measures.

In 2020, a new Offshore Energy and Nature Coalition was launched, a partnership between leading environmental NGOs, transmission system operators, and the wind industry, seeking to preserve nature and marine ecosystems, while expanding offshore wind energy.

Quick expansion. Added global wind energy in 2023–2025 is expected to be 65 GW per year and could be 100 GW if accelerated. This is rather quick expansion, which could stretch the value chain, and requires a clear regulatory framework, more investment in grids, policy support, and places additional demands on offshore vessels. Another important task is related to the integration of offshore wind turbines with the existing grids.

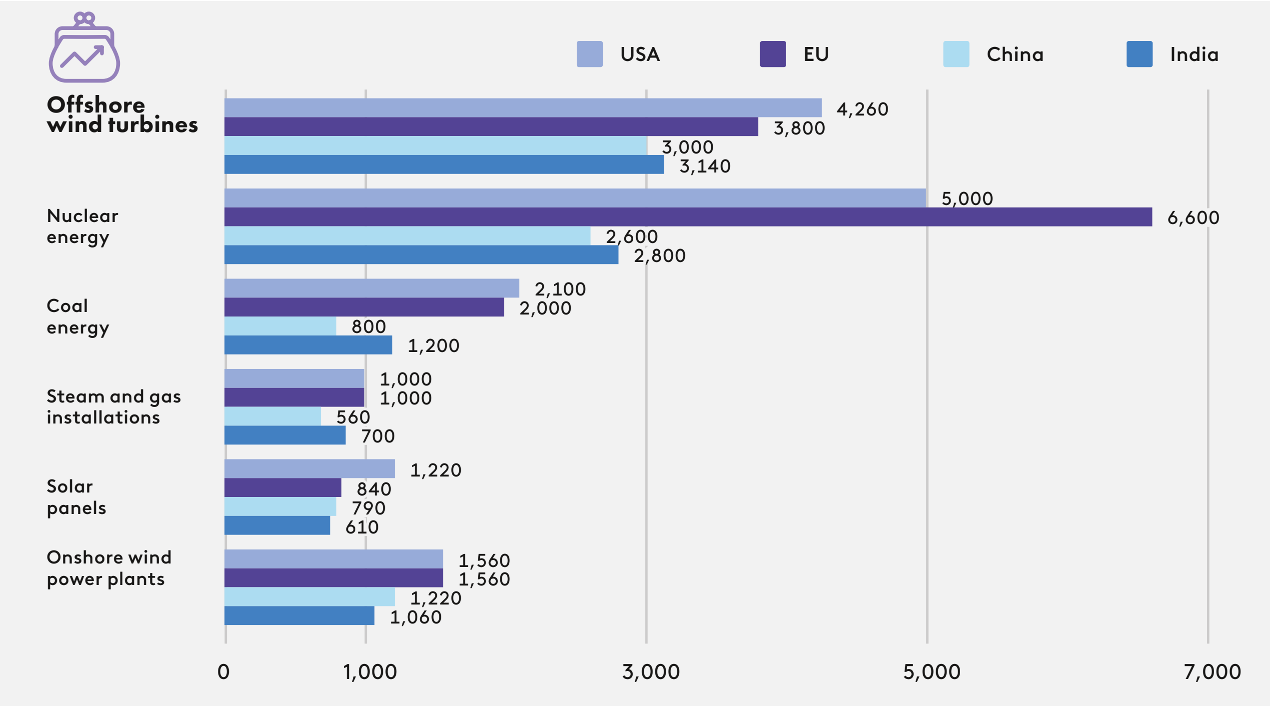
Costs. Offshore wind energy is still more expensive than onshore wind, or most other energy-generation technologies. The higher energy costs are related to the higher costs of energy transmission and installation, as well as other technical challenges. Still, the costs are being reduced every year. The global weighted average cost of offshore electricity was USD 0.127/kWh in 2018 (more than twice as high as onshore, hydro, etc.), and USD 0.115/kWh in 2019. Reduction of wind energy costs by 37–49% is expected by 2050, thanks to technology innovation and industry maturation, competitive incentives, and economic factors (Wiser et al., 2021).

TRENDS IN DEVELOPMENT OF WIND ENERGY

Several promising directions of development of offshore wind energy are being explored.

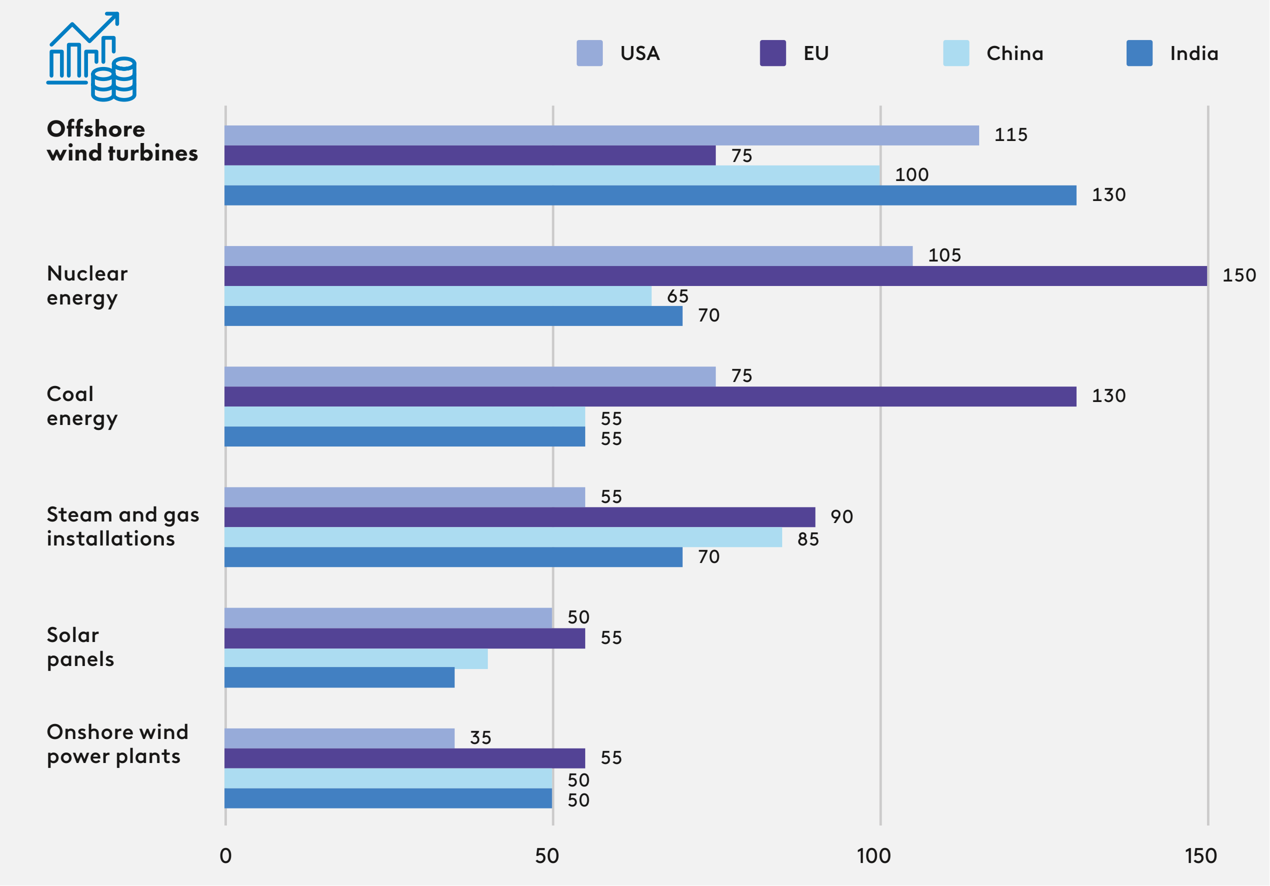
Large and extra-large wind turbines. The bigger the wind turbines are, the bigger the swept area, and thus, the more energy is generated. The average rated capacity of offshore wind turbines has been continuously increasing during the last decade, by more than 200% from 2010 to 2018 (Fernández-Guillamón et al., 2019). Several large companies are now working on large and very large offshore wind turbines. GE developed the largest operating 12 MW wind turbine, Haliade X, and upgraded it to 13 MW, with 107-metre-long blades and a 220-metre rotor. Siemens Gamesa in 2020 announced its work on developing wind turbines with 15MW capacity and a 222-metre rotor, which is expected to be commercially available in 2024.

Figure 12. Capital expenditures, 2019, $/kW



Source: IEA.

Figure 13. Total present value of electricity, 2019, $/MWh



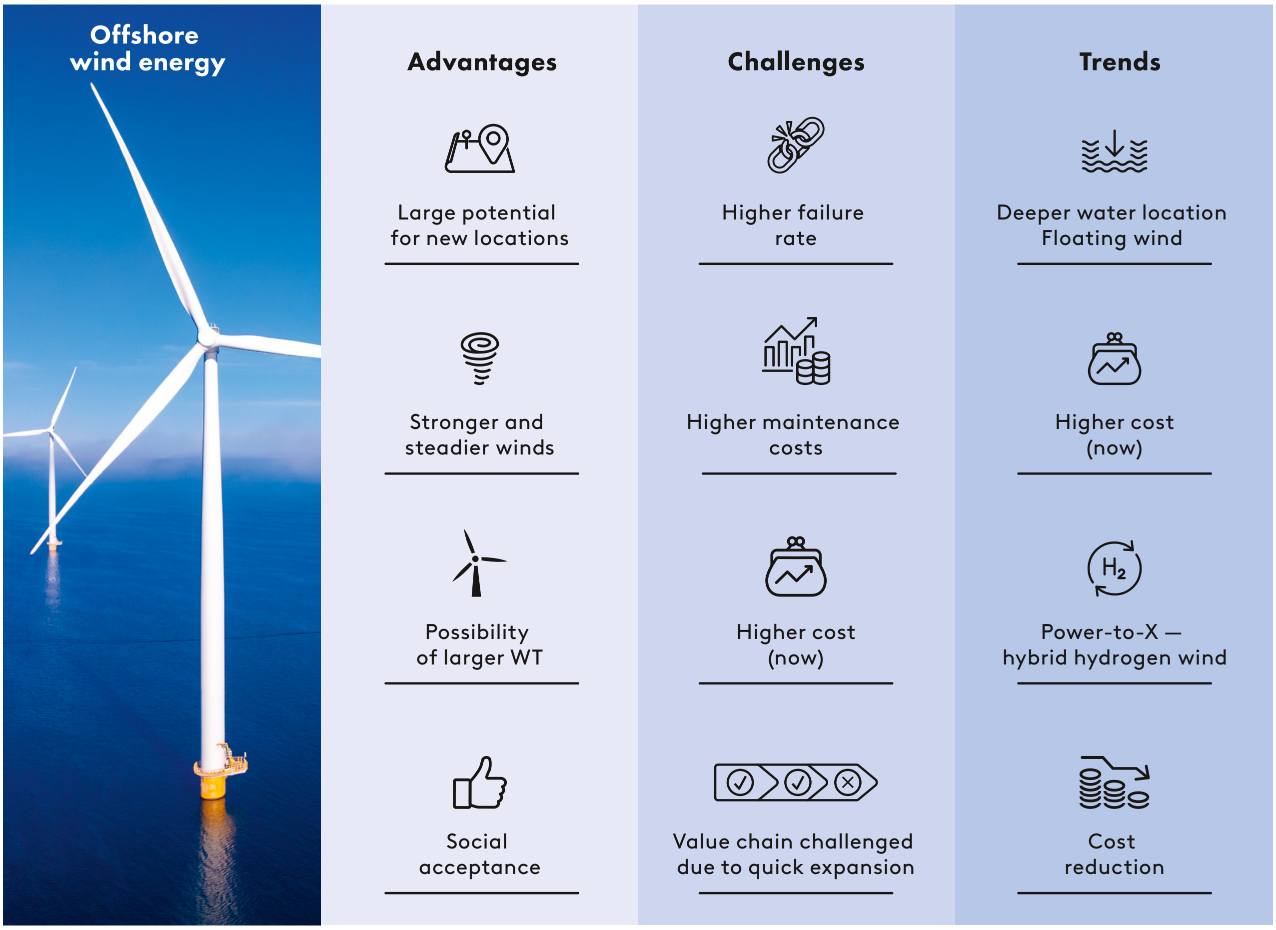
Source: IEA.

