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At the Heart of Europe's Nuclear Industry

June saw three events proving that Rosatom's position in Central Europe is strengthening. Rosatom's nuclear fuel division TVEL announced the beginning of tests on a new modification of fuel assemblies for the Dukovany nuclear power plant in the Czech Republic. Rosatom, Framatome SAS and GE Steam Power signed memorandums of cooperation in bidding for the strategic investor role in the Belene NPP construction project (Bulgaria). A package of documents prepared by Rosatom was submitted to the Hungarian regulator to obtain a construction license for Paks II.

Czech Republic

TVEL is carrying out durability tests on a dummy fuel assembly RK 3+ for VVER-440 reactors. The tests were commissioned by the state-owned Czech energy company ČEZ operating the Dukovany and Temelin power plants. They are conducted at the facilities of OKB Gidropress (part of Rosatom's engineering division Atomenergomash).

The new modification differs in an increased distance between fuel rods in the assembly and absence of a duct, which is replaced with a framework structure with gussets. Cross-section enrichment profile of the fuel assembly has also been optimized.

Durability tests are part of an extensive testing program aimed at studying properties of the new assemblies. The goal of testing is to assess mechanical durability of fuel assembly components in the conditions closest to reality. The durability tests were preceded by hydrodynamic tests aimed at assessing hydraulic resistance of the fuel assembly. The next step will be vibration testing. Simultaneously, researchers are preparing a safety case for the use of RK 3+ fuel assemblies at the Dukovany NPP. TVEL plans to complete the tests in late 2020 or early 2021. The entire process of licensing the introduction of the RK 3+ fuel assembly at the Dukovany NPP is planned to be completed by the end of 2021.

The purpose of modifications is to extend the refueling interval. The extended interval will bring down refueling costs and make the overall operation of the nuclear power station more cost efficient. Another advantage of the modified fuel assemblies is the possibility of increasing Dukovany's heat generation capacity. The Czech nuclear station has been running on Russian fuel since the very beginning of its operation.

Bulgaria

Rosatom signed memorandums of understanding with Framatome SAS and GE Steam Power to cooperate in bidding for the strategic investor role in the Belene NPP project in Bulgaria.

The procedure of selection a strategic investor for Belene was launched in May 2019. In August of the same year, Rosatom filed an application to participate in the procedure. The short list of candidates for the strategic investor role also includes China National Nuclear Corporation (CNNC) and Korea Hydro & Nuclear Power Co. (KHNP).

If Rosatom becomes a strategic investor of the Belene nuclear power plant, General

Electric will be considered as a potential supplier of the turbine island equipment, including Arabelle steam turbines. Framatome SAS will be considered as an instrumentation and control (I&C) technology vendor.

"The memorandums we have signed testify to an invariably high level of trust between our companies. We are confident that collaboration between global leaders in nuclear technology will create optimal financial and technical conditions for the Belene project to come into reality," Kirill Komarov, Rosatom's Deputy Director General for Corporate Development and International Business, said.

Belene is not the first example of cooperation between the three companies. Framatome SAS is a supplier of I&C systems for Paks II in Hungary and Hanhikivi 1 in Finland. General Electric, in a joint venture with Atomenergomash (Rosatom's engineering division), is a supplier of the turbine island equipment for the Akkuyu nuclear power plant in Turkey and El Dabaa in Egypt.

Hungary

On June 30, Paks II Ltd., an owner of the same-name nuclear power plant project, filed an application with the Hungarian Atomic Energy Authority (HAEA) for a construction license.

The application contains a safety assessment report, a set of supporting documents describing the VVER-1200 technology, and earlier obtained licenses, including the environmental license. The Hungarian regulator has 12 months to analyze the documents, to be followed by three more months of an independent assessment by the IAEA experts. During this period of time, the HAEA will study the application and, if needed, request additional documents and information. While the application is being considered, Atomstroyexport will develop construction engineering documents for the project and build a construction yard. Preparatory works on the site are expected to start in 2021. First, workers will dig a foundation pit and then stabilize the soil under main facilities because the Paks II construction site is located not far away from the Danube.

Paks I four units (each VVER-440) generate up to 50% of electricity in Hungary, but all of them will be put out of operation in the 2030s. Two units of Paks II will replace the retiring capacity and increase the share of carbon-free energy up to 60% of the national energy mix. At present, some of the electricity consumed in Hungary is imported from neighboring countries. New generation capacity will make Hungary less dependent on energy imports.

