EXSOLUTION-BASED NANOPARTICLES FOR LOWEST COST GREEN HYDROGEN VIA ELECTROLYSIS

EXSOTHyC

Market study

(Deliverable D7.1)

The project is supported by the Clean Hydrogen Partnership and its members		
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NOTICES

For information, please contact the project coordinator, Mari Šavel, e-mail: mari.savel@stargatehydrogen.com. This document is intended to fulfil the contractual obligations of the EXSOTHyC project, which has received funding from the Clean Hydrogen Partnership and its members, concerning deliverable D7.1 described in contract 101137604.

Authors

Marek Roostar, Stargate Hydrogen Solutions OÜ

Mari Savel, Stargate Hydrogen Solutions OÜ

Reviewer(s)

Mari Savel, Stargate Hydrogen Solutions OÜ

Table of revisions

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List of Partners

Stargate Hydrogen Solutions OÜ (Stargate)
University of St Andrews (St Andrews)
Agfa-Gevaert NV (AGFA)
Eindhoven University of Technology (TUE)
Fraunhofer IFAM (IFAM)

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List of Abbreviations

ALK – Alkaline

CAPEX – Capital Expenditure

CCD – Catalyst Coated Diaphragm

EC – European Commission

EU – European Union

GW – Gigawatt

IEA – International Energy Agency

IPCEI – Important Project of Common European Interest

IRA – Inflation Reduction Act

LCOH – Levelized Cost of Hydrogen

MW – Megawatt

NZIA - Net Zero-Industry Act

OPEX – Operational Expenditure

PEM - Proton Exchange Membrane

PGM – Platinum Group Metals

PTE – Porous Transport Electrode

PtH – Power to Hydrogen

PTL – Porous Transport Layer

R&D – Research and Development

RED - Renewable Energy Directive

RFNBO - Renewable Fuels of Non-Biological Origin

SAF - Sustainable Aviation Fuels

TWh – Terawatt-hour

UK – United Kingdom

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Table of Contents

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1 Introduction

Governments, executives, researchers, and other parties around the world are looking to accelerate the ongoing energy transition to reach carbon neutrality. Aligning economies with the targets laid out in the Paris Agreement, limiting global warming to well below 2°C, while pursuing efforts to limit the increase to 1.5°C, requires replacing legacy systems powered by fossil fuels with low carbon energy sources such as renewables.

Clean hydrogen is now clearly recognized as a potential breakthrough to overcome these limits. Hydrogen is a versatile molecule, which can be used directly via fuel cells or for electricity generation, and as feedstock to produce more suitable derivatives, such as ammonia, methanol, or sustainable aviation fuels (SAF) to specific industrial and transport applications.

For reaching the goals, alkaline electrolysis could be considered as one of the most promising technologies. Namely, alkaline electrolysis is one of the most mature and widely used methods for hydrogen production. It involves the electrolysis of water (H_2O) into hydrogen (H_2) and oxygen (O_2) using an alkaline electrolyte.

Advantages of Alkaline Electrolysis

- **Mature Technology:** Alkaline electrolysis is a well-established technology with decades of operational history.
- **Scalability:** It is capable of being scaled up for large-scale hydrogen production.
- **Cost-Effectiveness**: Generally, it has lower capital costs compared to other types of electrolysers like proton exchange membrane (PEM) electrolysers.
- **Durability:** Alkaline electrolysers are known for their long operational life and robustness.

By improving electrode materials and their fabrication methods, EXSOTHyC aims to enhance the performance of alkaline electrolysers, making hydrogen production more efficient and cost-effective.

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2 Market size and growth

According to Clean Hydrogen Monitor 2023, clean hydrogen consumption announcements by industrial offtakers continue to increase every year. The largest volumes have been announced in ammonia, steel, and refining which reflects the positive prospects for both the decarbonisation of existing industry and the generation of additional clean hydrogen demand.