Figure 14. The leading edge erosion of a wind turbine blade

Floating wind turbines. Offshore wind farms are typically located in shallow waters (up to 60 metres deep); however, the projected minimum distance to shore is expected to increase by 53% in Europe from 2020 to 2029. Around 80% of Europe's offshore wind resources are located in waters more than 60 metres deep (Tacx, 2019). With increased water depth, the costs of bottom-fixed offshore wind structures increase, and the wind farms become less financially attractive, especially, for water deeper than 60 metres. The development of floating wind energy (offshore wind turbines mounted on a floating structure) creates new possibilities for expansion of wind energy in deeper water. The resources in regions with water depths exceeding 50–60 metres exceed the shallower depth resource by a factor of 10 (Stiesdal, n.d.). In countries with limited shallow water, for instance, Japan, this is an especially promising direction. The Hywind Scotland floating wind farm, with five floating turbines and a total capacity of 30 MW, was developed by the Norwegian energy company Equinor ASA and commissioned in 2017. Floating offshore wind turbines require a mooring system and a flexible cable that can follow the movements of the floating foundation, and that can increase the energy costs. An important direction in the development of floating wind turbines is the development of floating foundations, which should dampen the movement from waves.

Hybrid wind energy and hydrogen generation systems. Offshore wind turbines can power water electrolysis to produce hydrogen, which can be used in vehicles and power plants. In 2020, the EU issued its "hydrogen strategy for a climate-neutral Europe" (EU Hydrogen Strategy), in which hydrogen is considered "a key priority to achieve the European Green Deal and Europe's clean energy transition". Currently, 75 millions tonnes of

Figure 15. Advantages, challenges, and trends of offshore wind energy



Source: developed by the author.

hydrogen are produced annually in the world, mostly from fossil fuel, emitting 830 $MtCO_2$ every year (Siemens Gamesa, 2021). If hydrogen is produced from wind energy, it will allow drastic reductions of CO_2 emissions. A number of companies are working now on developing hybrid offshore wind and hydrogen generation systems. Siemens Gamesa together with Siemens Energy are working on the development of a fully integrated offshore wind-to-hydrogen system (Rasmussen, 2021), in which hydrogen is produced by electrolysis directly on the turbine platform, thus reducing losses in the system. Shell and Eneco are working to create a green hydrogen hub in the Port of Rotterdam, with the 759 MW Hollandse Kust Noord offshore wind project in the North Sea, and the 200 MW electrolyser in the Port of Rotterdam.

Hybrid wind–hydrogen systems generally belong to a group of so-called Power-to-X technologies, where power (electricity) is converted into other substances, typically a form of storable chemical energy. Apart from hydrogen, on the "X" side, the power can be stored in heat or in chemicals (Fernández-Guillamón et al., 2019).

Energy islands. The Danish government has recently unveiled a new climate package, which includes building two giant "energy islands" (one of them artificial), which will act as hubs connecting several offshore wind farms, and distributing power between the countries connected to the island. The artificial energy island in North Sea will serve as a hub for 200 offshore wind turbines.

Figure 15 summarises the advantages, challenges, and trends of offshore wind energy.

CONCLUSION

Offshore wind energy is an efficient and environmentally clean energy-generation technology, which is expected to play a key role in the transition to renewable energy. The advantages of offshore wind energy include the possibility of building larger turbines, steadier wind, and higher wind speeds compared to onshore structures. Europe is now the leading region in offshore wind development, and European companies represent the main part of the global market for offshore wind energy. However, other regions are also developing ambitious programmes for offshore wind energy. The challenges in the development of wind energy include higher maintenance costs, higher failure rates, currently higher energy costs (which are, however, being reduced), and the possibility of stretching the value chain with quick expansion of offshore wind energy. Recent trends in the development of offshore wind energy include building larger and taller wind turbines, developing floating wind turbines, with the potential to expand the wind turbine location to deeper water, and also dealing with the challenge of energy storage. All this proves the essential character of offshore wind energy for the CIS region with a special emphasis on Russia, as well as the need to implement the latest technologies within the sphere.

ARTICLE OF YOUNG RESEARCHERS

HYBRID MATERIALS FOR ALTERNATIVE ENERGETICS

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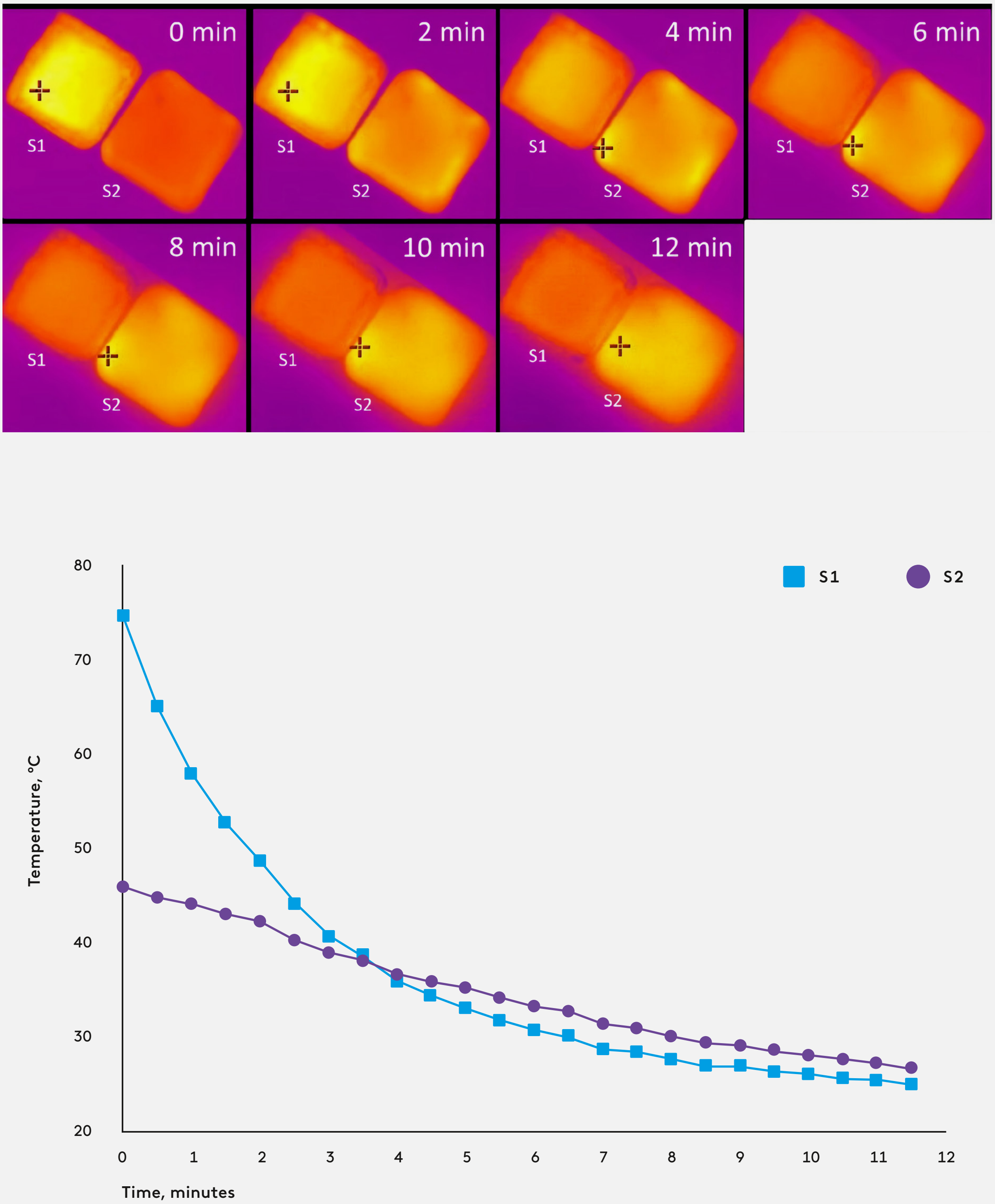
A systematic approach to solving the issue of sustainable economic development requires the development of fundamentally new functional materials for alternative energetics, which can ensure a smooth and crisis-free transition to a carbon-free economy. Hybrid materials consisting of natural and synthetic components are of particular interest. Such materials become indispensable in the development of highly efficient systems for storage and transportation of components of greenhouse gases (methane, carbon dioxide), solar cells, chemical current sources, hydrophobic and superhydrophobic coatings, piezo- and thermoelectric generators, thermal storage devices, photocatalysts for generating hydrogen from water, new catalysts to improve the processing of carbon-containing raw materials, etc.

