

Development of electrolysis technologies for hydrogen production in the Russian Federation

Elena Galitskaya

ISSP RAS: Institut fiziki tverdogo tela Rossijskoj akademii nauk

Oleg Zhdaneev (✉ oleg_1978@mail.ru)

A V Topchiev Institute of Petrochemical Synthesis Russian Academy of Sciences: Institut neftehimiceskogo sinteza imeni A V Topchieva Rossijskaa akademii nauk <https://orcid.org/0000-0002-5287-4397>

Research Article

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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 NPV of hydrogen production units by the alkaline electrolysis method will amount to US \$ 35 thousand per kW, while the cost of plants with a solid polymer or a solid-oxide electrolyzer will be at US \$ 30 thousand per kW and US \$ 26 thousand per 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 PV. 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

Greenhouse gas emissions from human activities cause global warming [1]. 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. [2]. The Paris Agreement aims to focus efforts on limiting this increase to 1.5°C by 2100 compared to the pre-industrial levels [3].

The energy sector accounts for over 60% of the world's greenhouse gas emissions from fossil fuels. The atmospheric concentrations of CO₂ are currently at 417 ppm (3 ppm more than last year) directly affecting the climate change [2].

The European Union has a plan to achieve climate neutrality by 2050 with an interim target to reduce greenhouse gas (GHG) emissions by at least 55% by 2030 [4]. A Net Zero transition requires all states to significantly strengthen their climate policies. [5, 6]. Russia is one of the world's largest GHG emitters, accounting for about 5% of total GHG emissions [7]. Nevertheless, over the past 30 yr, 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 1584 million tons of CO₂-eq. At the same time, the fuel and energy complex 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 [8] allowing to achieve Net Zero commitments. TRL 9 reached no more than 30% of technological solutions. In general terms they can be divided into 4 categories corresponding to the 4R concept (Reduce, Reuse, Remove, Recycle) [9]:

Reduce – reducing CO₂ emissions through improved energy efficiency and the introduction of hydrogen, nuclear and renewable energy technologies;

Reuse – capturing and utilizing CO₂, recycling CO₂, by repairing, regrinding and refurbishing equipment;

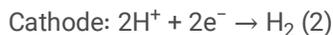
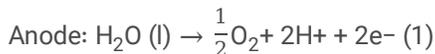
Remove – CO₂ capture and storage, sequestration by natural ecosystems;

Recycle – development of bioenergy.

Hydrogen technologies, along with renewable energy sources and carbon capture and utilization technologies (CCUS) 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 CO₂ emissions in 2021-2050, which is 6.5% of the total cumulative emission reductions [10]. The development of hydrogen energy directly contributes to the implementation of the Sustainable Development Goals (SDGs), developed by the UN General Assembly. Prioritize Goal 7: Affordable and clean energy and Goal 13: Climate action.

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 [11]. 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. Electrolysis is the electrochemical decomposition of water (H₂O) into hydrogen (H₂) and oxygen (O₂) under the impact of electricity in accordance with the Eqs. (1), (2) and (3) [12]:



Currently, electrolytic projects with a total capacity of more than 20 GW are being announced all over the world, they vary according on the stages of development. 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 [13]. 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) [14], incl. electrolysis with anion exchange membranes (AEM) [15];

proton-exchange membrane electrolysis (PEMEL) [16];

high-temperature electrolysis with solid oxide electrolyte (SOEL) [17].

Comparative characteristics of electrolysis technologies are presented in the Table 1.

Table 1
Comparative characteristics of electrolysis technologies.

Parameter	AEL	PEMEL	SOEL
Efficiency (system), kWh kg ⁻¹ H ₂	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 ⁻¹	500-1100	700-1800	>2000

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) [18] 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 CO₂ emissions. The industrial sector emits 8.7 Gt of CO₂. The industry's demand for hydrogen is at 51 million tons per year. [19].

Steel production is the largest industrial subsector, accounting for about 7% of total global CO₂ emissions [20]. In the breakdown of greenhouse gas emissions in Russia, the industrial sector accounts for about 11% [21]. The industrial sector is faced with the

challenge of meeting growing demand for products while reducing CO₂ emissions. For Russia as an exporter of carbon-intensive metallurgical products (Russia's steel exports amounted to 31.5 million tons [22] in 2020) a number of significant threats arise, primarily associated with financial risks.

This work presents a model project for decarbonization of the direct reduction of iron ore for the production of green steel using electrolytic hydrogen. 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 [23], 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 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.

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. 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.

In order to determine the optimal electrolysis technology for the Russian Federation, it was assumed that the capital expenditure (CAPEX) [24] is US \$ 1100 per kW for AEL, US \$ 1800 per kW for PEMEL, US \$ 2800 per kW for SOEL, while operating expenses (OPEX) [25, 26] 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 begin to generate revenue until 2030, when the net present value (NPV) will be about US \$ 4 500 per kW (NPV10 (the sum of the discounted values of the flow of payments reduced to the present day, the discount rate of 10%)). For PEMEL technology, the plant will cease to be unprofitable by 2035, and by 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 per kW, for PEMEL the NPV would be lower (US \$ 30 000 per kW), and for SOEL it will amount to about US \$ 26 000 per 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 the NPV will potentially increase to US \$ 58 000 per kW. The profit may be US \$ 49 000 per kWh for PEMEL and US \$ 45 000 per 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, by 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 the question of state support.

