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Development of electrolysis technologies for hydrogen production: A case study of green steel manufacturing in the Russian Federation

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ABSTRACT

The article reviews a list of solutions to reduce the carbon intensity of the Russian fuel and energy complex. The technological scheme of green hydrogen production that is the most optimal for the Russian Federation has been determined. It is shown that by 2040, the net present value of hydrogen production units by the alkaline electrolysis method will amount to US $ 35 thousand/ kW while the cost of plants with a solid polymer or a solid-oxide electrolyzer will be at US$30 thousand/ kW and US $ 26 thousand/ kW accordingly. This paper presents a feasibility study of green hydrogen production from wind-powered electrolysis with further direct reduction of iron ore for green steel manufacturing. According to the analysis, the difference in cash flows between standard steelmaking technology and direct reduction of iron ore with hydrogen is 20% which in the long term could be reduced to 5%. Compared to the European Carbon Border Adjustment Mechanism, companies will be able to save about 3% of the present value. To achieve the commercial attractiveness of hydrogen production by electrolysis, the minimum amount of government subsidies should be at least 10% of capital expenditures from 2021 with a gradual increase to 20% by 2040 to support the emerging market.

1. Introduction

1.1. Greenhouse gas (GHG)

Now, rising global temperatures are associated with increased greenhouse gas emissions from human activities. The combustion of fossil fuels in end-use sectors results in the emission of most of the greenhouse gases (Hosseini et al., 2013). Over the past decade, the average annual temperature has averaged 1.09 °C higher compared to 1850–1900. The temperature rise is expected to exceed 1.5 °C over the next 20 years (IPCC, 2021). The Paris Agreement aims to focus efforts on limiting this increase to 1.5 °C by 2100 compared to the pre-industrial levels (UNFCCC, 2015).

The energy sector accounts for over 60% of the world's greenhouse gas emissions from fossil fuels. The atmospheric concentrations of CO_2 are currently at 417 ppm (3 ppm more than last year) directly affecting the climate change (IPCC, 2021).

The European Union has a plan to achieve climate neutrality by 2050 with an interim target to reduce greenhouse gas emissions by at least 55% by 2030 (IEA, 2021a). A Net Zero transition requires all states to significantly strengthen their

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List of abbreviations

NPV	net present value
PV	present value
CBAM	Carbon Border Adjustment Mechanism
SDG	Sustainable Development Goals
Ppm	parts per million
GHG	greenhouse gas
FEC	fuel and energy complex
CCUS	Carbon Capture, Utilization and Storage
AEL	alkaline electrolysis
PEMEL	proton-exchange membrane electrolysis
AEM	anion exchange membrane electrolysis
SOEL	solid oxide electrolysis
CAPEX	capital expenditure
OPEX	operational expenditure
H-DRI	hydrogen direct reduction of iron ore
BAU	Business as Usual
TRL	Technology readiness level

climate policies (Climate Action Tracker, 2021; Talebian et al., 2021). Russia is one of the world's largest GHG emitters, accounting for about 5% of total GHG emissions (IEA, 2021b). Nevertheless, over the past 30 years, GHG emissions from the industrial sector have decreased by more than 30% as a result of the use of less carbon-intensive technologies as well as due to equipment modernization. Net greenhouse gas emissions in 2021 are at 1,584 million tons of CO_2-eq. At the same time, the fuel and energy complex (FEC) accounts for about 900 million tons which requires the modernization and transformation of the entire chain of production, transportation and consumption of energy. The current vector of Russia's development is aimed at reducing emissions to zero by 2060.

There are more than 600 technological solutions (IEA, 2021c) allowing to achieve Net Zero commitments. No more than 30% of technological solutions have reached technology readiness level (TRL) 9. In general terms they can be divided into 4 categories corresponding to the 4R concept (Reduce, Reuse, Remove, Recycle) (Yu et al., 2021):

- Reduce — reducing CO_2 emissions through improved energy efficiency and the introduction of hydrogen, nuclear and renewable energy technologies;
- Reuse — capturing and utilizing CO_2, recycling CO_2, by repairing, regrinding and refurbishing equipment;
- Remove — CO_2 capture and storage;
- Recycle — development of bioenergy.

Hydrogen technologies (Abe et al., 2019), along with renewable energy sources (Qazi et al., 2019) and carbon capture and utilization technologies (CCUS) (Tapia et al., 2018) are key instruments for decarbonizing the global energy system. The share of hydrogen in the total final energy consumption is expected to grow from less than 0.1% in 2020 to 10% in 2050. Hydrogen will help avoid up to 60 Gt of CO_2 emissions in 2021–2050 which is 6.5% of the total cumulative emission reductions (BP, 2021). The development of hydrogen energy directly contributes to the implementation of the Sustainable Development Goals (SDGs), developed by the UN General Assembly (UN, 2015). Prioritize Goal 7: Affordable and clean energy and Goal 13: Climate action.