At the Gubkin Russian State University of Oil and Gas, systematic research is being carried out in the field of natural nanomaterials based on aluminosilicates (halloysite, sepiolite, etc.), as well as nanocellulose. These materials, with their availability and low cost, have extremely high resistance to external factors (temperature, pressure, aggressive media), mechanical strength, and biocompatibility. This makes them very competitive compared to expensive and toxic synthetic carbon nanomaterials.

One of the most promising directions in energy saving and decarbonisation of heat-generation processes is the use of phase change materials (PCM) for heat accumulation. It is well known that during the transition of substances from a solid to a liquid state (melting), heat is absorbed from the environment; for many compounds, the value of the absorbed energy is very high. In the reverse process, with a decrease in temperature, the substance solidifies followed by the release of the accumulated heat back into the environment. In these processes, the temperature of the substance does not change, but energy is released or absorbed (the latent heat of fusion or enthalpy of fusion). As an example, consider the melting of ice: melting 1 kg of ice releases 335 kJ of heat. The same amount of heat is required to heat the same amount of water from 1 to 84 degrees Celsius. In addition to water, there are about 500 substances and materials that can be used as so-called phase change heat accumulators (PCHA). Examples of such applications are heat-storage building materials, thermal protection devices for radio-electronics, solar thermal collectors, and underfloor heating with heat-storage functions. Energy savings from the use of this effect in various sectors can reach up to 25%.

Figure 16. Top: thermography images of the composite polystyrene/microfibrillar cellulose matrix (S1) and the same matrix with 70 wt% loading of PCM (S2). Bottom: time dependence of the composites' temperature determined from the thermography images (black – S1, red – S2)



Among the serious disadvantages that prevent the widespread use of PCHA is a significant change in the volume of the material during the phase transition process (melting and solidification), and the need to keep the liquid phase within a fixed volume to avoid any leakage or evaporation as well as a toxic or corrosive effect. With such undesirable conditions, there is a constant decrease in the efficiency of the heat-storage devices, while the minimum period of their guaranteed stable operation in the industry is at least three years. To prevent such problems, either bulky containers or microcapsules containing PCM are often used. In all cases, the need to encapsulate PCM significantly increases the costs of energy saving and often reduces the total economic and environmental effects to zero.

Ideally, PCHA should represent a product in which a mechanically strong and heat-conducting matrix and the PCM itself are a single material, in which melting/solidification cycles are not accompanied by any visible changes (decrease in strength, evaporation, change in the volume of the working substance, etc.).

We have obtained new materials in which PCM is located in a matrix of microfibrillar cellulose or natural aluminosilicate nanotubes representing a mechanically robust system with a specific surface area of 200–250 m^2/g. Due to the high specific surface area and the presence of polar groups on the surface, PCM is strongly absorbed on the matrix, forming the core-shell system where the thickness of the shell (PCM) is extremely small and does not prevent adhesion interaction with the core, leading to coalescence into large droplets during the phase transition process. Therefore, melting does not cause any noticeable external changes in the material. Preliminary studies have shown that the obtained thermal accumulators scarcely change their mechanical and thermophysical characteristics during more than 150 heating/cooling cycles.

The second promising area of application of hybrid materials is related to the possibility of desalination of seawater using solar energy. The most interesting thing here is the development of a technology that mimics what takes place naturally in mangroves. There, capillary and osmotic forces induce the rise of saltwater from the root system to the developed outer surface of the leaves, and the salt concentration is adjusted by ion diffusion in the opposite direction. Unlike a natural process, evaporation of pure water can be carried out not only due to natural transpiration but also due to intensive heating of an artificial surface, due to the efficient conversion of solar energy into heat. For this purpose, highly porous and mechanically robust hybrid materials have been developed, providing an efficient capillary water rise via a tuned architecture of the materials based on hydrophobic thermoplastic polymers and nanocellulose. The transformation of solar energy into thermal energy is provided at the same time due to the melanin pigment extracted from the ascomycetes (so-called sac fungi) synthesized in the process of submerged cultivation. The productivity of the laboratory installation for desalting seawater ranged from 1.5 to 2.0 litres per square metre of a surface per hour.

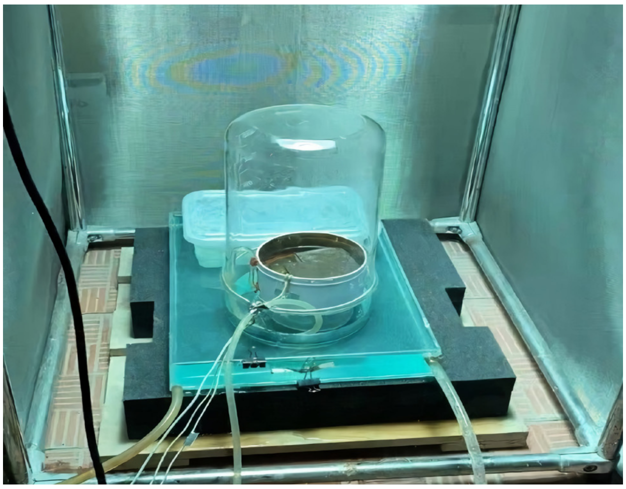
The freshwater obtained in this way can be used for further energy storage either as a source of hydrogen via its electrolysis on solid ion-conducting membrane elements powered by solar batteries, or employing the osmotic energy of mixing fresh and seawater. Bear in mind that a cubic metre of freshwater mixed with seawater is able to generate up to 0.75 kWh of “blue” energy.

An important direction in the development of processes for decarbonisation of the economy is methane and CO_2 capture in the form of solid gas hydrates. The main components of both natural (associated petroleum gas, mine gas) and man-made (flue gas) gas mixtures contributing to the greenhouse effect are carbon dioxide (CO_2) and methane (CH_4). These gases, as well as other components of the above mixtures (nitrogen, ethane, propane, hydrogen sulphide), are capable of forming gas hydrates. Moreover, the type of gas is one of the key factors affecting the thermobaric conditions for the formation of hydrates. This feature makes it possible to consider gas hydrates as a reliable basis for the development of a technology for separating gas mixtures as well as their sequestration. Note that the capacity of methane hydrate reaches 160 normal volumes of gas per 1 volume of hydrate, which makes these compounds promising for storage and disposal of greenhouse gases. The necessity for more energy is leading to a search for more efficient approaches to the storage/utilization/disposal of greenhouse gases such as methane and carbon dioxide.

Figure 17. Composite material based on microfibrillar cellulose and fungal melanin

Note: material is used for the capillary rise and evaporation of seawater.

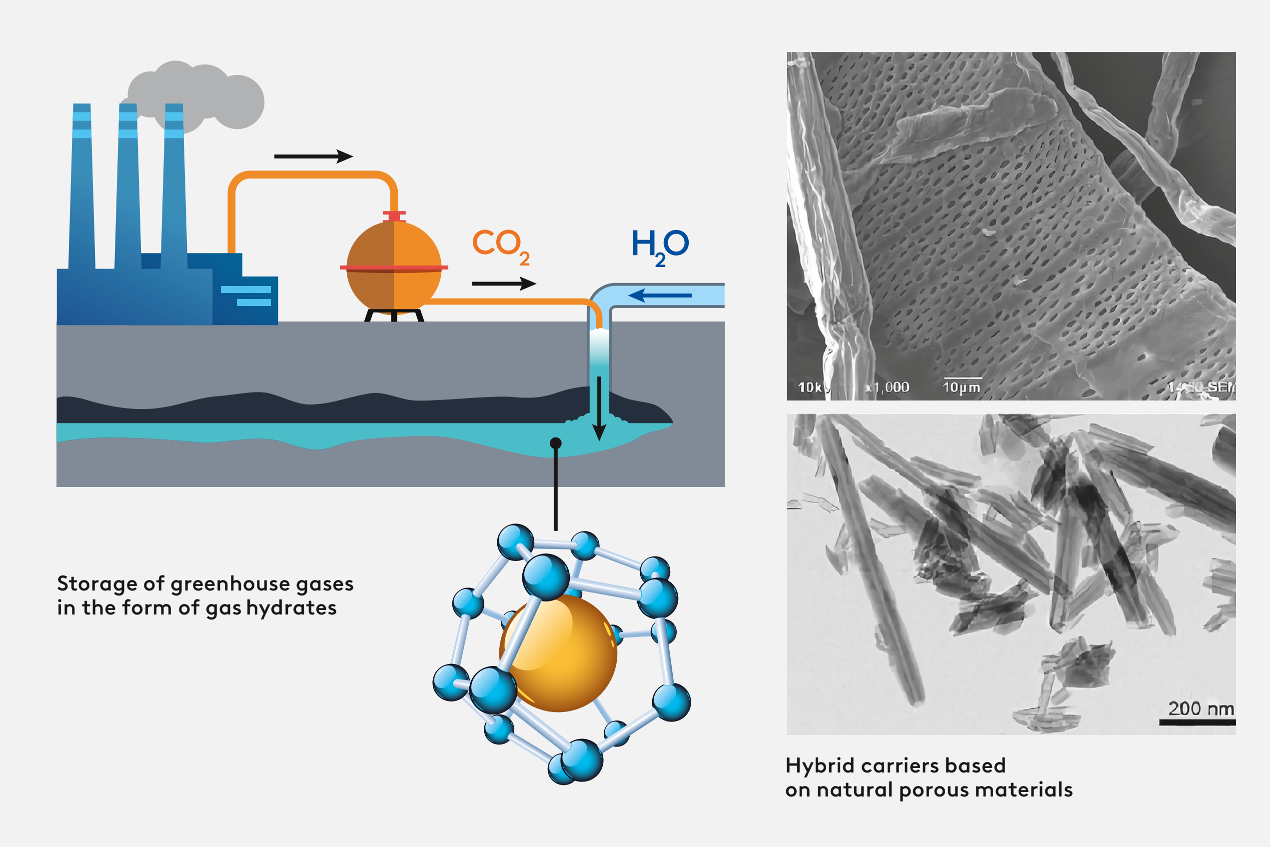
Figure 18. A working prototype for simulating the operation of a solar seawater desalination device based on a hybrid porous material



Note: the model of a quasi-solar emitter was made using a mercury-free gas-discharge plasma lamp.