By 2035 the balance between methods will be rearranged. Thus, the commissioning of PEMEL capacities will become cost-effective and amount to a share of 5%. After 2040, as a result of technological progress in the SOEL area and a decrease in capital expenditures to US \$ 2317 per 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, by 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 [27] 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 \$ 1800 and 2800 per kW respectively. In the future, it is possible to reduce capital costs to US \$ 200 for PEMEL and US \$ 300 per 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 [28], 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 by 2050 may be about 28 000 units. The total number of electrolysis plants of various capacities required for commissioning by 2050 is presented in Table 2.

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

Electrolyzer	100 kW (unit)	500 kW (unit)	1 kW (unit)
2035	1 870	4 523	3 100
2050	7 305	12 732	7 966

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.

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 by 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 $\text{kWh kg}^{-1} \text{H}_2$ to < 45 $\text{kWh kg}^{-1} \text{H}_2$, 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 per 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 per kg H_2 to < 45 kWh per kg H_2 , time life of the stack from 50-80 000 hours 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 per 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 hours), long start-up times (> 600 minutes) and high capital costs (> US \$ 2000 per 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 < 20 000 h to > 80 000 h, the power of the stack from 5 kW to 200 kW and the area of electrodes from 200 cm^2 to

> 500 cm² as well as decreasing electricity consumption from 40-50 kWh per kg H₂ to < 40 kWh per kg H₂, cold start time to < 300 min and capital costs to < US \$ 300 per kW.

Actual cost reductions for SOEL (Fig. 3) 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 [29], 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 (WPPs) are operating in Russia, of which more than 700 MW were commissioned in 2020 [30].

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 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⁻¹ [31]. In addition, the region is implementing a state program to support renewable energy sources through 2035 [32]. 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. An alternative method called direct reduction with hydrogen H-DRI omits the use of coke. Oxygen reacts with carbon to form water. The technology is currently at a pilot stage [33]. Now, the consumption of coke is 480 000 tons per year. The equivalent volume of hydrogen consumption will be equal to 14 000 kg H₂ per year. Re-equipment of the plant with new technology will be the most expensive part of the project amounting to US \$ 4106 million.

For the corresponding hydrogen demand, a 500 kW PEMEL electrolyzer is proposed with a production volume of 16 200 kg per year. A key factor in the selection of PEMEL is the dynamic system response (< 1 sec) [34] 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.

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 H-DRI process is flexible in operation. The cell responds to fluctuations in the power supply by producing more or less hydrogen than is required for ore reduction and storage. 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 80 thousand kg per year

PEMEL electrolyzer capacity - 500 kW

Electricity consumption by electrolyzer - 55 kWh kg⁻¹ H₂

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 yr
- The reduction in CO₂ emissions is estimated at 68%.

The calculation results are shown in Fig. 5.

As can be seen from Figure 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.

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.

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 US \$ 9 per kg and 12 kg CO₂-eq per kg H₂, respectively. State support measures and their possible effects are presented in Table 3.

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. SMR has over 39% of the market, even with significant capital grants (covering 100% of the cost) allocated to electrolysis hydrogen production.
Bans on SMR 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 SMR unprofitable compared to electrolysis.

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 per kg H₂ 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.

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 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 by 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 CO₂ 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. Reduction of CO₂ emissions upon replacement of coke with a water pipe is estimated at 68%.

Declarations

Availability of data and materials

All data generated or analyzed during this study are included in this published article [and its supplementary information files].

Competing interests

The authors declare they have no competing interests.

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Authors' contributions

Elena Galitskaya: Data curation, Methodology, Investigation, Writing- Original draft preparation.

Oleg Zhdaneev: Conceptualization, Resources, Supervision, Writing - Review & Editing.