1.2. Hydrogen production

Hydrogen is a sustainable energy carrier capable of reducing carbon dioxide emissions to save the world from global warming. The energy potential of hydrogen lies in its ability to accumulate chemical energy, serve as an energy source and a raw material for various industries. Today, most of the hydrogen is produced from fossil fuels, mainly by steam reforming of methane, and only about 4% of the world's hydrogen comes from water electrolysis (IEA, 2021d). In the context of the transition to Net Zero, the production of electrolytic hydrogen from water and the use of renewable energy sources are in priority (Newborough and Cooley, 2020). Hydrogen derived from renewable electricity will play an important role in the deep decarbonization of industry. However, adding more electrolyzer capacity to a low-carbon electricity system also increases the need for additional power generation from variable renewables. Hydrogen production from sustainable solar and wind power and abundantly available water is an environmentally friendly solution to meet global growing energy demand. Among the various ways to produce hydrogen by solar and wind power, research is focused on hydrogen production through three electrolysis systems including alkaline water electrolysis, polymer electrolyte

Table 1
Comparative characteristics of electrolysis technologies.

Parameter	AEL	PEMEL	SOEL
Efficiency (system), kWh/KgH2	50–78	50–83	> 90
Voltage range, V	1.4–3	1.4–2.5	1.0–1.5
Nominal current density, A/cm^2	0.2–0.8	1–2	0.3-1
Operating temperature, °C	70–90	40–60	700–850
Lifetime (stack), h	60.000	50,000–80,000	< 20,000
System startup time, min	20–120	< 1	> 300
Capital Costs (system), US$/kW	500–1.100	700–1800	> 2000

membrane electrolysis, and solid oxide electrolysis. The cost of renewable hydrogen has a very large range due to the different technologies used. The challenges, pros and cons of various commercialization methods and processes are noted (Hosseini and Butler, 2020; Hosseini and Wahid, 2020, 2016; Mostafaeipour et al., 2016).

Electrolysis is the electrochemical decomposition of water (H_2O) into hydrogen (H_2) and oxygen (O_2) under the impact of electricity through the following reactions (Ursúa et al., 2012):
Anode: $H_2O\ (l) \rightarrow 1/2\ O_2 + 2H^+ + 2e^-$
Cathode: $2H^+ + 2e^- \rightarrow H_2$
Full reaction: $H_2O\ (l) \rightarrow H_2 + 1/2\ O_2$

To date, electrolytic projects with a total capacity of more than 20 GW have been commenced all over the world, and many of them have been even implemented to a certain project stage. Over the past several years, more than 80 of the world's largest companies with revenues exceeding US $ 2.6 trillion have joined the Hydrogen Council, a leading initiative for industries using hydrogen as an energy solution (Hydrogen Council, 2021). The Russian Federation, with its significant natural reserves, has all the necessary resources, financial, scientific, and technological foundations for the development of hydrogen energy domestically, as well as for the export. The purpose of this work is to determine the development prospects and priority areas for electrolysis technologies in Russia in the short and long terms.

There are three main electrolysis technologies, depending on the type of electrolyte used:

– alkaline electrolysis with liquid electrolyte (AEL) (Schalenbach et al., 2016; Shen et al., 2018; Zakaria and Kamarudin, 2021), incl. electrolysis with anion exchange membranes (AEM) (Hnát et al., 2017; Kraglund et al., 2016);
– proton-exchange membrane electrolysis (PEMEL) (Marshall et al., 2007; Park et al., 2021);
– solid oxide electrolysis (SOEL) (Jensen et al., 2016; Song et al., 2019).

Comparative characteristics of electrolysis technologies are presented in Table 1 (IRENA, 2020a).

1.3. The Russian steel industry

It should be noted that the climate agenda has a significant impact on the development of both the global and Russian economies. In July 2021, the European Commission published a regulation on the Carbon Border Adjustment Mechanism (CBAM) (EU, 2021) that will be launched on January 1, 2023. CBAM will primarily affect the chemical and metallurgical industries. Industry which accounts for 38% of total energy demand, is the largest end-use sector and contributes 26% of the global energy system's CO_2 emissions. The industrial sector emits 8.7 Gt of CO_2. The industry's demand for hydrogen is at 51 million tons per year. IEA (2021d).

Steel production is the largest industrial subsector accounting for about 7% of total global CO_2 emissions (Pérez-Fortes et al., 2014). In the breakdown of greenhouse gas emissions in Russia, the industrial sector accounts for about 11% (Bravkov et al., 2020). The industrial sector is faced with the challenge of meeting growing demand for products while reducing CO_2 emissions. For Russia as an exporter of carbon-intensive metallurgical products (Russia's steel exports amounted to 31.5 million tons Zhdaneev and Chuboksarov, 2020 in 2020) a number of significant threats arise, primarily associated with financial risks.

This work presents a model project of direct reduction of iron ore with hydrogen as an attractive alternative to the reduction with carbon, to eliminate the CO_2 emissions in green steel making. In addition, a region of the Russian Federation is selected for a pilot project.

2. Economic model for the development of electrolysis technologies

In accordance with the Concept for the Development of Hydrogen Energy (Government of the Russian Federation, 2021a) potential volumes of hydrogen exports from Russia could reach 0.2 million tons in 2024, 2–12 million tons in 2035 and 15–50 million tons in 2050 depending on the pace of the low-carbon economy development and the growing demand for hydrogen in the world market. Considering the current production capacity does not guarantee the achievement of a positive scenario of 50 million tons, a conservative scenario with a hydrogen production of 15 million tons by 2050 was adopted for calculation purposes. Production costs are a major barrier to a widespread use of electrolytic hydrogen.

Table 2
Total number of electrolysis plants of various capacities toward 2050.