- In 2022, Europe's total hydrogen demand reached 8.2 Mt, and industrial offtakers have outlined plans to consume 7.1 Mt/y of clean hydrogen by 2030, of which 4.3 Mt/y are dedicated to new demand from emerging applications and greenfield initiatives.
- The most advanced offtakers are currently in the ammonia and steel sectors, strategically locating projects in areas with large existing hydrogen demand such as Germany and optimal access to low-cost renewable sources and low-carbon grid infrastructure such as Spain and Sweden.
- If the currently announced pipeline of electrolytic projects in industry materialized and complied with RFNBO rules, 10 Member States would satisfy the REDIII industry target by 2030.

Potential market by sectors

Clean hydrogen could prove as one of the key elements of decarbonization, helping to overcome the limits of electrification to decarbonize following sectors:

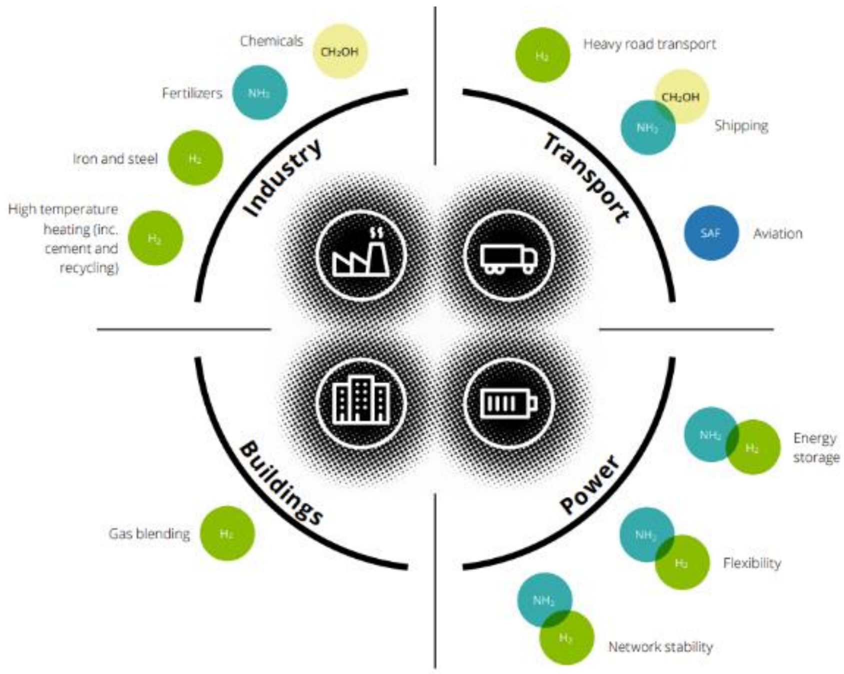

Figure 1: Main end uses of clean hydrogen and its derivatives in a climate-neutral energy system
Source: Deloitte analysis based International Energy Agency (IEA) 2023