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References

1. US EPA. Trends in Global CO₂ and Total Greenhouse Gas Emissions, 2020 <https://www.pbl.nl/en/publications/trends-in-global-co2-and-total-greenhouse-gas-emissions-2020-report> (accessed November 14, 2021).
2. IPCC. Sixth Assessment Report, 2021 <https://www.ipcc.ch/report/ar6/wg1/> (accessed November 14, 2021).
3. UNFCCC. Paris Agreement to the United Nations Framework Convention on Climate Change, 2015 https://unfccc.int/sites/default/files/english_paris_agreement.pdf (accessed November 14, 2021).
4. IEA. Net Zero by 2050 - A Roadmap for the Global Energy Sector, 2021 <https://iea.blob.core.windows.net/assets/4719e321-6d3d-41a2-bd6b-461ad2f850a8/NetZeroBy2050-ARoadmapfortheGlobalEnergySector.pdf> (accessed November 14, 2021).
5. Climate Action Tracker, 2021 <https://climateactiontracker.org/> (accessed November 14, 2021).
6. Talebian H, Herrera OE, Mérida W. Policy effectiveness on emissions and cost reduction for hydrogen supply chains: The case for British Columbia. *Int J Hydrogen Energy*. 2021;46:998–1011.
7. IEA. Energy Atlas, 2021 <http://energyatlas.iea.org/#/tellmap/1378539487> (accessed November 14, 2021).
8. IEA. ETP Clean Energy Technology Guide, 2021 <https://www.iea.org/articles/etp-clean-energy-technology-guide> (accessed November 14, 2021).
9. Yu KH, Zhang Y, Li D, Montenegro-Marin CE, Kumar PM. Environmental planning based on reduce, reuse, recycle and recover using artificial intelligence. *Environ Impact Assess Rev*. 2021;86:106492.
10. BP. Statistical Review of World Energy, 2021 <https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html> (accessed November 14, 2021).
11. IEA. The Future of Hydrogen, 2019 https://static1.squarespace.com/static/5c350d6bcc8fedc9b21ec4c5/t/5e968939e89b9e37585b8134/1586923883881/IEA+-The_Future_of_Hydrogen.pdf (accessed November 14, 2021).
12. Ursúa A, Gandía LM, Sanchis P. Hydrogen production from water electrolysis: Current status and future trends. *Proc IEEE*. 2012;100:410–26.
13. IGEM. A Perspective on Hydrogen Investment, Deployment and Cost Competitiveness, 2021 <https://www.h2knowledgecentre.com/content/policypaper2264> (accessed November 14, 2021).
14. Schalenbach M, Lueke W, Stolten D. Hydrogen Diffusivity and Electrolyte Permeability of the Zirfon PERL Separator for Alkaline Water Electrolysis. *J Electrochem Soc*. 2016;163:F1480–8.
15. Hnát J, Plevová M, Žitka J, Paidar M, Bouzek K. Anion-selective materials with 1,4-diazabicyclo2.2.2.octane functional groups for advanced alkaline water electrolysis. *Electrochim Acta*. 2017;248:547–55.
16. Park JE, Kim J, Han J, Kim K, Park S Bin, Kim S, et al. High-performance proton-exchange membrane water electrolysis using a sulfonated poly(arylene ether sulfone) membrane and ionomer. *J Memb Sci*. 2021;634:119370. <https://doi.org/10.1016/j.memsci.2020.118871>.
17. Song Y, Zhang X, Xie K, Wang G, Bao X. High-Temperature CO₂ Electrolysis in Solid Oxide Electrolysis Cells: Developments, Challenges, and Prospects. *Adv Mater*. 2019;31:1902033.
18. EU economy and society to meet climate ambitions https://ec.europa.eu/commission/presscorner/detail/en/ip_21_3541 (accessed November 14, 2021).
19. IEA. Global Hydrogen Review, 2021 <https://iea.blob.core.windows.net/assets/3a2ed84c-9ea0-458c-9421-d166a9510bc0/GlobalHydrogenReview2021.pdf> (accessed November 14, 2021).
20. Pérez-Fortes M, Bocin-Dumitriu A, Tzimas E. CO₂ Utilization Pathways: Techno-Economic Assessment and Market Opportunities. *Energy Procedia* 2014;63:7968–75.
21. Bravkov, P.V., Durdyeva, A.A., Zhdaneev, O.V., Zuev, S.S., Korenev, V.V., Frolov, K.N., Chubokсарov, V.S. Technical policy issues of the fuel and energy complex of the Russian Federation. Zhdaneev, O.V., editor. Moscow: Nauka; 2020. p. 304 [in Russian].

22. Bogdanov S V. Assessment of the Competitive Trends in the Development of Production Business in the Main Segments of the World Steel Market. *Russ Metall* 2021;2021:801–8 [in Russian].
23. The concept for the development of hydrogen energy in the Russian Federation, 2021 <http://static.government.ru/media/files/5JFns1CDAKqYKzZ0mnRADAw2NqcVsexl.pdf> (accessed: 14 november 2021) [in Russian].
24. IEA. Hydrogen - Fuels & Technologies, 2021 <https://www.iea.org/fuels-and-technologies/hydrogen> (accessed November 14, 2021).
25. Brynolf S, Taljegard M, Grahn M, Hansson J. Electrofuels for the transport sector: A review of production costs. *Renew Sustain Energy Rev.* 2018;81:1887–905.
26. Glenk G, Reichelstein S. Economics of converting renewable power to hydrogen. *Nat Energy* 2019 43 2019;4:216–22.
27. Procurement Portal. <https://zakupki.gov.ru/epz/main/public/home.html> (accessed: 14 november 2021) [in Russian].
28. Concept for the development of production and use of electric motor vehicles in the Russian Federation for the period up to 2030, 2021 <http://static.government.ru/media/files/bW9wGZ2rDs3BkeZHf7ZsaxnIbJzQbJt.pdf> (accessed: 14 november 2021) [in Russian].
29. IEA. Renewables 2020. Analysis and forecast to 2025, 2020 https://iea.blob.core.windows.net/assets/1a24f1fe-c971-4c25-964a-57d0f31eb97b/Renewables_2020-PDF.pdf (accessed November 14, 2021).
30. Russian wind power market: Potential for the development of a new economy, 2021 <http://library.fes.de/pdf-files/bueros/moskau/17606-20210407.pdf> (accessed: 14 november 2021).
31. Global Wind Atlas <https://globalwindatlas.info/> (accessed November 14, 2021).
32. Order of the Government of the Russian Federation of 08.01.2009 N 1-r (as amended on 01.06.2021). http://www.consultant.ru/document/cons_doc_LAW_83805/ (accessed: 14 november 2021) [in Russian].
33. IRENA. Hydrogen from renewable power technology outlook for the energy transition, 2018 https://www.irena.org/-/media/files/irena/agency/publication/2018/sep/irena_hydrogen_from_renewable_power_2018.pdf (accessed November 14, 2021).
34. Schmidt O, Gambhir A, Staffell I, Hawkes A, Nelson J, Few S. Future cost and performance of water electrolysis: An expert elicitation study. *Int J Hydrogen Energy* 2017;42:30470–92.