Electrolyzer	100 kW (unit)	500 kW (unit)	1 MW (unit)
2035	1870	4,523	3100
2050	7305	12,732	7966

Within the estimated costs, reaching the breakeven point (costs are compensated by revenues) ensures the growth of the share of electrolytic hydrogen from 1% (based on the hydrogen demand) to 16% in 2050. According to the estimates of the Ministry of Energy of the Russian Federation, in the case of the development of technologies in the field of hydrogen energy, demand for electrolytic hydrogen in 2024 may amount to 0,002 million tons and grow to 2,4 million tons by 2050. Taking into account the development of transport infrastructure and the renewal of fixed assets after the end of the recommended service life of the equipment, the total capital expenditures of Russian companies until 2050 may exceed US $ 79 billion.

Custom Discounted cash flow (DCF) model is used. In order to determine the optimal electrolysis technology for the Russian Federation, it was assumed that the capital expenditure (CAPEX) (IEA, 2021e) is US $ 1,100/kW for AEL, US $ 1,800/kW for PEMEL, US $ 2,800/kW for SOEL while operating expenses (OPEX) (Brynolf et al., 2018; Glenk and Reichelstein, 2019) are taken as 3% of CAPEX with the life cycle of 60 thousand hours, 70 thousand hours and 20 thousand hours respectively.

Calculations show that despite the fact that alkaline electrolysis AEL is the most advanced technology today, the construction of a green hydrogen plant in Russia will not be profitable until 2030 when the net present value (NPV) will be about US $ 4,500/kW. Net present value discounted at 10% (NPV10). Value of 10 was chosen because the average base rate on deposits is 10%. For PEMEL technology, the plant performance is expected to reach breakeven point by 2035. After 2040 all three methods (in case of technology development) will become cost-effective. With alkaline electrolysis still being the most cost-effective method, the NPV would be US $ 35,000/kW, for PEMEL the NPV would be lower (US $ 30,000/kW), and for SOEL it will amount to about US $ 26,000/kW.

By 2050, due to increased stack life and lower capital expenditures (CAPEX), the largest profit could come from the construction of an electrolysis plant based on SOEL technology while its NPV will potentially increase to US $ 58,000/kW. The profit may be US $ 49,000/kWh for PEMEL and US $ 45,000/kWh for AEL. It is important to note that the calculations are made on the assumption that R&D for all technologies is carried out continuously from today.

Based on NPV10 and the profile of hydrogen production due to the absence of industrial PEMEL and SOEL plants in Russia, around 2030 about 0.5 million tons of hydrogen will be produced by the AEL method. However, in case of the plant construction, the costs will exceed the revenues which raises a question of state support.

By 2035 the balance between methods will be rearranged. Thus, the commissioning of PEMEL capacities will become cost-effective and reach a share of 5%. After 2040, as a result of technological progress in the SOEL area and a decrease in capital expenditures to US $ 2,317/kW, the commissioning of SOEL capacities will become commercially attractive and will amount to 17% while PEMEL will grow to 33%, and AEL will still account for 50% of all commissioned electrolysis facilities.

Given significant technological progress, around 2050 SOEL, PEMEL and AEL can reach the shares of 38%, 32%, 29% correspondingly. Analysis of the unified information system in the field of procurement (Procurement Portal of Russia, 2021) indicates that today there is a demand for all three types of electrolysis systems. However, greater interest is shown to the industrial implementation of PEMEL and R&D for SOEL, the capital costs for which currently are US $ 1,800 and 2,800/kW respectively. In the future, it is possible to reduce capital costs to US $ 200 for PEMEL and US $ 300/kW for SOEL.

3. Forecast of reduction in the cost of electrolysis technologies

Today electrolytic hydrogen in Russia is mainly used to cool powerful turbine generators at nuclear power plants, state district power plants, thermal power plants, etc. The use of hydrogen for electrification in hard-to-reach regions, in shipping and aviation, in the chemical and the metallurgical industries will be valid. In addition, according to the Concept for the Development of Production and Use of Motor Vehicles in the Russian Federation for the period up to 2030 approved by the Government Decree No. 2290-r of August 23, 2021 (Government of the Russian Federation, 2021b), one of the key targets is the commissioning of at least 1000 hydrogen-refueling stations which will result in the need for electrolyzers with a capacity of 100–500 kW.

The projected level of production capacity will contribute to scientific, technical and industrial progress in the field of hydrogen production by electrolysis. In the context of growing demand for hydrogen in the domestic and foreign markets, it will be reasonable to create electrolyzers with a capacity of 500 kW–1 MW to increase the efficiency of the units. The total number of commissioned electrolysis plants toward 2050 may be about 28,000 units. According to the Ministry of Energy of the Russian Federation the total number of electrolysis plants of various capacities required for commissioning around 2050 is presented in Table 2 (Ministry of Energy of the Russian Federation, 2021).