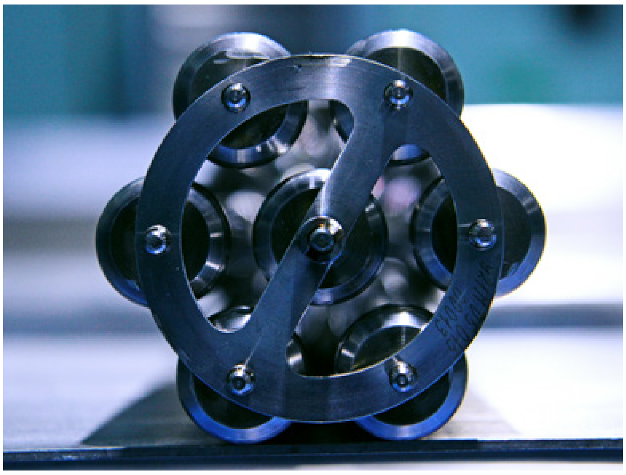
Paks II is a good example of international cooperation in nuclear projects. As said above, machinery and equipment for the turbine island will be supplied by GE, while I&C systems will be supplied by a consortium of Framatome and Siemens.

Nuclear engineers from the Czech Republic, Bulgaria and Hungary have gained much experience in working with their Russian colleagues. International cooperation has always been an integral part of the Soviet/Russian civil nuclear policy (for details see the Cooperation Timeline below). This year, Rosatom celebrates the 75th anniversary of the Russian nuclear industry.

Cooperation Timeline

- **1957** — Czechoslovakia commissions its first research reactor VVR-S (now LVR-15) in Řež near Prague (now Czech Republic) with support from the Soviet Union. The first self-sustaining nuclear chain reaction is initiated in the country.
- **1958** — Czechoslovakia begins the construction of the first nuclear reactor KS-150 at Bohunice Unit 1 (now Slovakia) with input from the USSR. The design of KS-150 was developed jointly by Czechoslovakia and the Soviet Union.
- **1959** — Hungary commissions a Soviet-designed 2 MW VVR research reactor in Csillebérc (Budapest) with input from Soviet engineers.
- **1961** — Bulgaria starts up a 2 MW research reactor IRT-Sofia built with support from the Soviet Union. The reactor achieves its first criticality.
- **1970** — Construction of a nuclear power plant begins at Kozloduy (Bulgaria) with support from the Soviet Union. The plant has Soviet-designed VVER-440 reactors.
- **1974** — Construction of a nuclear power station begins at Dukovany (Czechoslovakia) with support from the Soviet Union. The plant has four Soviet-designed VVER-440 reactors.
- **1974** — Construction of an 800 MW nuclear power plant begins at Paks (Hungary) with support from the Soviet Union. The plant has Soviet-designed VVER-440 reactors.
- **1981** — Construction of a nuclear power station begins at Temelin (Czechoslovakia) with support from the Soviet Union. The plant has two Soviet-designed VVER-1000 reactors.
- **2014** — Rosatom and Hungary sign an agreement to build two Russian-designed VVER-1200 reactor units at Paks II.

Nuclear Energy Becomes Renewable



"In 2022, Russia will have the first nuclear reactor running entirely on a renewable nuclear fuel," a press release issued by the Beloyarsk nuclear power plant read. With technology advancing, there are now more reasons to see nuclear as a renewable energy source.

In 2022, the BN-800 reactor at Beloyarsk NPP Unit 4 will be running entirely on mixed uranium-plutonium oxide fuel (MOX fuel) for the first time in history of the Russian nuclear industry. This will be an important step towards 'closing' the nuclear fuel cycle.

MOX fuel and breeders

Conventional thermal reactors use nuclear fuel, in which only U-235 nuclei are involved in the fission reaction.

MOX fuel pellets are made of plutonium oxide extracted from spent nuclear fuel, and uranium oxide produced from depleted uranium hexafluoride (tailings of the uranium enrichment process). In other words, the new fuel is fabricated using waste from the irradiation process and waste from the enrichment process. MOX fuel is loaded into fast reactors. In Russia, it is BN-800.

The use of fast reactors in combination with conventional thermal reactors ("the two-component scheme") addresses several challenges. **"First, we will have a wider range of materials that could be used to make nuclear fuel. Second, we will be able to re-use spent nuclear fuel (after reprocessing) instead of storing it. Third, we will be able to dispose of large accumulated amounts of depleted uranium hexafluoride and plutonium,"** Vitaly Khadeev, Vice President for Closed Nuclear Cycle Technology at Rosatom fuel division explained. Another advantage of fast reactors is their ability to burn fission products and minor actinides, highly radioactive isotopes of transuranium elements. Burning helps decrease their radioactivity.

According to expert estimates, repeated reprocessing of the same material extends its use in the fuel cycle 100-fold. This figure is not pulled out of a hat: there is less than 1% of U-235 in uranium occurring in nature, while tailings contain 100 times more of U-238. Even rough estimates show that if the amount of uranium produced over a 10-year period is used in the closed fuel cycle, it will be sufficient for 1,000 years.