Figures

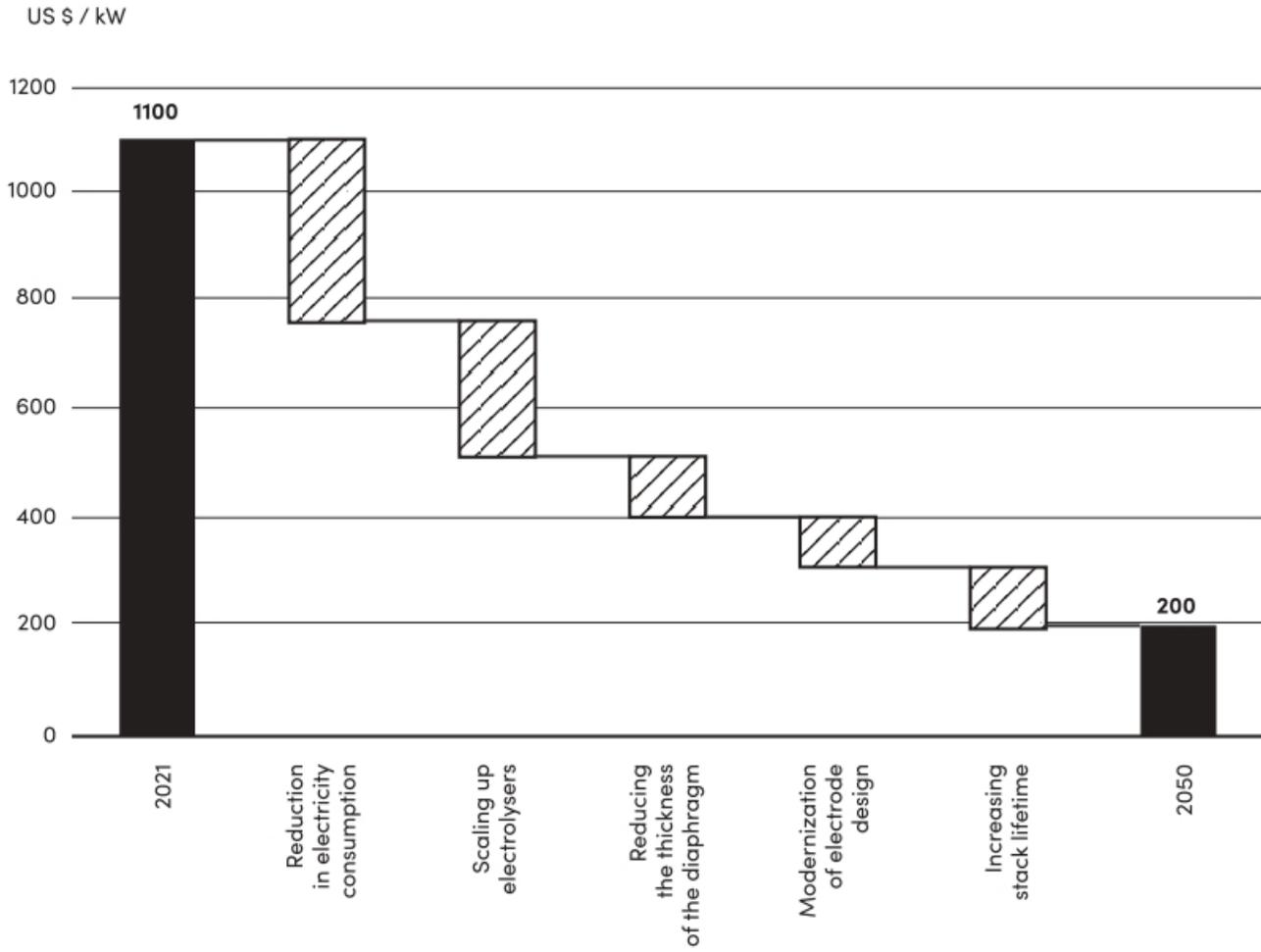


Figure 1

Forecast of the decline in the cost of AEL

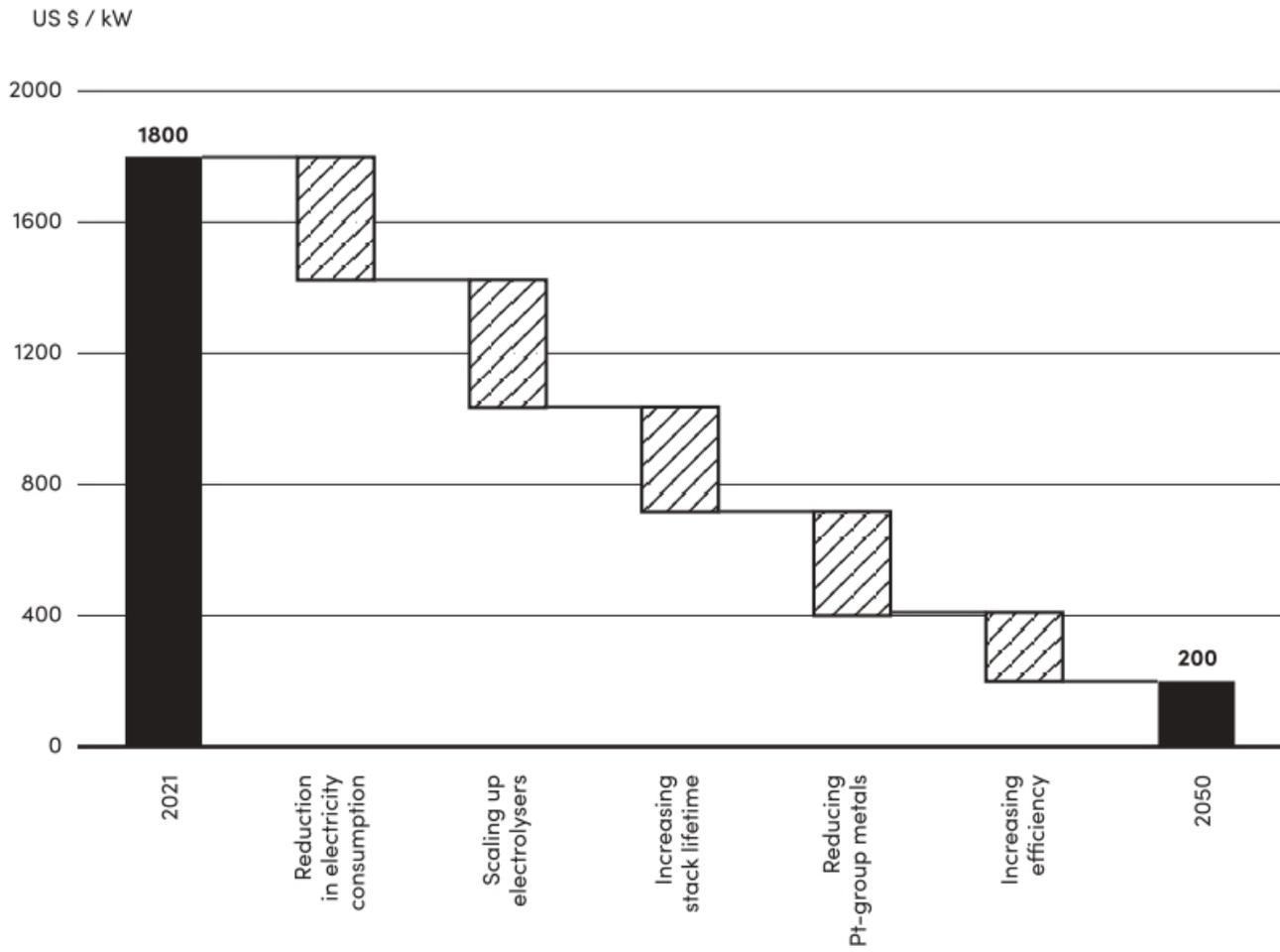