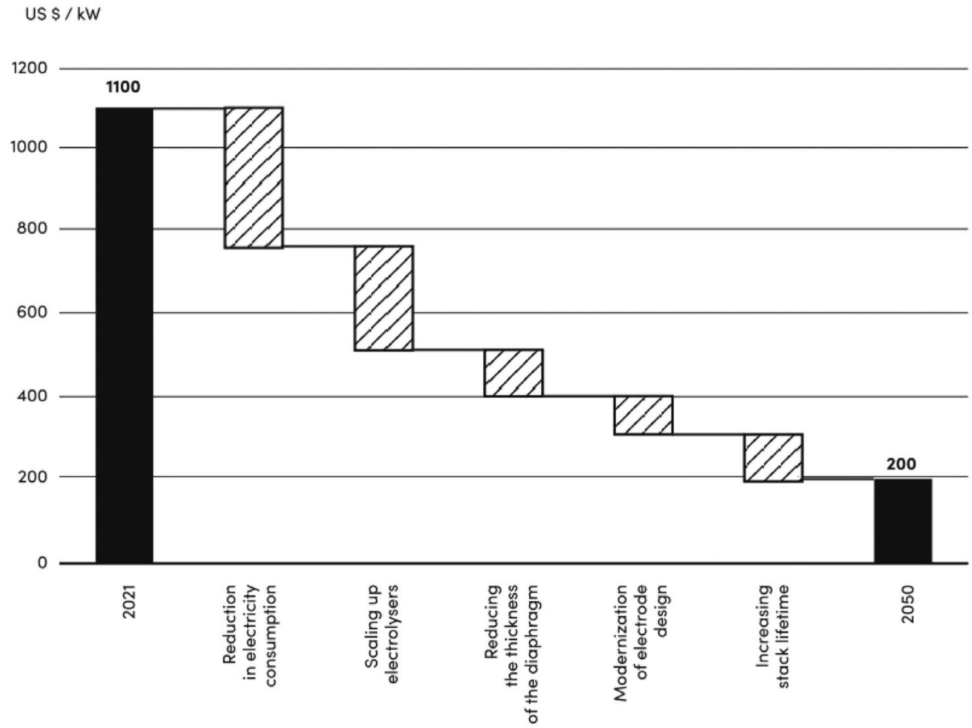

Fig. 1. Forecast of the decline in the cost of AEL.

For the competitive production of environmentally friendly hydrogen, a significant factor is the reduction in the cost of electrolyzers. The cost reduction is mostly achieved due to technology development and production scaling. Figs. 1–3 show depreciation projections for AEL, PEMEL and SOEL, respectively (Ministry of Energy of the Russian Federation, 2021).

For AEL, cost reduction is possible by increasing the operating temperature limit replacing thick 460 diaphragms by 50 μm (a power density of 2–3 W/ cm^2 can be achieved), processing catalytic compositions, developing new electrodes. There is a projection of an increase in current density around 2050 from 0.2–0.8 A/cm^2 to 2 A/cm^2 as well as a reduction in power consumption from 50–78 kWh/kg H_2 to < 45 kWh/kg H_2, cold start time < 30 min, an increase in stack life from 60,000 h to 100,000 h, an increase in the stack power from 1 MW to 10 MW, an increase in the electrode area from 1,500 cm^2 to > 10,000 cm^2 and a reduction of capital costs to < US $ 100/kW.

For PEMEL, replacing thick membranes, reducing the amount of Pt loading in the catalyst, creating Platinum-free catalysts, removing or replacing titanium coatings of porous transport layers, developing and scaling up production will help lower the cost of the technology. Substantial competitiveness can be achieved by increasing the current density from today's 1–2 A/cm^2 to 4–6 A/cm^2, electrical efficiency of the electrolyzer from an electricity consumption of 50–83 kWh/kg H_2 to < 45 kWh/kg H_2, time life of the stack from 50–80,000 h to 100–120,000 h, stack power from 1 MW to 10 MW, electrode area from 1.5 m^2 to > 10 m^2 and reducing capital costs to < US $ 200/kW.

SOEL technology is currently at the prototype and demonstration stage. SOEL has the highest electrical efficiency (over 70%) with the main drawbacks being short stack life (less than 20,000 h), long start-up times (> 600 min) and high capital costs (> US $ 2,000/kW). System cost reduction is expected by increasing the current density from 0.1–0.3 A/cm^2 to 2 A/cm^2, the lifetime of the stack from < 20 thousand hours to > 80 thousand hours, the power of the stack from 5 kW to 200 kW and the area of electrodes from 200 cm^2 to > 500 cm^2 as well as decreasing electricity consumption from 40–50 kWh/kg H_2 to < 40 kWh/kg H_2, cold start time to < 300 min and capital costs to < US $ 300/kW.

Actual cost reductions can be achieved even faster if renewable hydrogen becomes more competitive. Differences in renewable energy sources make the production and use of electrolytic hydrogen specific to given regions. According to estimates (IEA, 2020), in 2020 renewables accounted for nearly 90% of the world's new installed generating capacity. During the year, 200 GW of new green generation was built, of which 65 GW are wind power plants. Russia has a significant potential in the wind energy sector. As of the beginning of 2021, more than 1 GW of wind power plants are operating in Russia of which more than 700 MW were commissioned in 2020 (FES, 2021).