In fact, the repeated use of the same material in the power generation cycle makes it a renewable source of energy. Mikhail Chudakov, the IAEA deputy director

general, believes that the use of two-component scheme (breeders and thermal reactors) allows designating nuclear a renewable energy source, **“First, breeders produce materials that can be further used in a chain reaction. And second, fast reactors are needed to burn man-made minors, i.e. minor actinides.”**

Nuances of technology

Rosatom is working on two technologies of the closed nuclear fuel cycle. The technology based on using MOX fuel in breeders is being put into practice, step by step. MOX fuel for the BN-800 reactor is fabricated at the Mining and Chemical Plant. The first 18 fuel assemblies were loaded into the reactor in January 2020. Another 180 assemblies will be loaded in 2020. It is expected that the loading of MOX fuel will be completed in the first halve of 2022, enabling BN-800 to run entirely on the mixed oxide fuel.

The second technology is dubbed ‘Proryv’ (Russian for ‘breakthrough’). For the technology to be mastered, Rosatom will build a dedicated pilot center that will consist of a fuel fabrication/re-fabrication department, a spent fuel reprocessing section, and a lead-cooled fast neutron reactor, BREST-OD-300 (a Russian acronym for ‘300 MW passively safe pilot demonstration fast neutron reactor’). Unlike sodium-cooled BN-type reactors, BREST uses lead as coolant.

The BREST design provides for the reactor core to be placed in a concrete pool filled with liquid lead. Steam generators and primary loop circulation pumps are also placed inside a pool. Nuclear fuel heats lead, which then flows to the steam generator and transfers heat to water in the secondary loop.

The lead coolant and the reactor design make it possible to use a smaller containment and a smaller core catcher and make many auxiliary systems redundant. The integral design (the core and steam generators in a single pressure vessel) enables bringing coolant leaks under control and excludes loss-of-coolant accidents. BREST will use mixed uranium-plutonium nitride (MUPN) fuel. As the name implies, this fuel contains a blend of nitrides, not oxides.

Construction of the fuel fabrication/re-fabrication department will be finished in 2022. Its equipment is already being installed. BREST-OD-300 is planned to be put into operation in 2026, and the spent fuel reprocessing section at the end of the decade.

Rosatom’s initiatives aimed at closing the nuclear fuel cycle remind us of the words of Anatoly Zrodnikov, the former director of the Institute of Physics and Power Engineering (part of Rosatom), 13 years ago, **“What will the closed fuel cycle give**

us? (…) The answer is very interesting in philosophical terms. Initial raw materials become almost inexhaustible – they will suffice for a very long, historically meaningful period, say, more than 1,000 years. And we can fabricate as much secondary fuel as we need. In other words, power generation will not depend on limited resources, but on technology and intellectual assets, which are reproducible. Ultimately, this will mean that nuclear energy has become a fully renewable source.”

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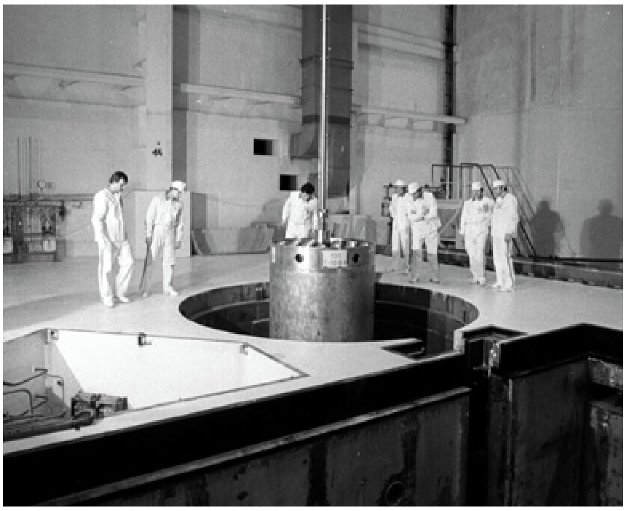
Dukovany's Triple Anniversary

This year, Czech Dukovany NPP celebrates its 55th anniversary. Its first unit was brought online on February 24, 1985. But on a closer look, it is a triple anniversary.

In April 1955, the Czechoslovak Socialist Republic and the Soviet Union signed an agreement on peaceful uses of nuclear power. As soon as June same year, the Czechoslovak government issued a decree establishing a nuclear physics institute in Řež and a nuclear physics and engineering faculty at the Czech Technical University. In September 1957, the country's first research reactor in Řež went critical. The initial agreement between the two countries was signed 65 years ago, and this is the first anniversary.

In 1970, Andrej Barčák, the Czechoslovak Minister for Foreign Trade, and Semyon Skachkov, Chairman of the Council of Ministers' Foreign Trade Committee, signed an agreement to construct two nuclear power stations in Czechoslovakia, Bohunice and Dukovany. This happened 50 years ago, and this is the second anniversary.