The formation of gas hydrates in porous materials as carriers has obvious advantages, such as mild reaction conditions due to a decrease in the supercooling required for hydrate nucleation (increased contact area of water and gas; formation of a hierarchical material surface that catalyses hydrate nucleation), the high absorption capacity of a gas and the high rate of conversion of water into hydrate (again due to the highly developed water–gas surface). The traditional porous materials are activated charcoal, sand, silica gel, and some zeolites. Such systems are often unstable (destroyed after the decomposition of the hydrate, such as systems based on silica gel) or their energy capacity is low, which is explained by the small surface area at high water content. A systematic study of hybrid carriers based on cellulose derivatives makes it possible to reveal the key parameters of these materials that affect the rate of gas binding to hydrate, gas capacity, and the selectivity of absorption of various gases. The directed design of such materials allows optimisation of the water content in solid hydrates, the temperature, and the pressure of the hydrate formation reaction at an acceptable mechanical strength of the carrier used. This will reduce the induction time for the nucleation of hydrates, increase the rate of their growth and the duration of their life cycle (for cyclic use, for example, in capturing carbon dioxide and its subsequent transformation into valuable organic compounds). In the case of their use for the disposal of carbon dioxide, the mechanical strength of the proposed carriers will preserve the required geomechanical properties of the stratum. The proposed materials will also meet environmental requirements. Specialists at the laboratory of gas hydrates of the Russian State University of Oil and Gas are currently conducting intensive research to find and develop the optimal structure of solid porous carriers that provide optimal rates of formation of clathrate compounds of methane and carbon dioxide in porous media, to solve the problems of decarbonisation and reduce the impact of greenhouse gases on the climate.

Figure 19. A schematic illustrating the application of natural cellulose materials and halloysite nanoclay tubes as the medium for synthesis of greenhouse gas hydrates



Storage of greenhouse gases in the form of gas hydrates

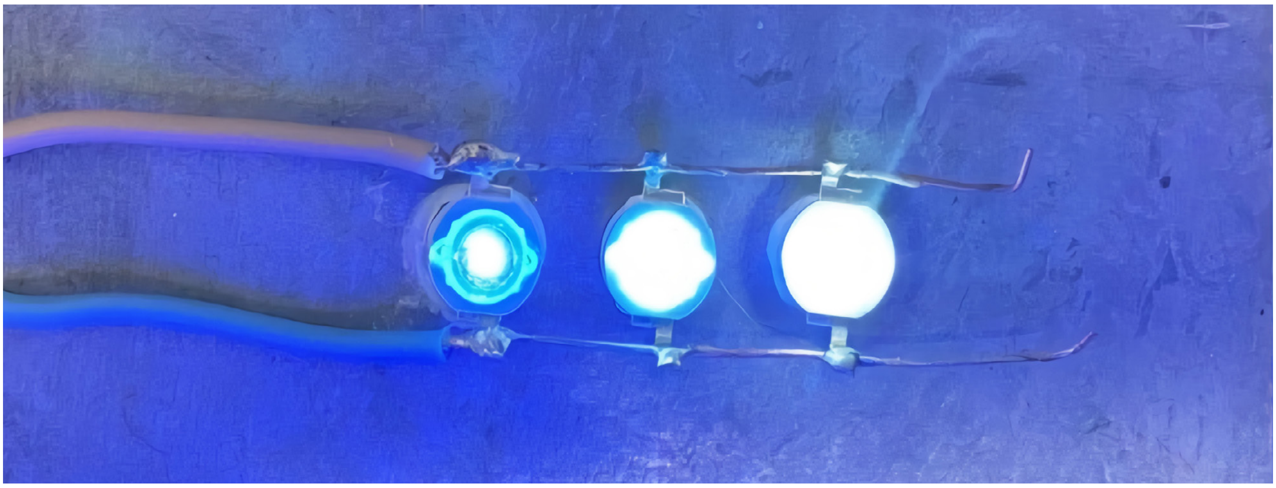
Hybrid carriers based on natural porous materials

The percentage of ultraviolet (UV) radiation in the solar spectrum is only 3–5%, but its negative role in the life processes of living organisms as well as in the long-term operation of numerous materials used by humans is extremely high. UV radiation is a powerful damaging factor in the process of photosynthesis, and the degree of inhibition of the photosynthetic ability of plants depends on both the wavelength and the intensity of irradiation. Almost all synthetic polymeric materials are extremely sensitive to short-wave radiation, which is accompanied by rapid oxidative degradation of materials. Traditional silicon batteries scarcely use the UV part of the light spectrum for conversion into electricity, thus reducing the efficiency of solar cell devices, and the new generation solar cells based on perovskite experience a strong UV destructive effect.

One of the ways to solve all these problems is to create stable and inexpensive materials capable of converting UV radiation into the visible part of the spectrum. Synthetic luminophores are typically very expensive and are synthesized using rare-earth elements, while the special dyes used are unstable and quickly lose their effectiveness.

Researchers from the Russian State University of Oil and Gas attempted to synthesize effective coatings that transform UV radiation into visible light by the design of carbon quantum dots directly in a solid matrix of synthetic polymers, which ensures unprecedented stability of their optical characteristics. During long-term testing of the material (more than a month), a continuous increase in the working power of silicon solar cells and the invariability of their fluorescence spectra were observed.

Figure 20. Radiation of high-power ARPL-1W-EPL UV365 LEDs without coating (left) and with polymer coating with CQD of different thicknesses (centre and right)



The coatings developed are very promising not only for processes of solar energy conversion, but also for the protection of polymer structural and decorative materials made of plastic, as well as in agriculture for protecting plants from stress and increasing their photosynthetic capabilities, and increasing the efficiency of photobioreactors and in photochemistry.

ARTICLE OF YOUNG RESEARCHERS

THE USE OF HYDROGEN AS AN ENERGY STORAGE SYSTEM FOR SOLVING CHALLENGES OF THE WATER AND ENERGY COMPLEX OF CENTRAL ASIA

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INTRODUCTION

The countries of Central Asia (CA) have significant technically exploited hydropower potential, estimated at 510.1 TWh/year, of which less than 10% is currently used (Eshchanov et al., 2019). This potential varies considerably from country to country, depending on their water availability. Large arid and semi-arid plains in Kazakhstan, Uzbekistan, and Turkmenistan have minimal or even no hydropower potential. Mountainous regions of the east and southeast of CA, including Tajikistan (61.1% of the total potential), Kyrgyzstan (19.4%), and partly Kazakhstan (12.1%), are characterised by a large water supply due to heavy rains and snowfall, which explains their high hydropower potential.

For a long period, the efficient operation of the water and energy complex of the region was ensured by the Soviet model of cooperation, where the key element was the United Energy System of Central Asia (CA UES). The CA water and energy complex was formed and developed in a complex manner, as an important component of the united CA economic region. In accordance with this, plans for the management of water and energy resources in CA were developed and implemented, providing a special mechanism to compensate for costs and distribute benefits among the countries of the region (World Bank, 2010). Most of the electricity generated by the Naryn (Syr Darya River basin) and Vakhsh (Amu Darya River basin) cascades of hydroelectric power stations (HPS) was transferred to neighbouring republics during the summer with irrigation water releases, and Kyrgyzstan and Tajikistan received in return (from the united reserve material and technical resources) electricity, natural gas, coal and fuel oil, for the operation of their thermal power plants in the autumn-winter seasons (Vinokurov, 2008).

After the disintegration of the USSR and the termination of centralised financing of the CA UES, the order of its operation was disrupted. Lacking their own energy resources, countries with a predominant hydropower industry began to release more water from reservoirs in the winter to cover the increased demand for electricity during this period, which led to a violation of HPS operation rules and abnormal water–energy modes of operation. The acute weakening of cooperation in the CA water and energy complex in the 2000s coincided with a rapid increase in pressure on the energy sector and additional depletion of the region's water resources. The decrease in the functionality of the CA UES was accompanied by a greater number of emergencies in the power systems, which led to a decrease in the reliability of the power supply in the region (Vinokurov et al., 2021).

The energy and water segments of the CA water and energy complex have faced a number of serious problems that need to be addressed at the regulatory and technological levels. One promising technological direction for the CA water and energy complex is the development of modern technologies for the accumulation and storage of electrical energy, the use of which could contribute to solving the problem of seasonal electricity shortages, more balanced management of water resources at the regional level, optimisation of investment resources, as well as the full use of the hydropower potential in the CA region. The main potential consumers of stored energy are countries experiencing seasonal power shortages and forced to discharge water from reservoirs in winter and spring instead of storing it for rational use in the water–energy and agro-industrial complex of the entire CA region.

Energy accumulation and storage systems are becoming increasingly important in energy systems around the world. Energy storage is a key solution for global energy, in particular in matters of reserve balance of energy resources in the context of integrating large power facilities based on renewable energy sources (RES) into energy systems. In European countries, such redundancy is mostly provided by special energy networks, but these countries also attach great importance to energy reserve technologies. In the future, the importance of energy accumulation and storage systems will significantly increase as a result of the growth in the use of RES and the emergence of new requirements for electric power systems (Analytical Centre for the Government of the Russian Federation, 2018).

KEY SOLUTION: ENERGY STORAGE DEVICES

The lack of opportunities for large-scale industrial storage of generated electric energy (EE) significantly reduces the efficiency of the global electric power system, which, in turn, inhibits the mass adoption and application of clean energy technology. The world's leading technology corporations are engaged in solving the problem, and are devoting enormous resources to the development of an efficient energy storage system (ESS), which ultimately should allow EE to be accumulated and mobile. It will also solve the problem of instantaneous consumption of generated energy. Currently, this task is being solved by balancing energy resources – a complex and expensive process that affects the cost of EE.

The commissioning of large RES facilities, the improvement of lithium-ion battery technologies, power electronics technologies, and the growing demand for electric transport have combined to catalyse the development of ESS. The structure of ESS periodically undergoes changes, and the predominance of a certain type of energy storage device lasts for 5–10 years.

Lithium-ion batteries. Widely used in modern electronic technologies and transport, in recent years, these batteries have begun to gain widespread use in energy systems. The common design of a lithium-ion battery consists of a graphite anode and a lithium cobaltite cathode, the advantage of which is due to its high energy capacity, low self-discharge, and a large number of charge/discharge cycles. The disadvantages are the use of rare-earth metals, plus if the proper charging conditions are not met, the batteries are highly flammable, which is an obstacle to the operation of lithium-ion batteries in large energy storage facilities.

Lithium-ion batteries are sensitive to world prices for rare-earth metals, especially cobalt. According to Bloomberg, prices and demand for cobalt in 2016–2018 almost tripled, and such a sharp jump in prices made it impossible to predict them. At the same time, demand for cobalt is expected to grow sixfold by 2030. In the long term, the use of cobalt in lithium-ion batteries may be a limiting factor for the development of this type of ESS. According to the Karlsruhe Institute of Technology (Germany), in the future it will be necessary to focus on production of batteries with a new chemical composition that do not require the use of cobalt, since in the long term difficulties with the supply of lithium and cobalt for the production of lithium-ion batteries are quite possible (Vaalma et al., 2018).