4. Typical Green steel manufacturing project

For the purposes of the model project calculation, the Abinsky District of the Krasnodar Krai was chosen as the location of wind power plants, electrolysis plants for the production of hydrogen and a hydrogen consumer. The natural features

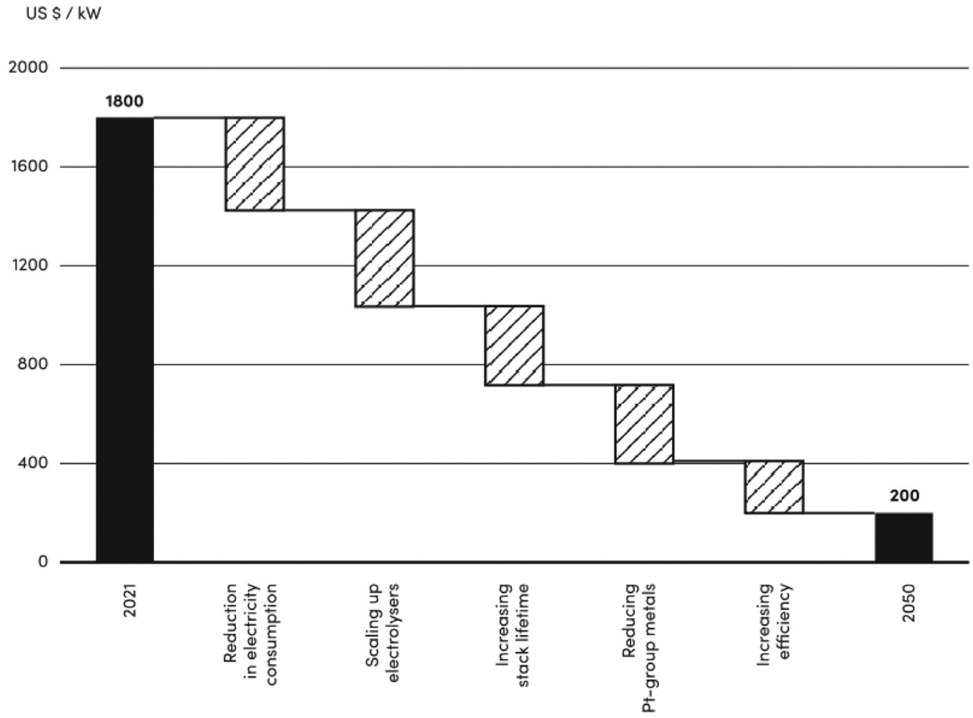

Fig. 2. Forecast of the decline in the cost of PEMEL.

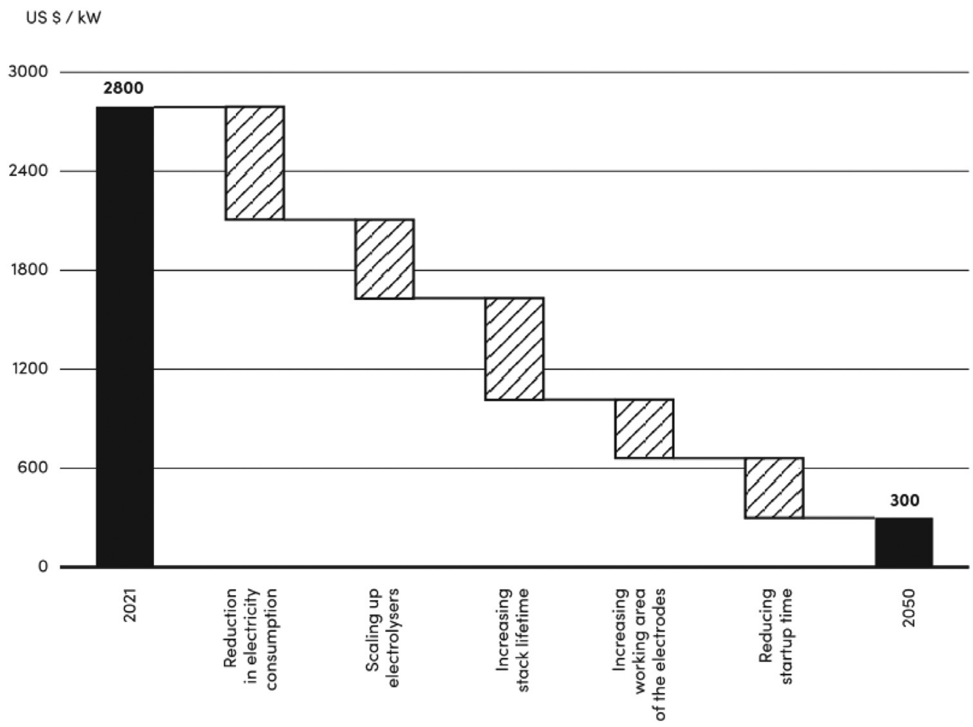

Fig. 3. Forecast of the decline in the cost of SOEL.

of the region are most optimal for the development of wind generation, the average annual wind speed in the region is 7.5 m/s (Global Wind Atlas, 2021). In addition, the region is implementing a state program to support renewable energy sources through 2035 (Government of the Russian Federation, 2021c). Wind power facilities with a total capacity of 4.8 MW are currently operating in the Krasnodar Krai.

The Abinsk Electrometallurgical Plant is located in the region. The volume of steel production is 1.2 million tons per year. Today in steelmaking, coking coal is used as a reducing agent for iron ore. Oxygen reacts with the carbon of the iron ore to form CO_2. An alternative method called hydrogen direct reduction of iron ore HDRI omits the use of coke. Oxygen reacts with carbon to form water. The technology is currently at a pilot stage (IRENA, 2020b). Now, the consumption of coke is 480,000 tons/year. The equivalent volume of hydrogen consumption will be equal to 14,000 kg H_2/year. Re-equipment of the plant with new technology will be the most expensive part of the project amounting to US $ 4,106 million.