Nuclear island equipment for Bohunice was supplied entirely by the USSR. Core equipment for Dukovany's primary circulation loop, including reactors, steam generators, circulation pipes, turbines and generators (more than 80% of the total equipment) was manufactured in Czechoslovakia. The USSR supplied instrumentation and control systems and nuclear fuel. The key vendor was Škoda Plzeň, a major engineering and manufacturing company, which was responsible for the production, delivery, installation and commissioning of the equipment.



Stefan Konstantinov, who was in charge of bringing the reactor to criticality, said in an interview to Atominfo.cz it had been a difficult task to make a project schedule that would provide for the commissioning of one reactor every year. But when the plans were aligned, it turned out that all the four reactor units could be brought online even faster. **"That was the first time in my life that a project schedule had become shorter instead of growing longer,"** Stefan Konstantinov said.

In 1974, preparatory works started on the construction site at Dukovany. In the same year, Škoda began manufacturing machinery and equipment for the primary circulation loop of the reactor unit and constructing a nuclear reactor production facility in the city of Plzeň. The company manufactured and supplied all the four VVER-440 reactor pressure vessels, as well as auxiliary equipment for the reactor operation, transportation and storage of spent nuclear fuel.

Construction of the first unit began in 1977. Almost 12,000 people were engaged in construction and installation works on the site at the peak of the project. In 1981, a group of companies, Elektrárna Dukovany (EDU), was established, with the head of Hodonin power plant Bogumil Vincenc appointed as its director. The first concrete was poured in 1979.

Dukovany is an example of how workers from different countries helped each other. **"I was responsible for testing a large-capacity make-up pump. When I came up to it during the test, I saw it was so hot that even the paint on it was blistering. I realized that some system, most likely cooling, was not functioning and that the pump needed to be urgently turned off. I grabbed my walkie-talkie trying to reach anyone in the control room, but no one responded – they either did not hear the signal or were busy. And suddenly I saw a Russian worker running to me, with a screwdriver in his hand. It was a moment when I was completely at a loss, and my colleague showed me what to do. I remembered it for life. After that, I was carrying a screwdriver every day,"** Leoš Tomíček, Senior Vice President of Rusatom Overseas, said reminiscing about the past. When working at Dukovany, he was testing machinery and equipment as a member of Škoda Plzeň's commissioning team.

Dukovany Unit 1 went critical on February 12, 1985 and was brought online on February 24, 1985.

It took less than three and a half years to connect all the four units to the grid. Unit 2 came online in January 1986, followed by Unit 3 in November 1986 and Unit 4 in June 1987.

The nuclear station has been operating accident-free. According to the Czech energy company ČEZ, an owner of Dukovany, systems and equipment of the nuclear station have been upgraded and replaced on a regular basis. After a major upgrade in 2005–2012, the capacity of each Dukovany unit reached 510 MW. In 2017, instrumentation and control systems were upgraded, with safety and redundancy systems improved. In particular, new earthquake-resistant mechanical-draft cooling towers were built, and the number of diesel generators was increased, with two 3.2 MW diesel generators installed to be used during the so-called station blackout (SBO). In 2016, the State Office for Nuclear Safety of the Czech Republic (SUJB) issued an indefinite operating license for Unit 1. Three other units of the nuclear station obtained similar licenses in the next year. **"The station's service life is expected to expire in 2037 and can be extended until 2047,"** a press release on the ČEZ website read.

From 1985 until mid-2020, the four units of the Dukovay nuclear power station generated more than 452 TWh of electric power. This amount of electricity is enough to meet the needs of the entire Czech Republic for seven years. Every year, Dukovany produces more than 14 billion kWh of electricity, or 20% of the country's annual consumption.

On March 25, 2020, ČEZ filed an application with the SUJB to construct two new power units with 1,200 MWe reactors. The new units will replace the retiring coal-fired

capacity. For instance, the coal-fired Prunéřov Power Station located in North Bohemia and owned by ČEZ was shut down on June 5, 2020 during a ceremony dedicated to the World Environment Day. According to its press release, ČEZ does not rule out that the regulator will make a decision to build only one nuclear power unit.

Rosatom offers its technology and a wide range of cooperation opportunities to Czech engineering companies. If the parties reach an agreement, they might repeat the success of the 1980s again, and Czech companies will manufacture machinery and equipment for nuclear plants in their own country and other countries of Central and Eastern Europe.

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Era of Hydrogen

Hydrogen economy is a new energy trend, much like the renewables were twenty years ago. Hydrogen programs have been developed by the European Union and individual European countries. Germany has allocated funding for its national hydrogen strategy. Rosatom wants to be in the forefront of the hydrogen economy: the Russian nuclear corporation is developing proprietary hydrogen production technology and studies feasibility of electrolysis for industrial applications.