The most recent major investment projects in the world for ESS based on lithium-ion batteries are those of Gateway Energy Storage, with an installed capacity of 250 MW, implemented by LS Power in San Diego County, California. The project was put into operation (LS Power, 2020). Another project, Pacific Gas & Electric, together with Tesla, began construction of a large 182.5 MW ESS in Monterey County, California (HSE University Energy Institute, 2020).

Post-lithium batteries. The second most common type of ESS, these use the intercalation effect. Despite the widespread application of post-lithium batteries, most technologies for their use are at an experimental stage. The composition of post-lithium batteries includes aluminium-ion, sodium-ion, magnesium-ion, potassium-ion, and other electrochemical cells with a longer life cycle and greater energy density.

The advantage of post-lithium technologies is the use of "non-critical elements" such as sodium or magnesium, as well as zinc, calcium, and aluminium, which can reduce the rare element pressure. Thus, unlike lithium-ion batteries, post-lithium batteries do not require the use of cobalt, which significantly reduces the cost of the technology for producing post-lithium batteries and in the long term, due to price competition, can win the market sector of lithium-ion batteries.

Metal-air batteries. The production of this type of ESS uses a metal anode, mainly made of zinc or aluminium, and in this case air acts as a cathode, which makes the battery cheaper and simplifies its design. It has high energy density and a long life cycle. Until now, metal-air batteries have been non-rechargeable and have only been used as small batteries in household electrical appliances. Recently, the technology of rechargeable zinc-air batteries has emerged, which in the future may replace expensive lithium-ion batteries.

Redox flow batteries. Redox flow batteries consist of a container with two reservoirs, which are filled with liquid anode and cathode electrolytes. The principle of operation is as follows: electrolytes are pumped by two pumps through a membrane to generate electric energy. The electrolyte is a solution of sulfuric acid and vanadium salt, as well as chlorine, zinc, or salt water.

Redox flow systems are characterised by a long discharge time and a long life cycle (up to 20 years). Significant disadvantages of this type of batteries are their large dimensions and a complicated recycling process.

Hydraulic accumulators. According to their principle of operation, hydraulic accumulators are similar to dam HPS. Like lithium-ion batteries, they are widely used as energy storage devices for large-scale industrial energy storage.

While in dam HPS systems, one large reservoir is used to store water, in hydraulic accumulator systems there are two reservoirs connected by a pump and a turbine. The reservoirs are located at different heights to create a differential pressure. In the absence of demand for EE, pumping units supply water from the lower reservoir to the upper one. During peak hours, the accumulated water flows from the upper reservoir to the lower one, rotating the turbines and generating EE.

The hydroelectric equipment of hydraulic accumulators and HPS is identical and has high efficiency. The advantage of such ESS is the minimum dependence on the inflow of water, and the disadvantage is the huge investment needed and the specific requirements for such facilities location in different regions: the preferable locations are mountainous areas (to create an elevation difference between the reservoirs).

Compressed air energy storage. The principle of operation of such ESS is to pump and compress air in storage tanks. During peak hours of high EE demand, compressed air is released and rotates the turbines. Compressed air reservoirs can be located in special containers, underground, in mines, pipes, and under water.

The technology has low efficiency due to heat loss during air compression. To increase efficiency, additional processes for capturing and storing the released air are required. The methods of using the released thermal energy from the compressed air energy storage are divided into the following types: isothermal (heat exchange with the environment), diabatic (heat dissipation), and adiabatic (heat storage).

Compressed air energy storage technologies are not very common, and the ongoing projects are experimental. To date, several projects with large capacities have been implemented, including the German power plant Huntorf (290 MW) and the American Mackintosh (110 MW).

Gravity energy storage. One of the promising energy storage technologies, this is being tested in various countries, but has not yet been implemented on an industrial scale. The algorithm of action of this type of ESS is structurally based on the principle by which an elevator operates, where the counterweight (heavy load) is lifted to the highest point of the structure. When required, the counterweight is released, and when it falls, EE is generated. Such an energy plant is mainly built in deep mines or in special tall towers. The excess EE generated can be used to lift the counterweight, and to trigger the counterweight later to generate EE during peak hours. The gravitational storage unit responds in less than a second, allowing instantaneous EE generation to meet the surge in demand in power systems.

The leaders in this market sector of ESS are the Scottish company Gravitricity and the Swiss Energy Vault. Gravitricity plans to deploy its technology in decommissioned mines around the world (Bradshaw, 2021), and Energy Vault intends to build a tower-type gravity energy storage system with an installed capacity of 4 MW (35 MWh of power discharge) for the energy company Tata Power.

Super flywheel energy storage. This is a type of flywheel that is safer, more energy efficient, and more durable than conventional flywheels. The super flywheel rotor is wound with modern flexible and durable materials such as carbon-fibre composite and plastic graphene tape. Its hub spins up using a motor-generator when connected to the power grid, and when braking, it supplies energy to the motor-generator. The technology is highly efficient, since there are no energy losses due to conversion into heat.

Hydrogen energy storage is a promising direction of energy storage due to the widespread application of hydrogen. For example, hydrogen can be used as a fuel; it can be accumulated and stored for a long time; and it can be easily transported to end consumers. The hydrogen energy can then be converted to EE or water energy.

Most of the hydrogen produced is used to improve the quality of fertilisers, oil products, and steel, in the processes of hydrotreating, hydrodesulphurisation, hydrocracking, and catalyst regeneration. Products manufactured using hydrogen are known not only for their improved quality, but also for their low or no carbon dioxide emissions.

The main stop factor in the development of hydrogen energy is the high cost of producing hydrogen. It is currently much more expensive than fossil fuels. With the gradual development of the relevant technologies and the emergence of efficient technological solutions, the cost of hydrogen production will decrease, which should allow hydrogen to compete with fossil fuels.

OPTIMAL TYPE OF ESS: HYDROGEN-BASED ENERGY STORAGE DEVICES

Most energy storage devices used on an industrial scale can only cover peak energy demand during the day. This is due to the short storage life of energy: for example, lithium-ion batteries provide energy up to four hours, hydraulic accumulators about 12 hours. To solve the problem of electricity shortages in autumn and winter and its surplus in spring and summer in some CA countries, in particular Kyrgyzstan and Tajikistan, ESS should provide a period of energy storage of at least one year. Hydrogen can be stored in cryogenic and liquid states, as well as in the form of compressed gas, for a long time (according to some estimates, up to 10 years), which is a significant advantage over other types of ESS (Radchenko et al., 2019). As a storage system, hydrogen has the advantage of long-term storage without loss of energy capacity, in contrast to electrochemical batteries.

The international convention is to classify hydrogen by colour to indicate the environmental performance of the relevant technological processes. The largest amount of carbon dioxide is emitted during the production of grey hydrogen (obtaining hydrogen from coal or methane). The method of producing hydrogen from natural gas using CCS (carbon capture storage) technology or without emitting carbon dioxide (experimental pyrolysis) results in blue hydrogen. Hydrogen obtained by electrolysis of water based on RES is classified as green; it does not harm the environment since there are no carbon dioxide emissions.

Significant improvement in electrolysers, combined with government support for hydrogen energy projects, could provide the impetus for greater industrial-scale and serial production of green hydrogen, followed by its widespread distribution and use as an energy storage system.

The cost of green hydrogen includes a significant share created by the costs of water purification for electrolysis. On average, 9 tonnes of purified water are required to produce 1 tonne of hydrogen. In turn, to obtain 1 tonne of pure water, twice the volume of untreated water is required. Consequently, with corresponding losses, the production ratio reaches 20 tonnes of water per tonne of hydrogen. It is possible to reduce the cost of producing green hydrogen by locating production facilities near HPS in Kyrgyzstan and Tajikistan, where inexpensive hydropower is in the price range of 2–2.3 c/kWh, and the total natural average annual flow of the Syr Darya and Amu Darya rivers reaches 95,000 km^3. These factors create favourable conditions for the development of hydrogen energy (Vinokurov et al., 2021).

The CA countries have vast reserves of fossil fuels and the natural and climatic conditions for the development of hydrogen energy. Among the CA countries, Kazakhstan has the greatest potential, which makes it possible to obtain blue, grey, green, turquoise, and brown types of hydrogen. Turkmenistan and Uzbekistan have enormous potential for the production of blue hydrogen from natural gas. Kyrgyzstan and Tajikistan have sufficient potential for production of green hydrogen.

The advantages of these countries include the cheap hydropower and water resources of their mountain rivers (critically required conditions for the production of green hydrogen at a competitive price).

HPS in Kyrgyzstan and Tajikistan in the months of high water inflow can convert surplus electricity to hydrogen using water electrolysis. The resulting hydrogen can then be stored in various forms, depending on the technology of the storage system. On demand (in the winter), the accumulated hydrogen is easily converted into electricity using fuel cells. In fuel cells, an electrochemical reaction takes places (oxygen enters the cathode, and hydrogen enters the anode), in which electrical and thermal energy are generated, and the only by-product is water.

The development of hydrogen technologies is constrained by the problems of hydrogen storage systems: relatively low efficiency and technological labour intensity.

At present, the hydrogen storage process seems to be expensive and energy-consuming. This is because hydrogen in liquefied or gaseous form has its own technologically difficult storage conditions, such as a high pressure or low temperature environment, which are very different from the storage conditions of current hydrocarbon energy carriers. Also, the storage system is subject to strict technological safety rules and requires highly qualified service personnel. By eliminating these difficulties, it will be possible to obtain technically and economically efficient hydrogen storage systems, which will solve most of the problems in the world energy sector. The creation of compact, reliable, and inexpensive hydrogen storage systems remains a key challenge in the development of hydrogen energy.

Hydrogen storage systems can be classified into two types, based on physical and chemically bound storage methods (see Table 1).

In one of the pilot projects for hydrogen energy storage, presented in Innopolis (Tatarstan), it is suggested to accumulate the excess energy generated by HPS in the summer. Instead of pure hydrogen, it is proposed to use a liquid organic hydrogen carrier (LOHC) as an energy storage system. Hydrogen is converted to LOHC or separated from this compound by catalytic hydrogenation and dehydrogenation, and the carrier liquid is N-Ethylcarbazole (see Figure 21). The main advantages of this method are the controllability of the storage of hydrogen in liquid form in the liquid-carrier compound, as well as the rapid forward and reverse processes of hydrogenation and dehydrogenation, which makes it possible to reduce the storage volume. To demonstrate the benefits of the solution, a pilot accumulation project was developed for a facility with an electricity demand of 15.75 MWh. The project used a hydrogen reserve with a volume of 4,375 Nm³ for a fully autonomous energy supply (Gradient Kilby, 2017).