For the corresponding hydrogen demand, a 500 kW PEMEL electrolyzer is proposed with a production volume of 16,200 kg/year. A key factor in the selection of PEMEL is the dynamic system response (< 1 s) (Schmidt et al., 2017) to AC power and cyclic on/off, far superior to AEL and SOEL, making PEMEL the most suitable for use in conjunction with RES. In addition, PEMEL has a more compact design compared to the other two technologies. Fig. 4 shows a typical project for steel production using green hydrogen (Ministry of Energy of the Russian Federation, 2021).

Renewable electricity from the wind power plant is fed into an electrolytic cell for an electrochemical water separation reaction, and the resulting hydrogen is then used to convert iron ore to iron in a direct reduction process. The HDRI process is flexible in operation. The cell responds to fluctuations in the power supply by producing more or less hydrogen. Pressure vessels can be used to provide a continuous supply of hydrogen. To generate the required amount of energy, it is planned to install two Russian-made wind turbines (NovaWind JSC) with a nominal capacity of 2.5 MW each.

To calculate cash flows in two scenarios (BAU — Business as Usual and H-DRI), the following values were taken:

– Production capacity of the plant is 16,200 kg/year
– PEMEL electrolyzer capacity — 500 kW
– Electricity consumption by electrolyzer — 55 kWh/kg H_2
– Costs for the PEMEL electrolyzer — US $ 70,000 (average price based on the current project costs)
– Capital investments in the construction of a wind farm — US $ 4.2 million
– Total capital expenditures — taken as US $ 416 million
– Additional operating costs — 3% of total capital costs
– Annual maintenance costs — 1% of capital costs
– The amortization period is estimated at 30 years.

The calculation results are shown in Fig. 5 (Ministry of Energy of the Russian Federation, 2021). Note that in Fig. 5 the present value cash flow is shown as a project lifecycle. At Figs. 6–7 there is shown NPV10 as a cumulative figure. NPV10 is obtained by summing the PV of the cash flow and discounting at a rate of 10%.

As can be seen from Fig. 5, due to high capital costs, on average the cash flow decreases within 20% of the baseline scenario of the plant's operations. However, in the long term (starting in Year 10), the difference decreases to 10% and then to 5% due to lower O&M costs. The sensitivity assessment of the calculated costs is shown in Fig. 6 (Ministry of Energy of the Russian Federation, 2021).

In the analysis, the assumptions and results obtained in the above calculations vary by $+/-20\%$. Compared to the CBAM approved in the European Union, the company will be able to save about 3% in the long term which may not be enough to make a final investment decision.

5. Measures of state incentives for electrolysis technologies

The price gap for fossil fuel-derived hydrogen is also a key obstacle to low-carbon hydrogen. However, with sufficient government support (Fig. 7) and in case of a potential reduction in capital costs due to cheaper technologies, such retrofitting can become common at Russian metallurgical plants (Ministry of Energy of the Russian Federation, 2021). Prohibiting steam methane reforming without CCUS and Production tax credit would require additional investments that will lead to drop of NPV.

The average hydrogen price and greenhouse gas emission reductions per unit of hydrogen production over a 30 year period for the baseline scenario were taken as USD $ 9/kg and 12 kg CO_2-eq/kg H_2, respectively. State support measures and their possible effects are presented in Table 3 (Talebian et al., 2021).

The effectiveness of the subsidy was determined by three performance indicators:

– change in hydrogen price per dollar of subsidy cost;
– reduction of greenhouse gas emissions per dollar of subsidy cost;
– reduction of greenhouse gas emissions per 1 kg of hydrogen produced.

The proposed support measures increase the production of electrolysis hydrogen but have different efficiencies. Thus, the effect of a tax credit on electrolysis hydrogen production at a constant rate of US $ 2/kg H_2 is comparable to the effect of a 100% electricity subsidy. Capital subsidies and grants are ineffective subsidies. The permanent tax credit removes steam reforming hydrogen production in favor of electrolysis.