This year has become a milestone in the history of the hydrogen industry. Hydrogen technology has gone a long way from analyst forecasts and isolated attempts of individual companies to national and international strategies backed by solid funding. The pioneers in this field are the European Union and individual European companies.

Why hydrogen? Germany's example

Germany is one of the European countries on the forefront of promoting the idea of carbon neutrality. On June 10, 2020, the Government of Germany adopted a National Hydrogen Strategy. However, why hydrogen?

One of the key reasons behind the choice of hydrogen is most likely the fact that massive expansion of renewable capacity in Germany has come to a halt, which became evident already in 2018. **"In Germany, renewable capacity additions declined in 2018, but the reasons are not clear yet,"** Alexander

Korchagin, CEO of NovaWind (a wind power company and a subsidiary of Rosatom), said. In the first half of 2019, Germany added as little as 290 MW of new wind capacity, down 80% year over year. In 2018, new capacity additions decreased almost twofold as compared to 2017.

Why was it decided to quietly curtail investments in renewable energy sources? The main reason is that the bet on wind and sun as sources of energy generation capable of drastically reducing the volume of greenhouse gas emissions, did not pay off. It was not until 2018 that emission began to decline. Until then, they had been growing. It is a paradox, but emissions in Germany were declining in parallel with shrinking investments in new wind power capacity, which accounts for a major share in the total renewable capacity of the country.

The second reason is that the existing installed renewable energy capacity is already 25% higher than the stagnating demand for electricity. According to data from Energy-charts.de as of July 3, 2020, the total installed renewable capacity in Germany is 125.76 GW, while total consumption stands usually at 40 GW and rises to 80–100 GW at peak hours.

Third, renewable generation is unstable. **"Caused by these changes, the secured power generation capacity in Germany will decrease from 87.2 GW in 2017 down to 54.8 GW in 2030, which will be for sure to less for a reliable energy supply of Germany with its peak load of 80–100 GW and based on its own capabilities,"** Prof. Harald Schwarz, Chair of Energy Distribution and High Voltage Engineering at the Brandenburg University of Technology, writes in one of his articles.

The fourth reason is power price fluctuations and unbalanced distribution. **"Unfortunately, renewable generation will often occur, when less energy will be needed. Therefore, several times per week the region distribution grids starts feeding back renewable overproduction to the overlaid 400 kV transmission grid,"** Harald Schwarz continues.

Fifth, the grids are not developed enough to accommodate large and often unstable energy flows. The German National Energy Agency published a survey concluding that Germany needs to build 10,000 to 20,000 kilometers of 110 kV power transmission lines across the country. Prof. Schwarz notes, however, that only a few hundreds of kilometers of new lines were built over the last decade.

Sixth, there are no more vacant sites for solar or wind farms. Their proximity unnerves local residents and cause concerns about their health effects.

Seventh, expansion of renewables has driven up power prices. Officials have to promise there will be no further price growth.

And finally, the eighth reason, which has not been fully realized yet, is that there is no solution for the disposal of wind power towers as some of them have approached, or are approaching, the end of their service life.

Quick recap: Germany admits that the growth of renewable generation capacity has not addressed the existing challenges. Rather than reducing greenhouse gas emissions, renewables have made the energy supply less stable, changed landscapes and produced a new source of hi-tech waste.

The German experience is of course unique in its own way, but, at the same time, it is a warning to everyone who believes that renewable energy sources can be the basis of energy supply for a highly developed economy. Obviously, political considerations will not allow Germany to abandon renewable energy sources, but problems with the stability of energy supply must be somehow solved. Hydrogen economy has been declared a solution to the existing problems. And it seems there are no alternatives yet as no high-capacity power storage systems have been created and no new grids have been built.

Hydrogen funding in Germany

Between 2016 and 2026:

• EUR 1.4 billion in funding will be provided

Between 2020 and 2023:

• EUR 310 million will be provided under the Energy and Climate Fund for practice-oriented basic research

• EUR 200 million is planned to be provided to strengthen practice-oriented energy research on hydrogen technology

• EUR 600 million will be provided to foster the 'Regulatory Sandboxes for the Energy Transition', which help speed up the transfer of technology and innovations from the lab to the market, not least for hydrogen solutions

• More than EUR 1 billion will be provided for investment in technologies and large-scale industrial facilities that use hydrogen to decarbonize their manufacturing processes

On June 3, 2020, the Coalition Committee approved:

• EUR 7 billion for speeding up the market roll-out of hydrogen technology in Germany

• EUR 2 billion for fostering international partnerships

• Precise amounts available for each of these programs depend on the budget estimates to be made by the responsible ministries

Not just Germany

Other countries show interest in hydrogen economy as well. **"Almost all Member States have included plans for clean hydrogen in their National Energy and Climate Plans; 26 have signed up to the Hydrogen Initiative, and 14 Member States have included hydrogen in the context of their alternative fuels infrastructure national policy frameworks. Some have already adopted national strategies or are in the process of adopting one,"** authors of the European Strategy stated. Here are some examples.