POTENTIAL AND COST OF HYDROGEN

Some 75 million tonnes of hydrogen are produced annually in the world, while electrical plants produce about 0.1 million tonnes of H_2, or less than 0.1%. According to the Association for the Development of Renewable Energy, reducing the carbon footprint is unattainable in such conditions, when 95% of all hydrogen is produced using the technology of steam conversion (reforming) of methane and coal, where the main by-product is carbon dioxide (RBC, 2019).

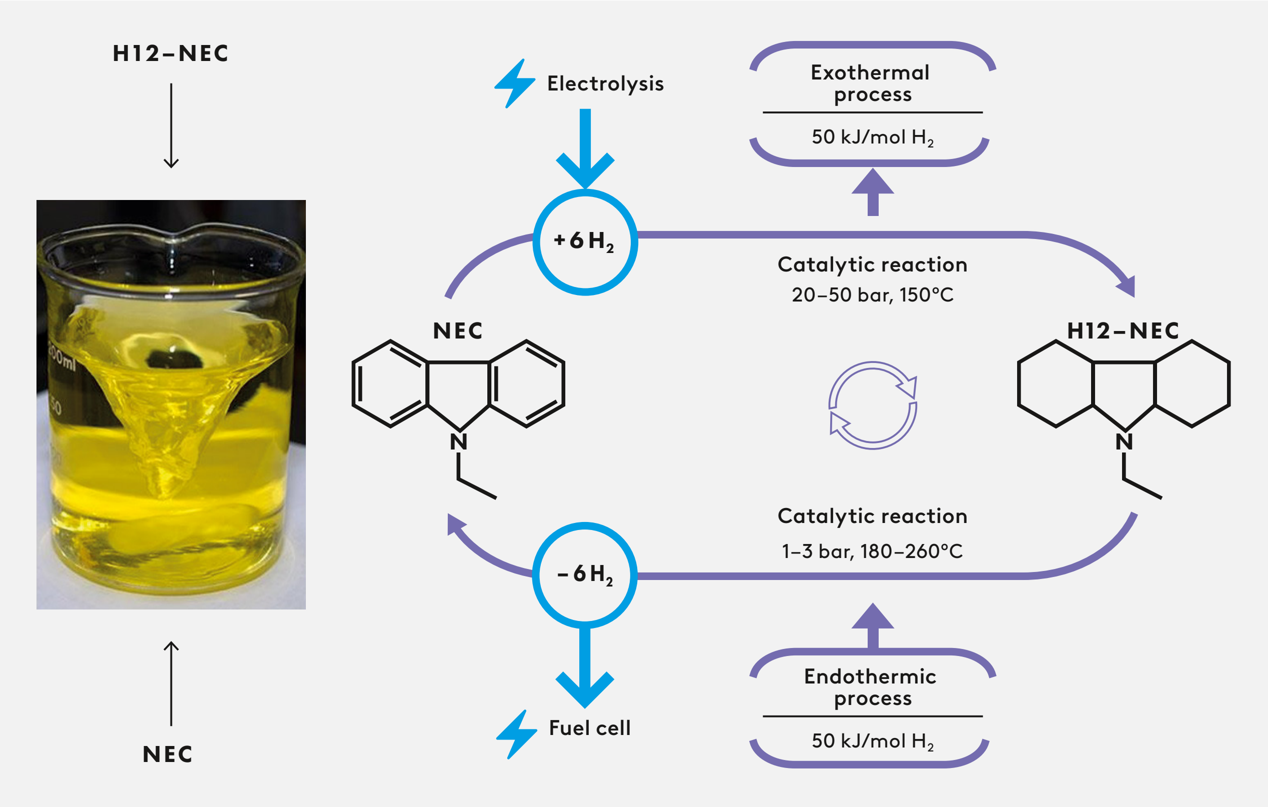
The potential of the hydrogen energy market is enormous. Bloomberg, in its Hydrogen Economy Outlook, predicts that by 2050, a quarter of the world's energy demand will be met by hydrogen, and the price for hydrogen will fall to the level of today's gas prices. Bloomberg experts say that under a favourable

Table 1. Methods of hydrogen storage

Method	Description	Types		Advantages and disadvantages
Physical	Physical methods of hydrogen storage in the form of compressed gas and cryogenic liquid	**Compressed gaseous hydrogen:** — stationary tanks, cylinders; — pipelines	**Liquid hydrogen:** — cryogenic vessels	— mastered technology; — serial production; — intensive operationally and in energy requirement; — hydrogen embrittlement effect
Chemically bound	Physical or chemical interaction of hydrogen or water with materials in which hydrogen is adsorbed or released	**Adsorption hydrogen:** — zeolites; — hydrocarbon nanomaterials; — mesoporous materials . **Adsorption in metal hydrides:** — metal hydrides	**Chemically bound:** — ammonia; — fullerenes; — organic hydrides; — water-reactive substances; — sponge iron	— promising; — small-scale; — by-products in some reactions

Source: compiled by the authors.

Figure 21. Liquid-carrier (N-Ethylcarbazole) interaction cycle



Source: Gradient Kilby, 2017.

development scenario over the next 30 years, the industry will attract about $11 trillion in investments, and global sales of hydrogen fuel will reach $700 billion a year (RBC, 2021).

Among the countries planning to make significant investments in the development of hydrogen energy, the leaders are Japan and Germany.

Japan was the first country in the world to adopt a national hydrogen energy development programme. Recently, the Japanese government decided to allocate more than $3.4 billion for projects to create the infrastructure for clean hydrogen energy (TASS, 2021).

Germany plans to invest more than EUR 10 billion in the industry by 2023, of which EUR 7 billion will be for "building the market" (creating framework conditions and stimulating domestic demand), EUR 2 billion for international cooperation, and an additional EUR 1 billion for specific needs of the industry, which, in turn, must implement hydrogen technologies in order to become the world's first hydrogen energy exporter (RBC, 2021). Today, hydrogen energy is considered by the German government as the most efficient way to use available energy sources (Zhukov, 2020).

The cost of producing hydrogen from natural gas, according to the International Energy Agency (IEA), is $1.5–3.5 per kg. Hydrogen produced using RES costs more than $2–6 per kg (IEA, 2019). According to the IEA forecast, by 2030 the cost of hydrogen production will decrease by 30%. In turn, BloombergNEF predicts a decrease in the cost of producing hydrogen from RES energy to $1.4 per kg by 2030, and to $0.8 by 2050 (BloombergNEF, 2019).

With a hydrogen production cost of about $2 per kg by 2030, global demand can be expected in the amount of 100 to 114 million tonnes of hydrogen per year, which is 35–55% more than in 2018 (Analytical Centre for the Government of the Russian Federation, 2020).

COMPARATIVE ANALYSIS OF TWO KEY METHODS OF HYDROGEN PRODUCTION. COST OF STORAGE AND TRANSPORTATION OF HYDROGEN

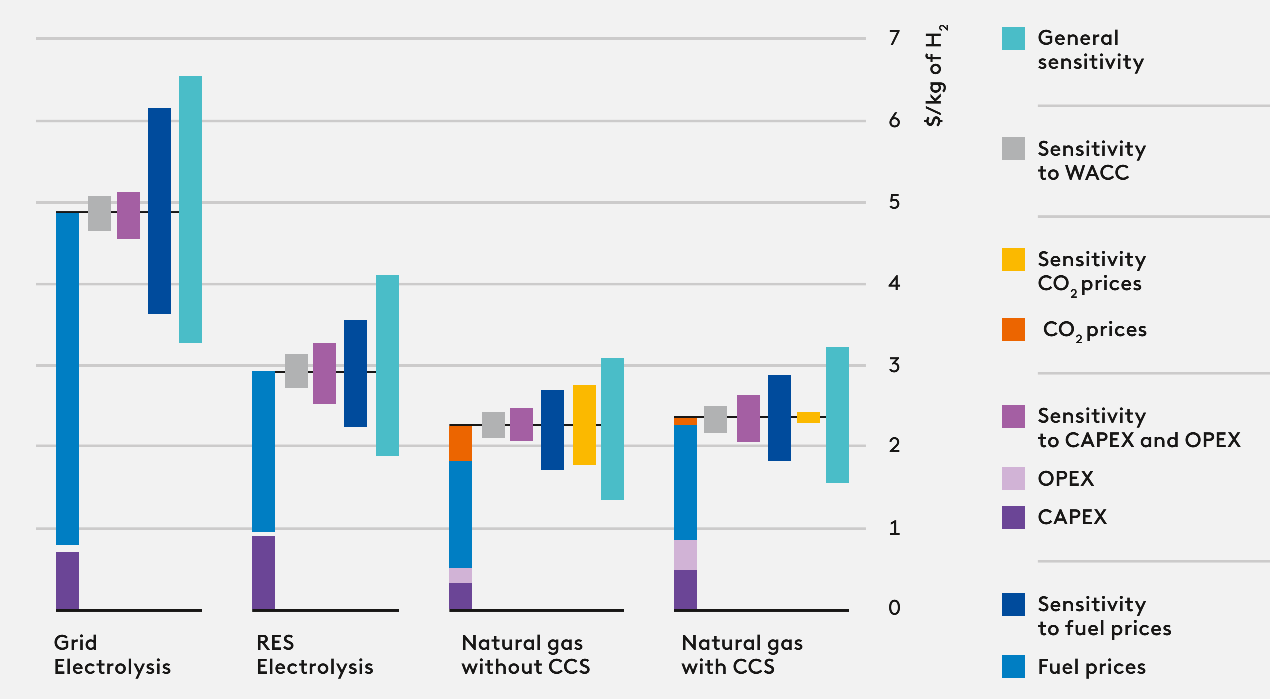
The first method is to obtain hydrogen from fossil fuels, in particular from natural gas (see Figure 22). This is the most common way, due to the cost-effectiveness of this technology. A significant disadvantage of the method is its non-ecological character. With stricter environmental regulations, it will be necessary to use corresponding CCS technologies.

The second method is electrolysis, which needs a lot of clean water and EE. Taking into account the natural resource potential of the CA countries, especially Kyrgyzstan and Tajikistan, water electrolysis is a promising solution to the challenges facing the countries' water and energy complex.

According to the EnergyNet Research Centre, after 2025, a noticeable, almost twofold decrease in prices for storing liquefied hydrogen is expected (from $2 to $0.9 per kg of hydrogen). The most cost-effective method will be to store hydrogen in the form of ammonia, with a storage cost of almost $0.1 per kg by 2025. No significant changes are expected in the cost of storing compressed hydrogen (see Figure 23).