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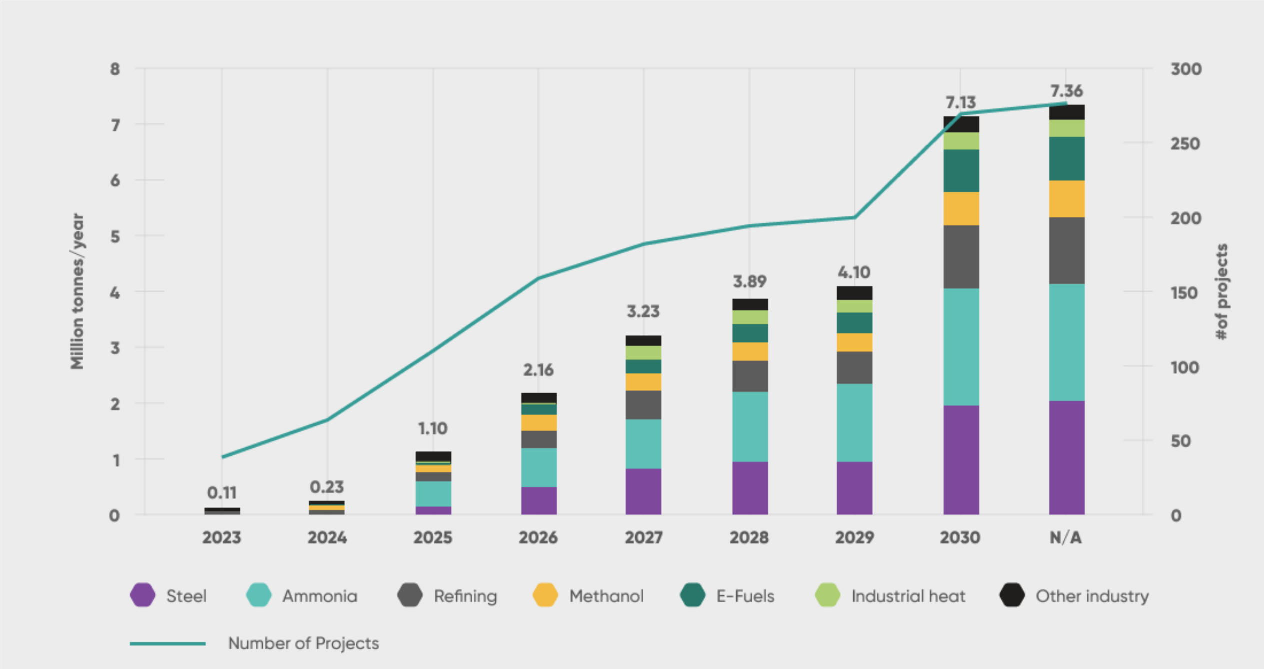

Figure 2: Cumulative announced consumption of clean hydrogen in industry by 2030 in Europe
Source: Hydrogen Europe

Achieving net-zero greenhouse gas emissions by 2050 will likely require the development of a 170-MtH_2eq clean hydrogen market by 2030, growing to nearly 350% to 600 MtH_2 by 2050. To put these numbers in perspective, in energy terms, 600 MtH_2eq is equivalent to more than 85% of the global electricity consumption in 2019 (22,850 TWh25).

As climate change becomes a global imperative, with all major economies looking to decarbonize their end uses, clean hydrogen demand will likely skyrocket around the world, leading to the formation of a truly global market (Figure 4).

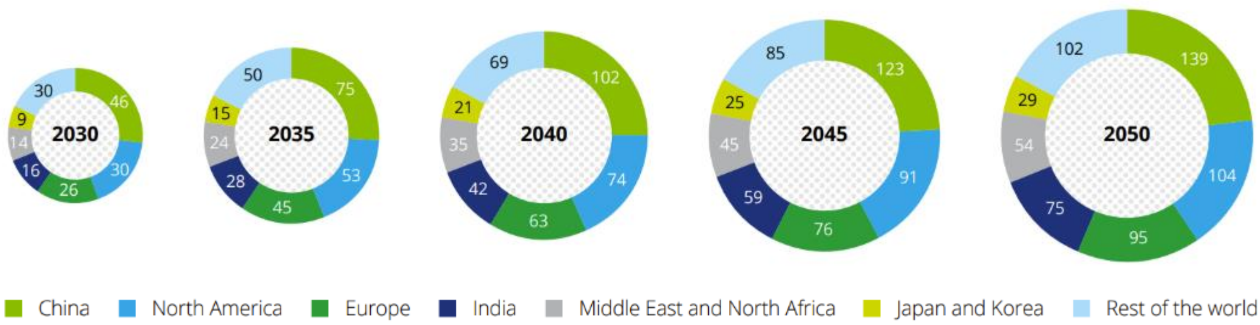

Figure 3: Regional demand for clean hydrogen and its derivatives, 2030 to 2050 (MtH_2eq)
Source: Deloitte analysis based on IEA 2023

Interregional trade is key to helping unlock the full potential of the clean hydrogen market, supported by diversified transport infrastructure. Regions that are currently able to produce cost-competitive hydrogen in quantities that exceed domestic needs are already positioning themselves as future hydrogen exporters, supplying other less-competitive regions and helping to smoothly facilitate the energy transition. Notably, global hydrogen

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trade is projected to generate more than EUR 259 billion in annual export revenues by 2050, with North Africa expected to benefit the most (EUR 102 billion per year) due to its high export potential.