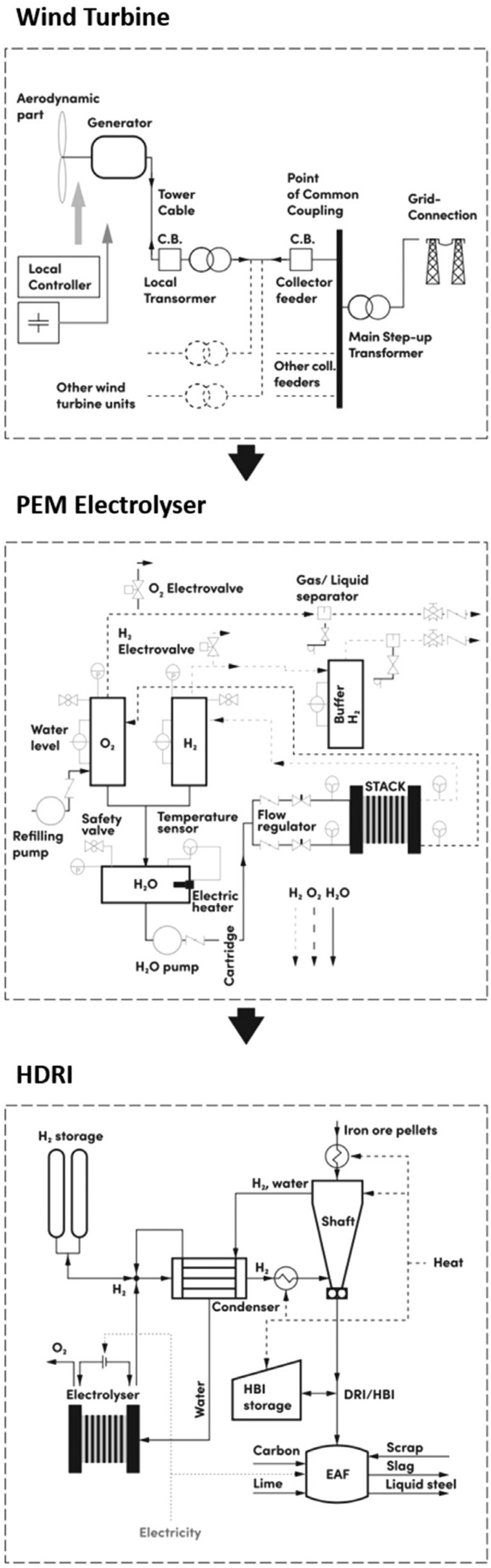

Fig. 4. Technological process for green steel production in the framework of the project.

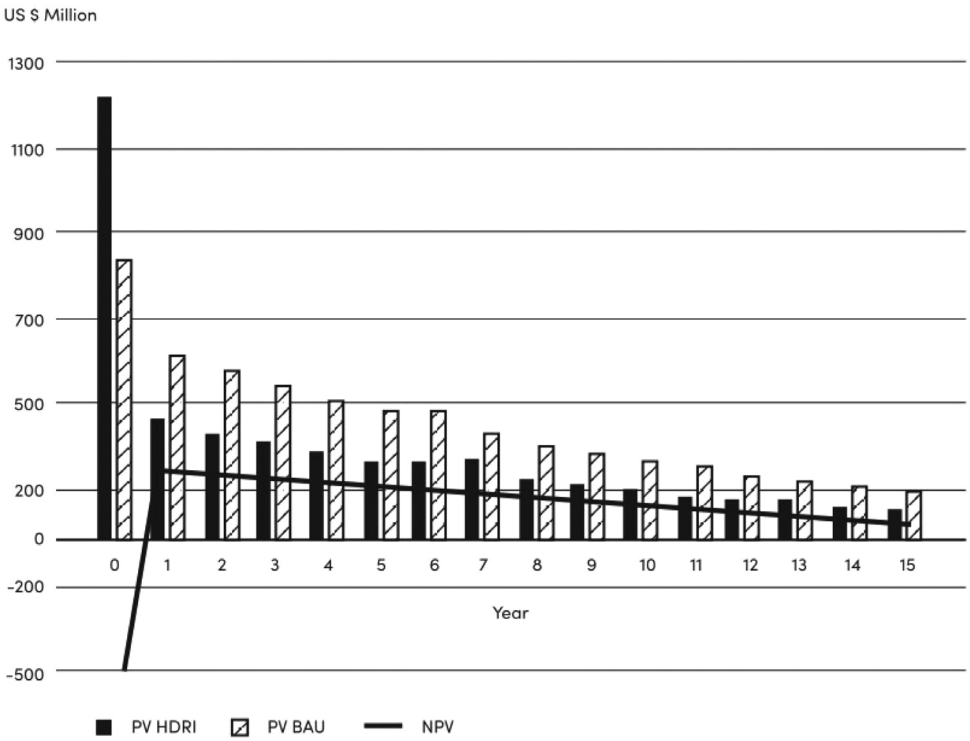

Fig. 5. Comparison of cash flows in two scenarios (BAU — Business as Usual and H-DRI).

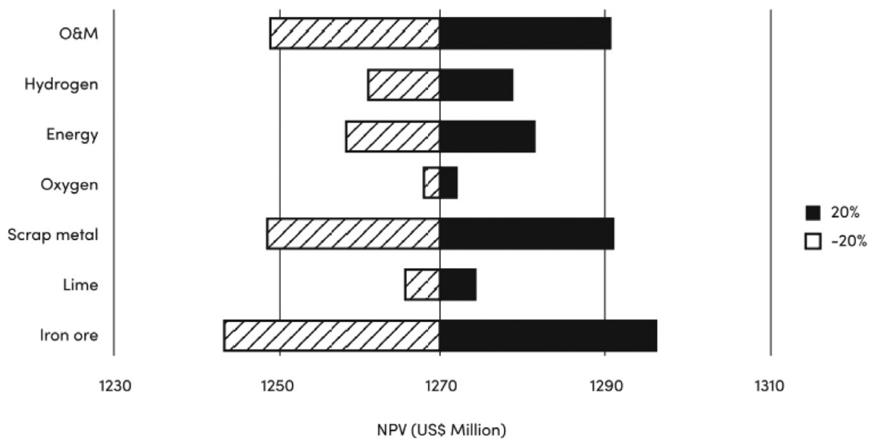

Fig. 6. Sensitivity analysis of the project (re-equipment of the plant to HDRI).

6. Conclusions

Given the growing relevance of the global climate agenda, the wide range of applications for electrolysis hydrogen makes it an integral part of the decarbonization process. In Russia, clean hydrogen solutions can be applied in heavy industry, construction and the transport sector, simultaneously encouraging the use of renewable energy sources.

With the current TRL, there is no profitable electrolysis technology in Russia which indicates the need for R&D. Today, AEL is a commercially advanced technology. AEL has the lowest cost while PEMEL has the potential to reduce its capital costs. In Russia in the short term the technologies of alkaline and solid polymer electrolysis are commercially attractive, and in the long term (after 2040) in case of scientific and technological progress the industrial introduction of solid oxide electrolyzers will be relevant.