In Spain, the latest edition of the alternative energy law designates hydrogen a key energy source. The Catalan Energy Institute has launched the Taula de l'Hidrogen project supported by 40 Spanish companies with the goal of promoting hydrogen technology.

In Russia, hydrogen is one of three components of the Roadmap for Development of the Power Storage Market in Russia.

In 2018, France adopted its Hydrogen Development Plan for Energy Transition, which will be included in the Long-Term Energy Program for 2019–2028.

TRENDS

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The U.S. Department of Energy is ready to partially fund the installation of electrolyzers at a nuclear power plant operated by Exelon.

Private companies are also interested in hydrogen technology. The largest European energy companies and associations including Akuo Energy, BayWa r.e., EDP, Enel, Iberdrola, MHI Vestas, SolarPower Europe, Ørsted, Vestas and WindEurope have sent an open letter to the European Commission, pointing out that **"Investment in renewable hydrogen has a great potential in terms of jobs and growth creation."**

Finally, the European Union has also developed a hydrogen strategy. Peculiarly, the strategy considers hydrogen to be 'clean' if it is produced with energy from renewable sources. The strategy reads, **"'Clean hydrogen' refers to renewable hydrogen."** The experience of Exelon and, as we will see, Rosatom proves that carbon-free production of hydrogen is possible at nuclear power plants. Yves Desbazeille, Foratom Director General, spoke up for the role of nuclear in the hydrogen market, **"Given the huge challenge Europe will face over the next 30 years, it is essential that policymakers do not focus only on variable renewables. Transforming our energy system is going to require ALL low-carbon solutions currently available. And the EU policy must reflect this."**

Who will pay for hydrogen?

It seems reasonable to assume that commitments of individual governments could be measured through allocated funds and announced project timelines. Exelon's project and Germany's strategy do have such measures.

The Exelon project is estimated at USD 7.2 million, with USD 3.6 million coming from the government. It is planned that the company will select an electrolysis site, complete 30% of the project, and simulate operation of the facility. The project is intended to diversify company's business and increase revenue from the nuclear power plant. **"Exelon has since 2018 been seeking ways to "re-purpose" its nuclear plants to make them more viable. The company's efforts included convening academic experts, former employees, and former federal regulators in a brainstorm session. And over the last several years, what we have boiled that table down to is, basically, hydrogen. Hydrogen is what we want to look at going forward. We think it fits in with potentially a future hydrogen economy,"** POWER Magazine quoted Exelon Nuclear Vice President for Engineering and Technical Support Scot Greenlee as saying.

As for Germany, the scope and sources of finance for the hydrogen economy are clearly detailed in the very beginning of its national strategy, **"… between 2016 and 2026, a total of EUR 1.4 billion in funding will be provided. In addition to this, the Federal Government has made use of the financial resources provided under the Energy Research Program to build an excellent research landscape. Between 2020 and 2023, EUR 310 million will be provided under the Energy and Climate Fund for practice-oriented basic research on green hydrogen and there are plans to provide another EUR 200 million over this period to strengthen practice-oriented energy research on hydrogen technology. In addition, EUR 600 million will be provided between 2020 and 2023 to foster the 'Regulatory Sandboxes for the Energy Transition', which help**

speed up the transfer of technology and innovations from the lab to the market, not least for hydrogen solutions. As part of Germany's decarbonization program, funding is provided for investment in technologies and large-scale industrial facilities that use hydrogen to decarbonize their manufacturing processes. More than EUR 1 billion will be provided for this between 2020 and 2023. There are also programs that promote the use of hydrogen in manufacturing and for the purpose of eliminating and utilizing carbon emissions in the base materials industry. These seek to encourage the industry to invest in hydrogen solutions. On June 3, 2020, the Coalition Committee adopted a 'package for the future' that makes available another EUR 7 billion for speeding up the market roll-out of hydrogen technology in Germany and another EUR 2 billion for fostering international partnerships. The precise amounts available for each of these programs depend on the budget estimates made by the responsible ministries."

The investment section of the EU Strategy contains expert estimates of future investments. **"From now to 2030, investments in electrolyzers could range between EUR 24 and EUR 42 billion. In addition, over the same period, EUR 220–340 billion would be required to scale up and directly connect 80–120 GW of solar and wind energy production capacity to the electrolyzers to provide the necessary electricity. Investments in retrofitting half of the existing plants with carbon capture and storage are estimated at around EUR 11 billion. In addition, investments of EUR 65 billion will be needed for hydrogen transport, distribution and storage, and hydrogen refueling stations. From now to 2050, investments in production capacities would amount to EUR 180–470 billion in the EU."**

Why not sooner?