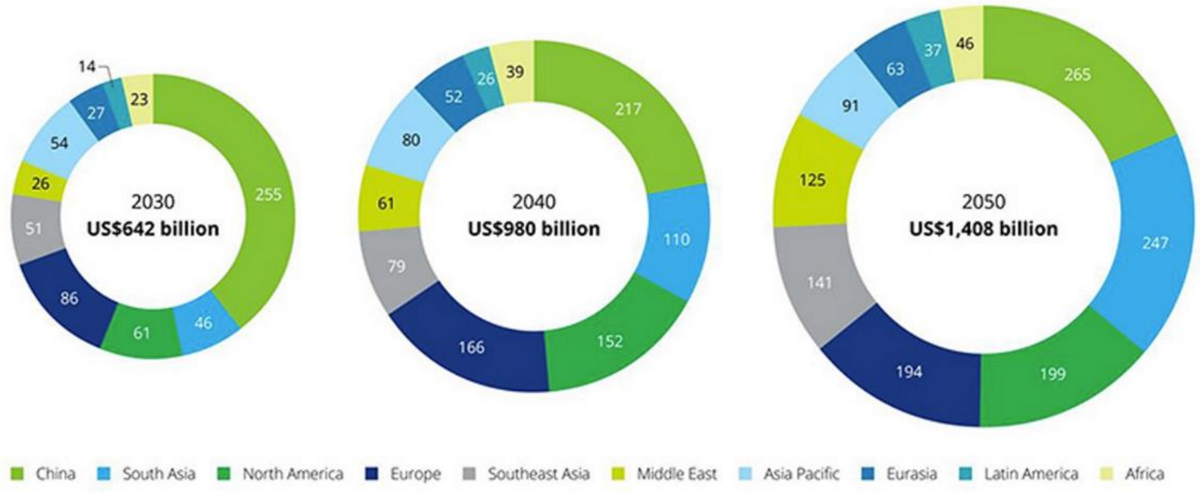

Figure 4: Regional clean hydrogen market dynamics, 2030 to 2050 (MtH_2eq)

2.1 Addressable market

Market size of Industry

Green and blue hydrogen are crucial for our industrial decarbonisation pathway. This is particularly relevant for iron & steel, ammonia, and fuels (including high value chemicals HVC) productions where hydrogen is primarily used as feedstock.

Green and blue hydrogen demand in these sectors can be expected to increase to 7,2 Mt in 2030 (EUR 25 billion), 212 Mt (EUR 735 billion) in 2040.

An additional demand could come from medium- and high-temperature industrial heat processes where hydrogen can partially substitute the current use of natural gas leading to at least 56 TWh in 2030, 165 TWh in 2040.

Market size of Transport

In transport, next to electrification and biofuels, there is a clear role for about 300 TWh per year of hydrogen as a fuel. Additional hydrogen will be needed to produce synthetic fuels in aviation. In 2040, hydrogen is forecasted to power 55% of trucks, 25% of buses, and 10% of airplanes. The demand for direct hydrogen in the transport sector in 2040 can be expected to be 285 TWh, with 68 TWh in aviation and 217 TWh in heavy road transport. Direct hydrogen is forecasted to account for 12% of total transport energy demand in 2040.

Market size of Power generation

The value of hydrogen over most other flexible power options is that it can be supplied and stored in large quantities at relatively cheaper investment costs, making it particularly

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appealing for long-duration storage. Hydrogen can cost effectively integrate and provide resilience to the highly electrified net-zero energy system (and economy) of the future.