A major cost component in the production of green hydrogen is the cost of the renewable electricity required to power the cell. The second largest cost factor is the cost of electrolysis units. Key cost reduction drivers for the three types of cells

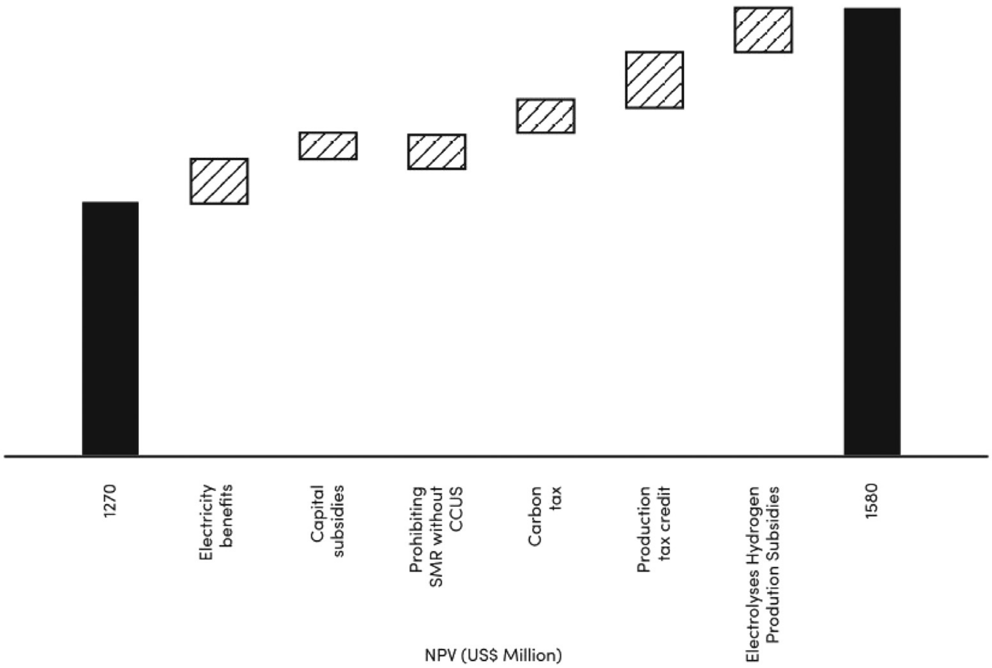

Fig. 7. Measures of state incentives for the electrolysis hydrogen production.

Table 3
Government incentives and their expected effects.

Government incentives	Effects
Subsidies for electricity covering from 100 to 25% of its cost until 2050	Reduced electricity subsidy term (up to 10 years) and a smaller subsidy size (in case of 25% of the electricity cost covered) impede the introduction of centralized electrolysis. The size (100%) and duration (30 years) of the subsidy are critical to the technology transition.
Capital subsidies, grants. One-time payment to cover 100 to 25% of capital costs	The most inefficient way to subsidize. Various capital subsidy schemes increase the share of on-site hydrogen production; however, they are not suitable for centralized electrolysis. steam methane reforming has over 39% of the market, even with significant capital grants (covering 100% of the cost) allocated to electrolysis hydrogen production.
Bans on steam methane reforming without CCUS	The emission reduction effect increases to 5 kg CO_2-eq/kg H_2.
A carbon tax of US $ 4 per ton CO_2	Leads to an emission reduction of 6.43 kg CO_2-eq/kg H_2 for every dollar of hydrogen price increase.
Production tax credit US $ 2/kg until 2050	Introduction of a production tax credit makes the production of steam methane reforming unprofitable compared to electrolysis.

include industrialization of cell manufacturing, improved cell efficiency, and an increase in operational and maintenance efficiency.

The production of green hydrogen in the absence of government support will slow down technological development and will require a more than twofold increase in capital costs compared to 2021. This will make the production of hydrogen economically unfeasible even in the long term (after 2050).

The main measure of state support is the subsidization of electrolysis technologies. To conduct R&D, create pilot plants and support the emerging hydrogen market, the amount of public investment in the development of electrolysis technologies will exceed US $ 7 billion toward 2040. The government subsidies could be discontinued after 2040 when all three electrolysis technologies become cost-effective and profitable.

New international challenges, including CBAM, may become an additional incentive for the development of green projects at the intersection of energy and industry. The availability of production facilities and competencies in the field of wind energy and electrolytic hydrogen can reduce the economic losses of Russian steel exporters caused by the introduction of CBAM.

The transition to direct reduction of iron ore with hydrogen requires a number of changes in the steel industry. It is also important to resolve the issue of CO_2 emissions arising from the production of lime which is required for slag foaming. Alternatively, it is possible to change the technological process by replacing lime with a new material. In addition, a solution is required for the issue of utilization of large volumes of oxygen produced during electrolysis. By-product oxygen can be fully utilized in many processes such as incineration, semiconductor manufacturing, wastewater treatment, medical applications. The use of by-product oxygen can help to reduce the large amount of electricity consumed in the production of oxygen using air separation technologies such as cryogenic air separation and pressure swing absorption.

CRediT authorship contribution statement

Elena Galitskaya: Data curation, Methodology, Investigation, Writing – original draft. **Oleg Zhdaneev:** Conceptualization, Resources, Supervision, Writing – review & editing.

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