The issue of hydrogen transportation is the most sensitive aspect of hydrogen energy. At the current stage, it is economically viable to transport hydrogen in the form of ammonia by sea and rail. Trucks are the most expensive mode of transporting it today (regardless of the form and type of hydrogen). It should be noted

Figure 22. Costs of hydrogen production in 2030 (by method of production)



Source: IEA, 2019.

that the transportation of hydrogen by motor transport in the form of ammonia is 10 times cheaper than the transportation of compressed hydrogen at 150 bar (see Figure 23).

MODEL OF COMPRESSED HYDROGEN PRODUCTION BY ELECTROLYSIS OF WATER USING HPS ENERGY

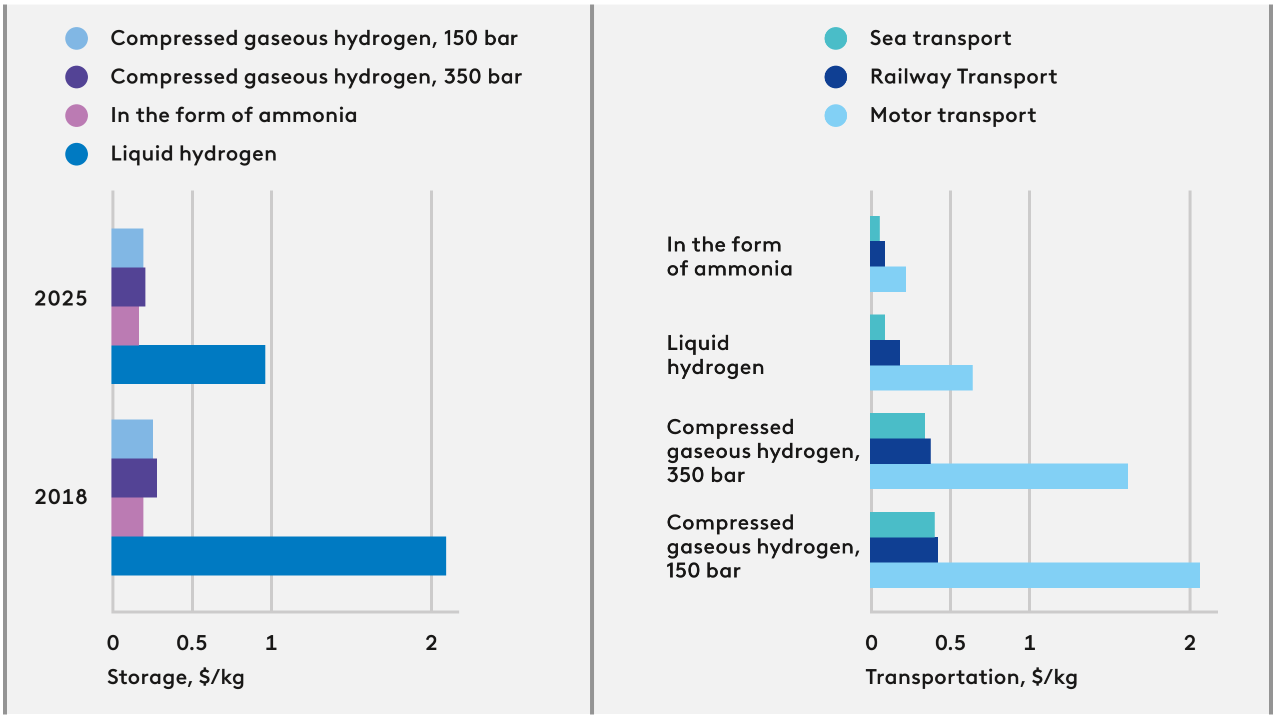
The development of hydrogen energy is possible in the mountainous regions of the east and southeast of the Central Asian countries, which have sufficient amounts of the required resources: huge unrealised hydropower potential, inexpensive hydropower and freshwater. Comparative calculations were performed based on the model of compressed hydrogen production by electrolysis of water using HPS energy (Sinyak, 2017). All parameters of this model are shown in Figure 24. There are no CO_2 emissions, so the hydrogen produced by this method is of the green type.

According to our calculations, the production of 1 kg of hydrogen requires the consumption of 9 kg of water, 55 kWh of electricity, and 8 kg of oxygen. With consumption of 100 tonnes of water per hour for the electrolysis process, about 267 tonnes of hydrogen will be produced per day with EE consumption of 14,610,000 kWh.

To calculate the technical and economic indices of hydrogen production, the forecasts of the Institute of Economic Forecasting of the Russian Academy of Sciences were used. The calculations were based on three scenarios of predicted energy prices for hydrogen production (see Table 2): optimistic, moderate, and pessimistic (Sinyak, 2017).

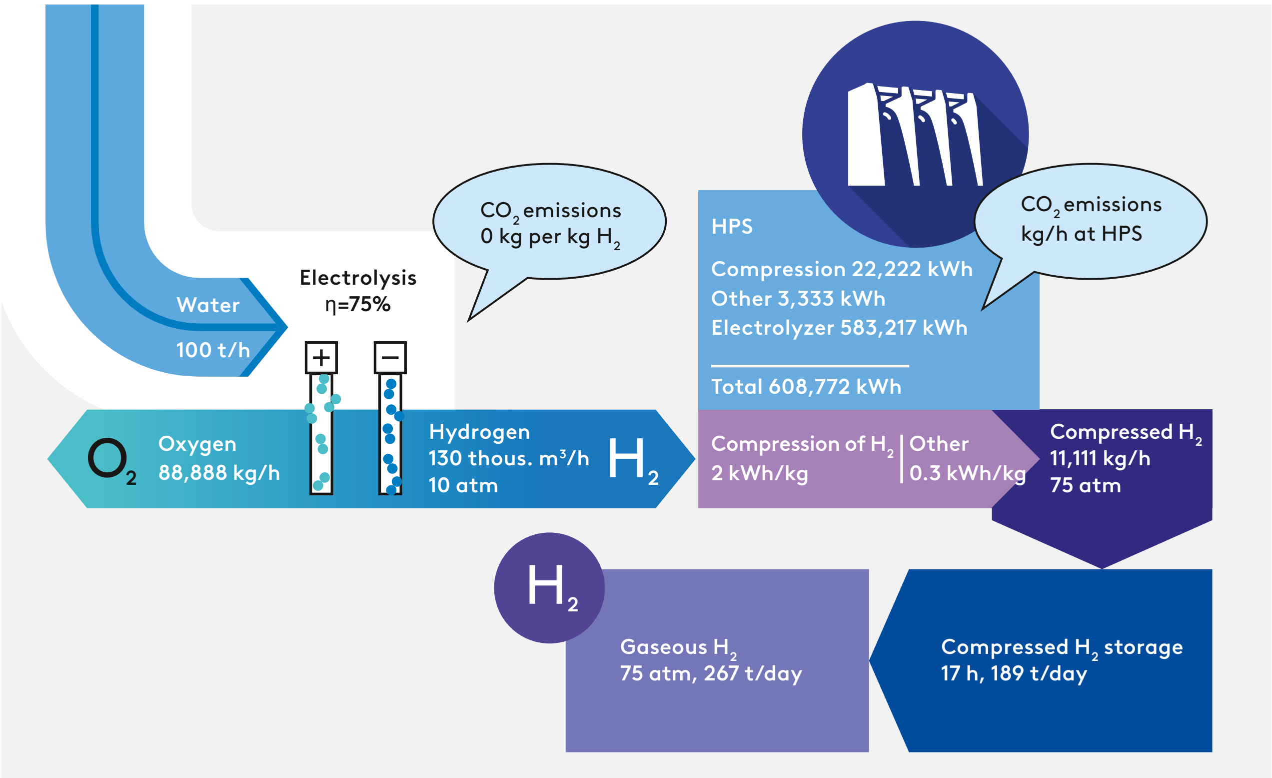
In terms of cost, the considered method will be inferior to other hydrogen production technologies (see Table 3).

Figure 23. Cost of storage and transportation of hydrogen



Source: EnergyNet.

Figure 24. Model of compressed hydrogen production by electrolysis of water using HPS energy



Source: authors' calculations based on corresponding materials (Sinyak, 2017).

Currently, the only significant advantage of the HPS-based electrolysis method is the absence of CO_2 emissions, in contrast to steam reforming of methane, which produces about 10 kg of CO_2 per kg of hydrogen, or the method of coal gasification, which produces 22 kg of CO_2 for 1 kg of hydrogen.

The production of hydrogen by electrolysis on the basis of existing HPS under current conditions will be at a competitive cost compared to other types of RES, due to the already incurred capital costs for the installation of HPS and the low cost of hydroelectricity.

In the long term, with the improvement of production methods and accumulation and storage technologies, as well as with the active stimulation of the state-supported development of hydrogen energy, the cost of hydrogen production can significantly decrease.

The widespread use of hydrogen technology can act as a driver for the energy storage industry. With the progressive development of hydrogen power engineering, hydrogen-based storage devices can become the optimal solution for eliminating energy shortages in Central Asian countries.

CONCLUSION

The fundamental factors that determine the demand for energy storage devices are the cost of energy accumulation and storage, the efficiency of the ESS technology, and the capital costs of its construction. In 10–15 years, a powerful breakthrough is expected in technologies for the production of hydrogen and systems for its accumulation. The possibility of long-term storage of hydrogen will create a huge demand for hydrogen energy.

The indisputable advantage of ESS is the ease of its integration into power systems, which contributes to solving problems and increasing the efficiency of power-generating facilities. The development of ESS is becoming a new step in the conceptual development of the energy sector, accelerating its digital transition, contributing to free energy exchange. Seasonal energy storage technologies are one of the main trends in the development of ESS, which will solve the problem of large seasonal fluctuations in electricity consumption.

The current efforts of the CA countries are aimed at sustainable operation of the national energy systems. Countries that do not have large reserves of fossil fuels, such as Kyrgyzstan and Tajikistan, face significant challenges. These countries are forced to use their accumulated hydropower capacity to meet the increasing seasonal demand for electricity, especially during winter, which involves water releases to generate electricity. The release of water in winter periodically leads to flooding of settlements, as well as to shortages of irrigation water in the spring and summer in the lower reaches of the Syr Darya and Amu Darya rivers. The development of hydrogen energy will make it possible to eliminate the problems in the energy systems of the Central Asian countries.