Hydrogen demand in the power sector is estimated to be 12 TWh in 2030, 301 TWh in 2040, and 626 TWh in 2050, accounting for 1%, 3%, and 7% of total EU and UK electricity demand in 2030, 2040, and 2050 respectively.

Hydrogen generated electricity is forecast to comprise up to 17% of the electricity generation per country, with Poland, Ireland, Italy, Germany, and Belgium expected to have the highest shares of hydrogen generated electricity in 2050.

Countries with high shares of gas-powered electricity generation (e.g. Belgium, Germany, Ireland, Italy, Poland and the UK) are expected to have high shares of hydrogen demand. Gas-fired power plants can transition from natural gas to hydrogen, making use of existing infrastructure and reducing necessary investment costs for the decarbonisation of dispatchable generators.

Market size of Buildings sector

Heating in buildings will be decarbonised using a range of technologies with significant regional variations. The hydrogen demand depends on renovation rates, the relative shares of biomethane and hydrogen, and the mix of heating technologies.

This study assumes Europe-wide accelerated renovation rates and hybrid heating systems in existing homes with a gas connection and in 30% of district heating. Such hybrid systems use electricity (in a heat pump) and renewable or low carbon gas. This approach reduces energy system costs, enabling lower cost to consumers and faster emission reduction. Assumed annual renewable and low-carbon gas demand in buildings will be around 600 TWh in 2050. All of this could be hydrogen, yet assuming a scale-up of biomethane as in previous Gas for Climate studies, annual hydrogen demand would be around 150 TWh.

3 Market drivers and trends

Market's main growth driver is the green energy transition and drastically increasing demand for green hydrogen. To reach deep decarbonisation of many economic sectors (e.g. chemical industry, cement, steel, heavy transport), no real alternatives to green hydrogen exist. Main drivers are:

- **Ambitious climate neutrality goals**
  (EU by 2050, Finland by 2035, China by 2060)
- **Tightening climate regulations**
  (Fit for 55, RePowerEU, EU RED II / III, EU NZIA)
- **ESG increasingly important in every sector**
  (among investors, businesses and government level)
- **Strongly increasing demand for green options from individuals**

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Main drivers in the period to 2030

The market ramp-up is likely underpinned by **replacing current grey hydrogen production with clean hydrogen**. Projects initially depend on **public support** to break even, as illustrated by various programs and initiatives such as the US Inflation Reduction Act and Infrastructure Investment and Jobs Act, the Australian Clean Energy Finance Corporation and regional strategies, the EU Fit-for-55 package and IPCEI program, and Japanese demand-side R&D support schemes such as Green Innovation Fund.

International trade plays a vital role, serving some 30 MtH_2eq in 2030, almost one-fifth of total demand. Trade flows emerge within regional clusters, between supply and demand hubs in proximity, mostly through ammonia shipping. Long-term contracts are crucial to help mitigate quantity risks and provide price stability (Deloitte´s 2023 global green hydrogen outlook).

For example, initiative like the Net Zero-Industry Act (NZIA) and others can significantly support exploitation of project's outcomes by simplifying regulatory frameworks. The NZIA also promotes investment and market access for net-zero technologies. NZIA offers support through the European Hydrogen Bank and Net-Zero Europe Platform, which can lead also to new investment opportunities and strategic projects.

Opportunities:

- Funding and investment: Access to EU funding and private investments through various platforms and funds.
- Partnerships and collaboration: Opportunities to collaborate with other industry leaders and research institutions.
- Market expansion: Enhanced access to European and global markets.
- Innovation and R&D: Support for developing and scaling up innovative technologies.

Main drivers in the period to 2040

However, leveraging economies of scale, they continuously catch up on cost terms. More broadly, in the future, clean hydrogen projects will become less dependent on public support. Increasing market size can also help improve liquidity, with long-term contracts gradually complemented by spot markets. Those contracts play a crucial role in securing strategic volumes as oil and gas markets may gradually decline.