On the one hand, the answer lies with the fact that only renewables have been seen as a silver bullet for growing emissions. On the other, hydrogen has inherent drawbacks, which became known almost a century ago. People have made many attempts at using hydrogen in different modes of transport, but they all failed for different reasons.

The first problem is that hydrogen mixtures with atmospheric oxygen are highly explosive and there are no safe and reliable storage systems. It is the explosion hazard that made airships a thing of the past, and this hazard has not gone away. In June 2019, an explosion destroyed a hydrogen fueling station in Sandvik (Norway). There were no casualties, but Uno-X, an owner of the station, suspended hydrogen sales at all of its three fueling stations in Norway, as well as in other European countries.

The second problem is high volatility of hydrogen and the smallest size of its atoms. Even a tiny leak in the tank will leave a vehicle without fuel. Just imagine that such

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Hydrogen funding until 2030 under the EU Strategy

- EUR 24–42 billion will be invested in electrolyzers
- EUR 220–340 billion will be required to scale up and directly connect 80–120 GW of solar and wind energy production capacity to the electrolyzers to provide the necessary electricity
- Around EUR 11 billion will be invested in retrofitting half of the existing plants with carbon capture and storage
- EUR 65 billion will be invested in hydrogen transport, distribution and storage, and hydrogen refueling stations

From now to 2050, investments in production capacities will amount to EUR 180–470 billion in the EU.

vehicle is an aircraft. As a result, hydrogen storage systems (such as tanks consisting of nanotubes filled with hydrogen) are very expensive, and the total weight and size of a vehicle increase. Storing wholesale amounts of hydrogen looks even more challenging. Harald Schwarz proposes storing hydrogen in gas holders, but it is just a proposal.

The third problem is related to consumer experience. It is well known that transport is a driver of almost any industry. But the infrastructure for hydrogen-powered cars is less developed than the infrastructure for electric vehicles with lithium ion batteries. Due to the economy of scale, electric cars are cheaper, and the maximum distance between charging stations is longer.

The fourth problem is that commercial production of hydrogen requires huge amounts of water. Ultimately, water will not disappear, but producers will have to calculate water balance for each specific lake or river, from which water will be sourced.

And finally, the main problem of hydrogen, particularly in terms of decarbonization, is its origin and price. Steam methane reforming is the cheapest and therefore most common method of hydrogen production. Coal gasification is the oldest method, while electrolysis is the most environmentally acceptable but expensive technique. Hydrogen produced by electrolysis is considered to be ‘green’ (see the Terms and Definitions below). According to the experts working on the French national hydrogen strategy, the cost of hydrogen produced by electrolysis is EUR 4–6 per kilogram provided that electricity costs EUR 50 per MWh and the electrolyzer works 4,000-5,000 hours per year. For comparison, the cost of hydrogen produced by steam reforming is EUR 1.5–2 per kilogram. The authors of the strategy believe that the cost of electrolysis might fell to EUR 2–3 per kg. According to the EU Strategy, the cost of green hydrogen ranges from EUR 2.5 to EUR 5.5 per kilogram and is expected to decline due to the economy of scale.

Transportation is another factor affecting the cost. According to the French strategy, it increases the end price in such industries as food processing, metallurgy, electronics, and glass production to EUR 10–20 per kg. After transportation, the price of hydrogen rarely remains below EUR 8 per kg. One might assume that transportation would make hydrogen a local product, but Germany’s national strategy provides for a portion of green hydrogen produced to be imported through the northern (the North and Baltic Seas) and southern borders.

With government support and lobbying excluded, hydrogen is acceptable but not the most attractive source of energy. According to Rusatom Overseas (part of Rosatom), hydrogen cars are manufactured by only Toyota, Honda, Daimler, Nissan and GM, while electric cars are made by almost every global car manufacturer.

Trains are a relatively recent addition to the range of hydrogen-powered vehicles. The most successful experiment is Coradia iLint, a hydrogen train servicing a 600 km line in Lower Saxony. The technology was developed by LHB, now part of Alstom. The government of Lower Saxony plans to launch 14 more hydrogen trains by 2022. Such trains can travel up to 1,000 kilometers without refueling at a speed of up to 140 km/h. The first hydrogen train in the UK, Hydroflex, was launched in February 2020, but its tank is enough for only 75 miles. In June 2020, Alstom signed a five-year agreement with Snam, one of major energy infrastructure companies, to develop hydrogen trains for Italy.

Quick recap: creating a new sector in the energy industry requires large investments from stakeholders to make the new energy source cheaper. Without them, the hydrogen industry is most likely to fill a few particular niches, such as intercity passenger trains traveling for a distance of up to 1,000 kilometers.