Figure 2

Forecast of the decline in the cost of PEMEL

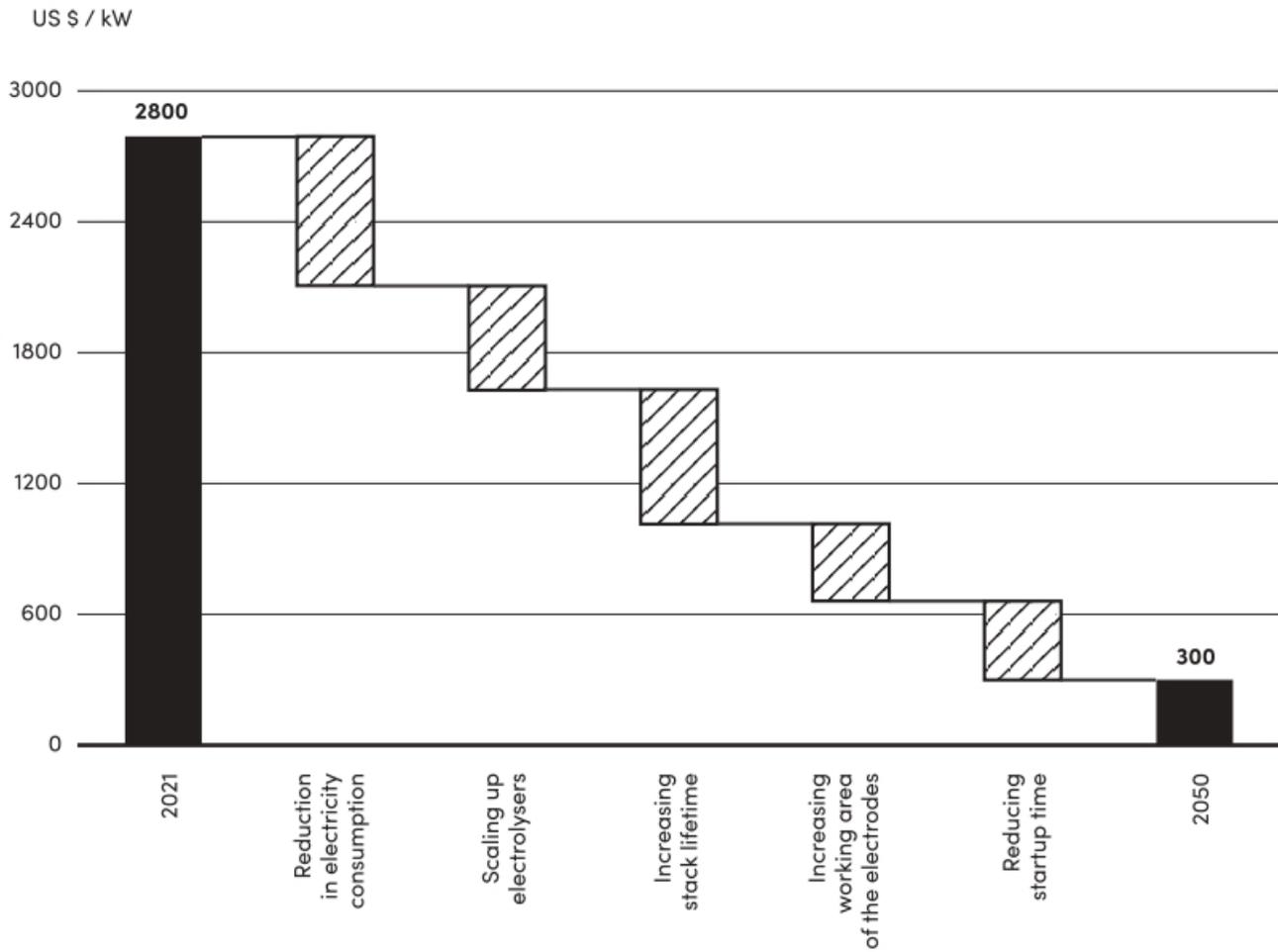


Figure 3

Forecast of the decline in the cost of SOEL