4 Technology, region and capacity assessment

By the end of 2022, the global installed water electrolyser capacity for hydrogen production reached almost 700 MW, a 20% increase compared to the previous year. Wherefrom alkaline electrolysers accounted for 60% of the installed capacity by the end of 2022.

GlobalHydrogenReview estimated that installed global capacity could more than triple to 2 GW by the end of 2023. However, it is unlikely that this was reached. Based on announced projects, global installed electrolyser capacity could reach 175 GW by 2030. The capacity

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in 2030 increases to 420 GW when projects at early stages of development are also taken into consideration.

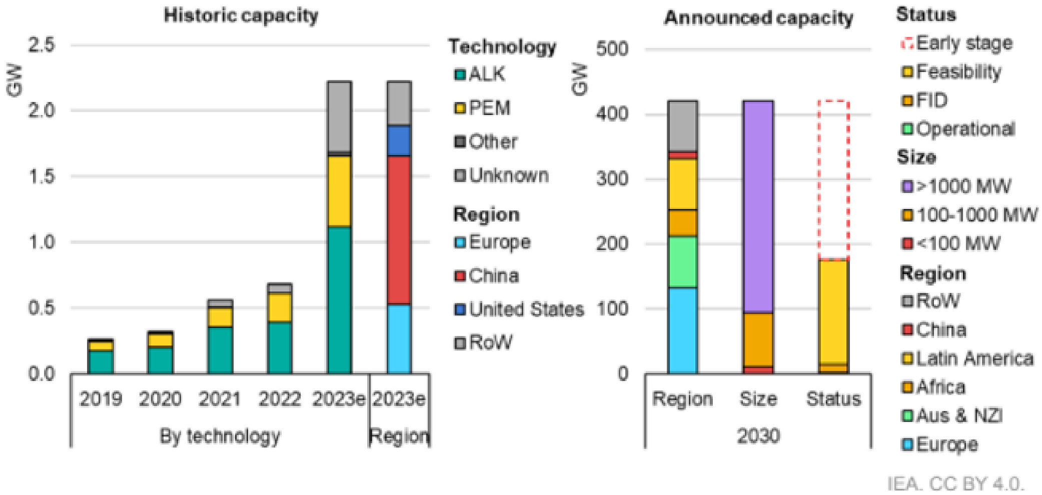

Figure 5 Global electrolyser capacity by technology (2019-2023) and by region, size and status based on announced projects by 2030

By the end of 2022, the available manufacturing capacity publicised by electrolyser manufacturers reached as high as 13 GW/y, half of which was in China. Based on companies' announcements, global electrolyser manufacturing capacity could reach 155 GW/y by 2030, with one-quarter of the manufacturing capacity located in China, one-fifth each in the United States and Europe, and 6% in India. 20% of the expansion plans by 2030 have been announced without a disclosed location, which means that the geographical distribution could change, for example if influenced by policy support to stimulate local demand and local manufacturing (such as the IRA in the United States, the Net Zero Industry Act in the European Union or the incentive schemes for electrolyser manufacturing in India). Three-quarters of manufacturing capacity today is for alkaline electrolysers – of which 70% is in China.[1]