Market specifics

Since the hydrogen market is driven by political will, it is not just production but also regulatory harmonization that needs to be stimulated. **"Measure 13: Advocacy for an international harmonization of standards for mobility applications for hydrogen and fuel-cell-based systems (e.g. refueling standards, hydrogen quality, official calibration, hydrogen-powered car type approval, licensing for ships, etc.),"** the German Hydrogen Strategy reads.

The draft version of the EU Strategy estimates the global hydrogen output at 74 million tonnes, and only 4% of this amount is 'green' hydrogen. Given the target price of EUR 1.5–2 per kilogram of hydrogen, it is easy to calculate that the current market size in monetary terms is about EUR 150 billion per annum. We will refrain from citing consumption and production forecasts because reality proved long-term forecasts futile.

Rosatom's technology

Rosatom has been developing hydrogen technology and solutions for almost half a century.

OKBM Afrikantov, a large nuclear research and engineering center and a subsidiary of Rosatom, has developed a design for a nuclear power plant with an MGR-T reactor intended to generate electricity and produce hydrogen from different raw materials.

Leipunsky Institute of Physics and Power Engineering, also part of Rosatom, is working on liquid metal electrochemical hydrogen generators. Liquid metal is used here both as heat transfer medium and chemical agent. It works as follows. Water steam is supplied to a lower part of the vessel containing liquid metal and reacts with it. The reaction yields gaseous hydrogen, while oxygen remains dissolved in the melt. Heat-and-mass transfer in the melt intensifies, and hydrogen is easily separated from water, which has not reacted, in a condenser. The project is now in the research and development phase.

Another promising technology involves high-temperature helium reactors (HTHR) operating at 1,000°C. Test stands have been installed, and key components of the technology (reactor, ceramic fuel, energy conversion, equipment and structural materials) have been developed and tested.

As the global focus of attention began shifting towards hydrogen technologies in 2017, Rosatom included hydrogen economy into its corporate research and development strategy. Last autumn, the Russian nuclear corporation initiated a new project to launch a hydrogen-powered train service in the island of Sakhalin. This is a pilot project intended to test the technology and acquire necessary capabilities. The role of Rosatom is to supply fuel cells.

The project is advancing: in June 2020, Russian Institute for Nuclear Power Plant Operation (VNIIAES, a Rosatom company) signed a contract with Rosatom's electric power division Rosenergoatom to conduct a feasibility study for a nuclear and hydrogen energy competence center to be established at the Kola nuclear power plant.

Terms and definitions *(from Germany's National Hydrogen Strategy)*

Grey hydrogen is based on the use of fossil hydrocarbons. Grey hydrogen is mainly produced via the steam reforming of natural gas. Depending on the fossil feedstock, its production entails considerable carbon emissions.

Blue hydrogen is produced using a carbon capture and storage (CCS) system. This means that the CO2 produced in the process of making hydrogen does not enter the atmosphere, and so the hydrogen production can be regarded on balance as carbon-neutral.

Green hydrogen is produced via the electrolysis of water; the electricity used for the electrolysis must derive from renewable sources. Irrespective of the electrolysis technology used, the production of the hydrogen is zero-carbon since all the electricity used derives from renewable sources and is thus zero-carbon.

Turquoise hydrogen is produced via the thermal splitting of methane (methane pyrolysis). This produces solid carbon rather than CO2. The preconditions for the carbon neutrality of the process are that the heat for the high-temperature reactor is produced from renewable or carbon neutral energy sources, and the permanent binding of the carbon.

"The purpose of the Competence Center will be validation of technology for the production, storage and transportation of electrolytic hydrogen. We are now at the very beginning of a long journey," a representative of Rosenergoatom explained. VNIIAES will also develop technical requirements and design specifications for a hydrogen fueling station, a concept design of a cryogenic storage tank for medium and long-distance hydrogen transportation by sea, and a modular hydrogen liquefying unit. In addition, VNIIAES will develop a basis of design for a liquid organic carrier system for the hydrogen storage and transportation by ice-class tankers via Northern Sea Route to Japan.

The Kola NPP has two electrolyzers producing 20.5 and 21.33 cubic meters of hydrogen per hour. With the balance-of-plant needs amounting to 4,500 cu m per annum, it is easy to calculate that the existing capacity is more than enough to produce hydrogen on a commercial scale and sell it to customers. The electrolysis process is more efficient when combines with high-temperature steam. Its thermal energy replaces some of electric energy, thus improving the ratio of electricity consumed to hydrogen obtained. So it is quite likely that the study of VNIIAES will show how the existing technology can be improved.

Quick recap: Rosatom is engaged in the development of proprietary solutions for the hydrogen economy and continues building relevant competencies to win a share in the hydrogen market. NL

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