The production of hydrogen by the electrolysis method will be inferior in terms of cost to the methods of steam reforming of methane and coal gasification; the only advantage of the electrolysis method is the environmental factor. Nevertheless, the production of hydrogen by electrolysis at existing HPS, relying on the existing infrastructure of energy facilities and direct access to clean water sources, will be cheaper than production based on RES.

The process of hydrogen consumption is not limited to its production; there are also processes of accumulation and storage, conversion to EE or back to water, which are quite costly. Calculations based on the model are

Table 2. Forecasts of the cost of energy resources for hydrogen production for the period 2020–2030

Three scenarios:	optimistic	moderate	pessimistic
Energy carrier prices:			
- natural gas, \$/thous. m^3	150	300	450
- coal, \$/toe	50	75	100
- EE from the power system, HPS, \$/kWh	0.05	0.1	0.15
- oil, \$/barrel	80	100	130
Specific investment in new technologies:			
SPS, \$/kW	1,000	2,000	3,000
WPS, \$/kW	500	1,000	1,500
Average annual use of the installed capacity of RES, %	45	30	15

Source: Sinyak, 2017.

Table 3. Analysis of technical and economic indices for the production of gaseous hydrogen in compressed form

H_2 production technologies	Energy resources consumption per kg of H_2		Variable costs (without energy resources), USD/kg of H_2	Fixed costs (without depreciation) USD/kg of H_2	Specific capital investments, thous. USD/t of H_2
	main	EE for auxiliary purposes			
Electrolysis from power systems and HPS	EE 50–52	2–2.5	0.05–0.12	0.6–1.0	13–23
Electrolysis from SPS	EE 50–52	2–2.5	0.75–0.9	3.9–4.5	85–90
Steam methane reforming	natural gas 5.5–6.5 m^3	0.7–0.9	0.05–0.1	0.1–0.3	2–8
Coal gasification	coal 5–7 kg c.f.	3.7–3.9	0.3–0.4	0.3–0.9	7–9

Source: Sinyak, 2017.

made only for the processes of obtaining and storing hydrogen and do not take into account such processes as transportation and conversion into EE or water.

Achieving the goal of decarbonisation is possible due to hydrogen produced by the method of water electrolysis based on the generation of RES. The development of this innovation is among the 17 interconnected UN Sustainable Development Goals (SDG), in line with its Goal 7: Affordable and Clean Energy.

AFTERWORD. A FULL-FLEDGED ENERGY SHIFT IS AHEAD

Evgeny Vinokurov, Chief Economist, Eurasian Development Bank and Eurasian Fund for Stabilization and Development

The power-generating sector currently produces about 75% of global greenhouse gas emissions. Its conversion is the key to preventing negative climate change impact. Achieving carbon neutrality and reducing global carbon dioxide (CO_2) emissions to zero by 2050 is an internationally recognised solution that might cap the global average temperature increase to about 1.5°C and thus prevent irreversible climate changes. Achieving such global goals would require a complete transformation of our ways of producing, accumulating, transporting, and consuming energy. Such a massive conversion does not mean a substitution of some energy sources with other ones – it still has to address the growing need of human civilisation for energy consumption. Economic growth requires energy. This is another reason why we believe that the next 30 years will be a time of massive transformation of world's energy sector.

A growing global political consensus with regard to the need for transformation of the energy sector on the basis of renewable energy sources and technologies that improve efficiency and energy conservation in order to achieve carbon neutrality, is encouraging considerable optimism about the progress the world can achieve. According to the International Renewable Energy Agency, in 2012–2020, the amount of new generating capacities based on renewable energy resources (RES) annually commissioned worldwide (except in 2014) exceeded the amount of all new generating capacities based on fossil fuel and nuclear power.

In 2020, the amount of new RES-based generating capacities reached a historical record of 260 GW, which is more than four times greater than new capacities based on traditional sources. During that year, Europe's RES-based energy production for the first time exceeded the amount generated by traditional thermal power plants, accounting for about 40% of total electricity production.

The realignment of the energy sector investment portfolio in favour of RES worldwide is explained by the significant potential and technical availability of these kinds of energy. Government investment decisions and the ensuing technological development have lowered the cost of electrical energy generation from renewable sources, which has become comparable to or below the cost of fossil fuel power generation in many OECD countries.

Innovative technological solutions are transforming the global energy system, paving the way to a decarbonised future. Technological and regulatory innovations are being implemented all over the world. Apart from the development of RES, we are seeing significant progress in electric vehicles, energy accumulators, digital technologies, and artificial intelligence. These technologies, which also constitute the basis for a structural shift, are contributing to the development of new trends in the sector, thereby contributing to increased investment in the sustainable use of rare-earth elements and other mineral resources, as well as investment in the circular economy. The development of smart grids helps to solve the problem of high volatility of energy production from renewables. Expanding the areas of RES deployment, including bioenergy and hydrogen, brings new solutions for transportation, construction, and industry.

The rapid worldwide spread of RES and other technological solutions in the energy sector is a promising trend for the future decarbonisation of the electricity sector. But is the overall outlook for its development so bright? Despite the shift of investment emphasis, the current state of many other indicators suggests that decarbonisation of the energy sector is lagging behind the momentum needed to reach the 1.5°C target by 2050. The International Renewable Energy Agency expects that implementation of the measures set forth by current state energy plans and targets can only help stabilise the level of global emissions, with a subsequent small decline by 2050. Thus, despite clear evidence of anthropogenic influence on climate change, broad support for the Paris Agreement and rapid development of environmentally clean, cost-effective, and sustainable energy sources, energy-related CO_2 emissions have been increasing by an average of 1.3% annually from 2014 to 2019. Fossil fuels (coal, oil, and gas) remain strategically important as the primary energy source for all humanity. According to OPEC's World Oil Outlook 2020, they account for 72.5% of the global energy mix.

In recent years, worldwide progress in the development of RES and new technologies in the energy sector has been significant, but uneven. It has been concentrated mainly in large developed and rapidly developing countries, which have a significant weight in the global energy balance. In many other regions of the world, energy poverty is widespread and continues to hold back economic progress and social well-being. In 2020, Europe, the USA, and China accounted for the largest share of new renewable capacities, while Africa accounted for only 1% of global energy capacities. EAEU member states are also lagging behind the global trend. Kazakhstan is making the most serious efforts in the field of RES. The RES-based capacity installed in this region is about 70.7 GW or only 2.5% of world capacities, despite the significant potential and burning urgency of the issue of developing wide access to modern forms of energy to achieve carbon neutrality. There are objective reasons for this, in the form of huge reserves of fossil fuels and capital investments already made. However, as we have noted, on the horizon of 30 years, the Eurasian region will face a major energy transition.

The transformation of the global energy sector needed to achieve the goal of emissions reduction and carbon neutrality by 2050 requires further study. There is a lot of work to be done to make the long-term 30-year plans a reality, especially in view of significant differences between countries, inter alia, in terms of their investment and technological capabilities. Recent trends show that the lag between where we are and where we should be is widening.

The challenge of modernity, wherein mankind assumes the responsibility to accelerate the transition to clean energy technologies, presents an essential research field for scientists and specialists around the world, in various fields of energy or their intersection. Research and development centres in Russia, Kazakhstan, Kyrgyzstan, Tajikistan, Uzbekistan, and other Eurasian countries are continuing to develop bodies of knowledge and practical solutions to meet the challenges of safe and sustainable future energy development. Meanwhile, the most important topics, such as development of the water and energy complex in Central Asia, are cross-border in nature and underlie the sustainable development of the entire region.

In the long term, intensifying the development of the RES sector in the EAEU looks like the best solution, which will not only contribute to the technological development of the industry, but also increase the share of clean energy, which is an important task in the context of increased global efforts to combat climate change and the transition to a highly efficient and sustainable future. Key areas in this regard are: hydrogen energy; offshore wind energy; new materials for alternative energy sources; and CO_2 capture, storage, and transportation technologies. These topics are analysed by leading dedicated experts in this report. Leading scientific teams and government organisations of the entire Eurasian region are paying special attention to all these significant areas of the energy sector today.

The report touches upon the industrial application of hydrogen energy, along with other kinds of energy, in the medium term. The use of hydrogen as an energy resource, the development of methods for hydrogen storage and transportation, discovering new ways to generate energy from hydrogen, as well as the applicable types of generating units and fuel cells, are a number of the problems whose solution would contribute not only to the development of hydrogen energy as a discipline, but also to meeting mankind's steadily growing demand for renewable and clean energy. Given the opportunities at hand, the subject of hydrogen energy is particularly interesting for the Eurasian region.

Offshore wind power is another efficient and environmentally clean energy production technology, which plays a key role in the transition to RES; it has its own advantages, problems, and development prospects. Strong and steady offshore wind, vast territories for installation of extra-large and floating wind turbines for deeper ocean areas, contribute to generating large amounts of energy. On the other hand, there is expensive maintenance, a higher turbine failure rate compared to onshore wind power, and the high cost of generating this energy (currently decreasing). Technical improvement of equipment for offshore energy generation is subject to the development and implementation of a body of knowledge related to the construction of larger and taller wind turbines, wind farms and floating wind power generation platforms with less expensive maintenance over time, as well as finding solutions to the problems of hybrid wind energy systems, hydrogen production, and energy accumulation and storage systems.

Commercialisation of innovative developments and creation of effective ways to use energy is impossible without deployment of new stable materials for alternative energy sources, capable of ensuring a smooth and crisis-free transition to a carbon-free economy. Of particular interest are hybrid materials consisting of natural and synthetic components, indispensable in the development of highly efficient energy storage and transportation systems, including but not limited to hydrogen. A promising field of application of hybrid materials is related to the possibility of seawater desalination with the use of solar energy. From this perspective, the development of technologies that imitate natural processes is of the greatest interest.

Carbon neutrality will be approached, inter alia, by the scientific and engineering community constantly creating new technologies for CO_2 capture and storage in order to achieve ambitious targets for reduction of carbon dioxide emissions. Although these are still in the development stage, they would open the door to decarbonisation of the energy sector.

Having understood the current trends in energy development and taken into account the need to reduce the carbon footprint, the Eurasian Development Bank (EDB) and the Global Energy Association prepared this joint report for your consideration. The EDB is actively increasing its investment portfolio in RES, focusing on investments in the Central Asian Water and Energy Complex, and its analytical team is engaged in relevant applied research. Since 2002, the Global Energy Association has promoted international energy research and projects on an annual basis, being engaged in energy cooperation; it has also promoted and supported industrial innovations. The two organisations share the view that the hydrogen economy has enormous potential importance.

In addition to its importance for the scientific community and general public, the report also provides an example of cooperation between two organisations for which ecology and decarbonisation are fundamentally important.

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