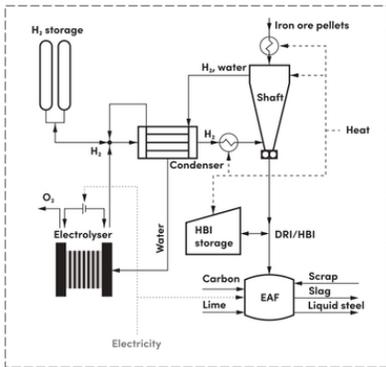
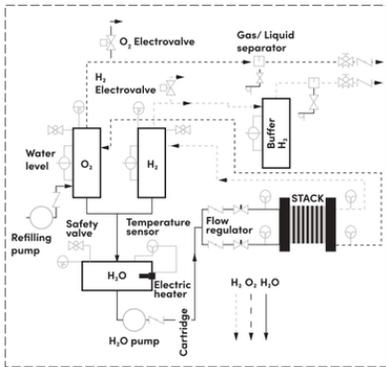
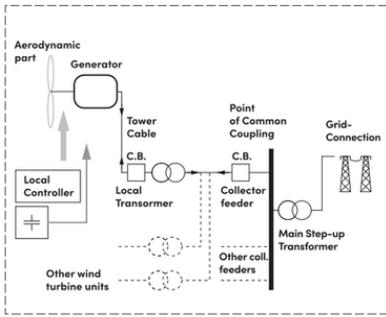


Figure 4

Technological process for green steel production in the framework of the project

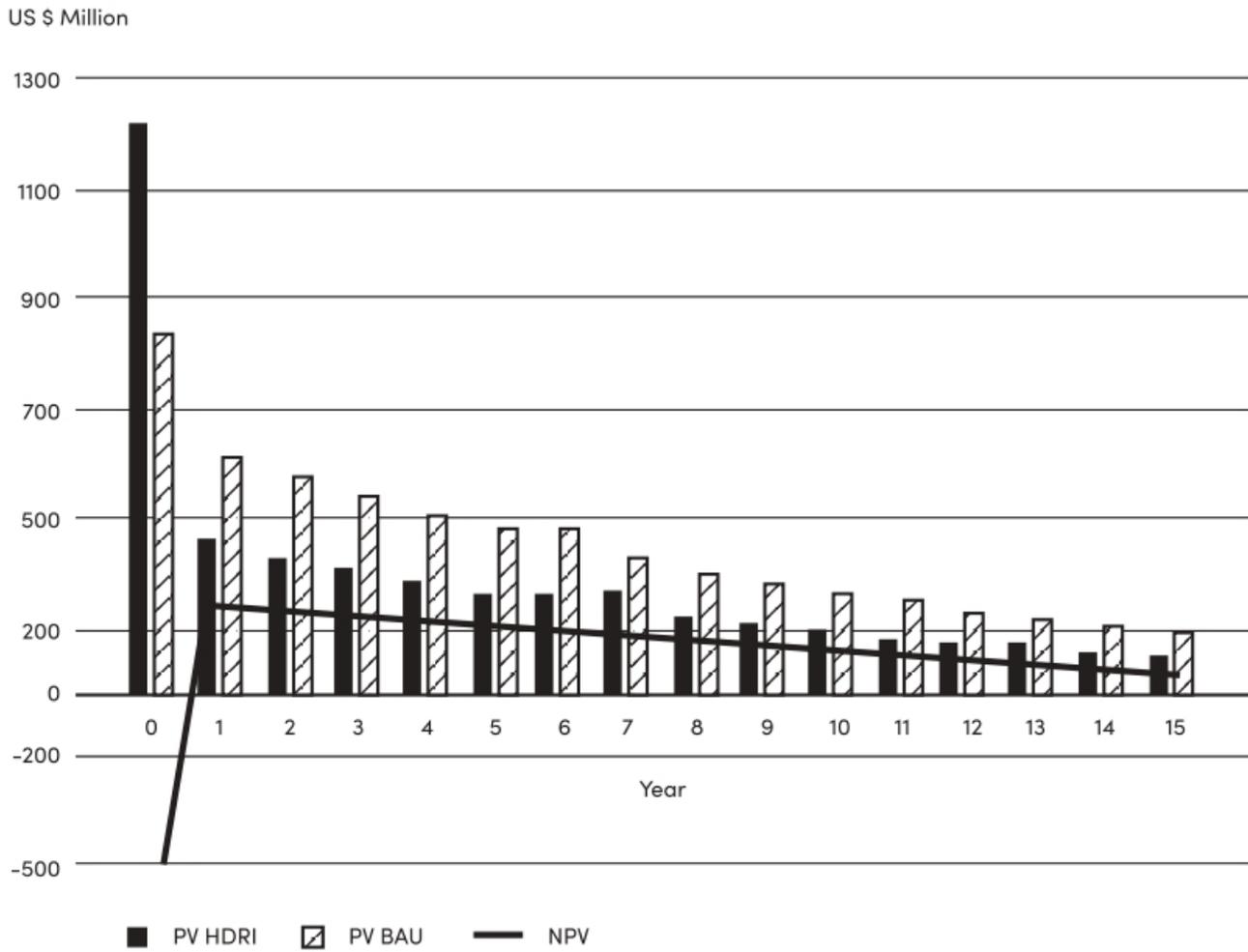


Figure 5

Comparison of cash flows in two scenarios (BAU – Business as Usual and H-DRI)

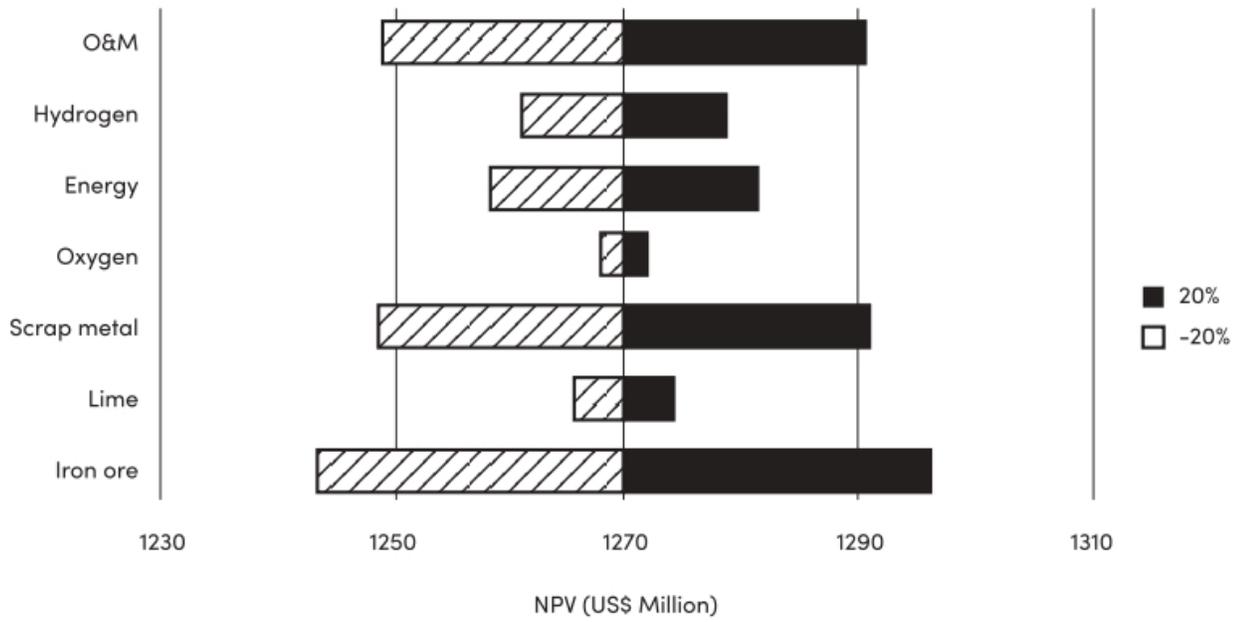


Figure 6

Sensitivity analysis of the project (re-equipment of the plant to H-DRI)

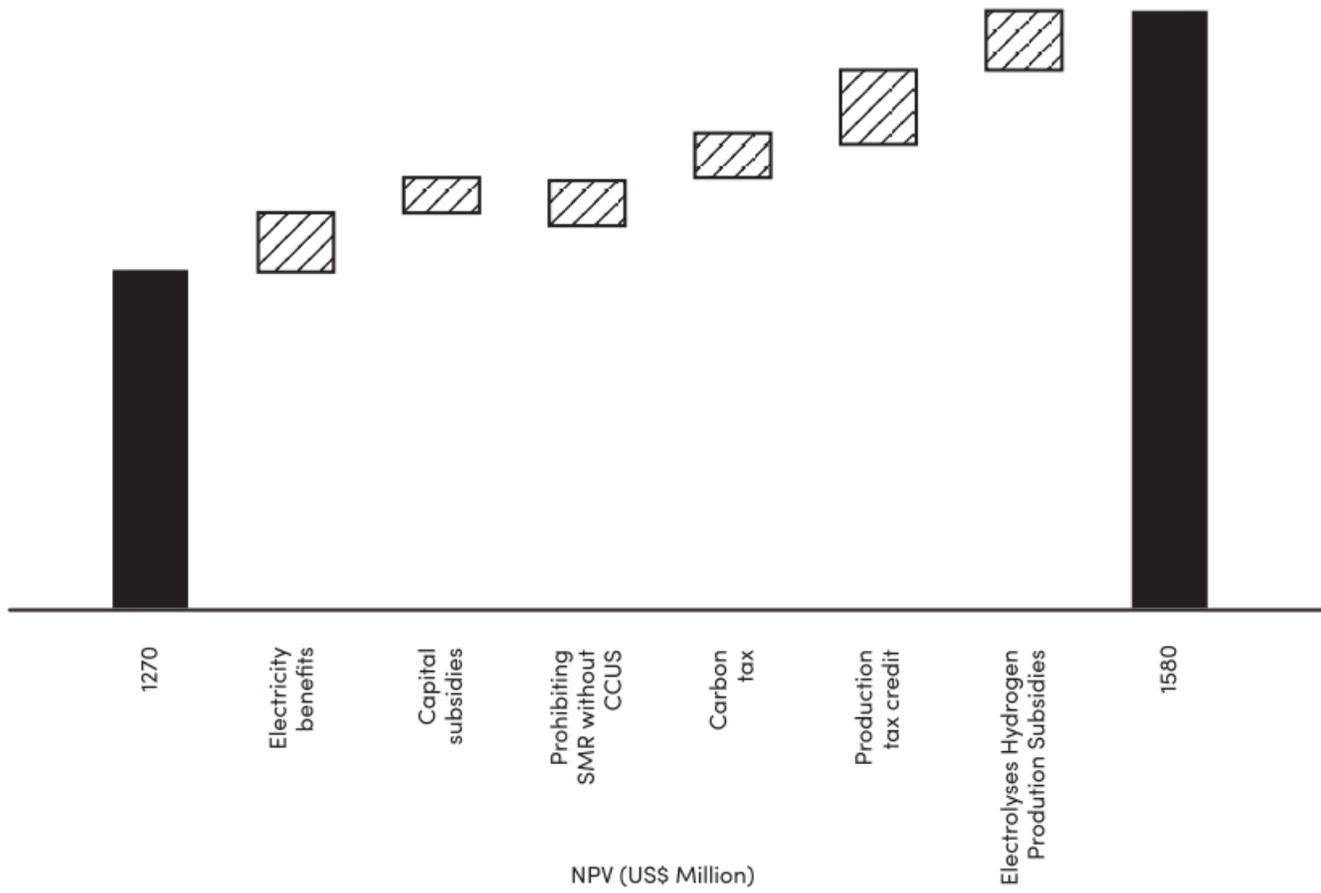


Figure 7

Measures of state incentives for the electrolysis hydrogen production