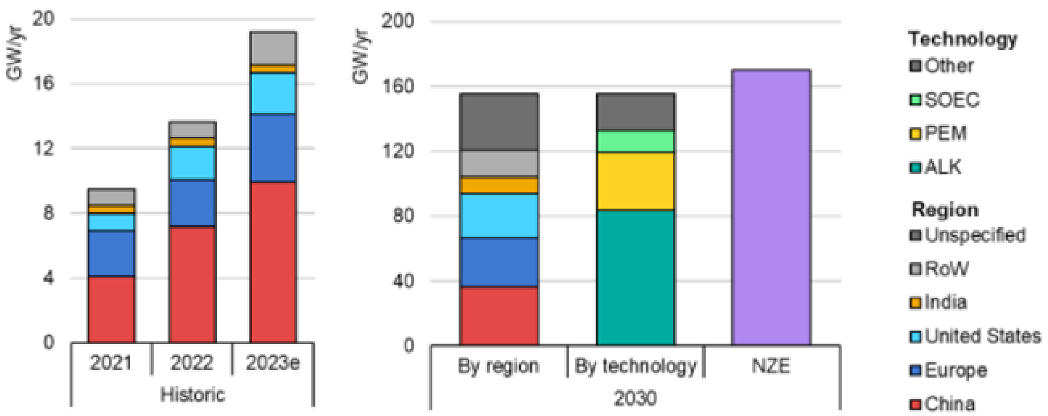

Figure 6 Electrolyser manufacturing capacity by region and technology according to announced projects and in the Net Zero Emissions by 2050 Scenario (20121-2030)

[1] EUROPE: Clean Hydrogen Monitor 2023, Global: Global Hydrogen Review 2023

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5 Competitive landscape

EXSOTHyC outcomes drive technological innovation, leading to the creation of new materials, catalysts, and production methods that can be applied to other areas of renewable energy and clean technology.

In the realm of enhancing electrolyser efficiency through advanced electrode materials, EXSOTHyC faces competition from leading companies and research institutions developing cutting-edge electrolysis technologies. Major competitors include:

Key competitors:

- Small scale: Green Hydrogen Systems, Hystar, H-TEC, Enapter
- Large scale: Thyssenkrupp Nucera, NEL, HydrogenPro, Plug Power

Company	Technology	Revenue last financial year (mEUR)	# of employees in the end of the last financial year	Capital raised EUR M
Green Hydrogen Systems	ALK	5,64	298	285
Hydrogen Pro	ALK	50,71	231	62
Enapter AG	AEM	31,61	200	130
ITM Power	PEM	5,96	359	555
Nel Hydrogen	ALK & PEM	158,22	673	684
Thyssenkrupp Nucera	ALK	652,80	675	520

6 Challenges and barriers

The success of the project and its outcomes is strongly dependent on regulations and legislations that allow for a plannable near future. If changes in regulations, legislation, and/or European goals targeting technologies and materials occur, the development of the above-described technologies might be hindered. Furthermore, economic and supply chain instability might affect the ability to order material necessary for research or scaling up of the developed approaches. The potential of other worldwide projects following similar approaches to upscale hydrogen production cannot be neglected, especially with funding focused on hydrogen production increasing in most western countries. Lastly, the projects baseline is funded in a European wide acceptance for renewable and sustainable technology from politics and the public. The implementation of the developed technologies might be severely hindered if broad support by society and politicians is undermined by forces outside of our control.

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7 Opportunities

The EXSOTHyC project, aiming to optimize electrolyser operations through advanced electrode materials, is positioned to capitalize on the surging demand for green hydrogen driven by global decarbonization efforts. By achieving lower voltages and higher efficiencies, EXSOTHyC can reduce the production costs of green hydrogen, making it a more viable alternative to fossil fuels. This project has the potential to forge strategic partnerships with renewable energy producers, industrial gas companies, and governments, providing funding, market access, and integration opportunities. Additionally, the innovative materials development and fabrication techniques developed within EXSOTHyC can be licensed to other manufacturers, opening new revenue streams.

EXSOTHyC is poised to make significant contributions to the hydrogen economy. By leveraging technological advancements, EXSOTHyC can meet the growing demand for sustainable energy solutions, offering environmental and economic benefits through reduced carbon footprints and lower operational costs.

Project specific opportunities

Industries such as chemicals, steel, and ammonia production, aiming to decarbonize, offer significant opportunities for integrating EXSOTHyC's hydrogen production technologies. Government incentives for renewable energy projects further support this potential.

Current high-performance alkaline electrolysers use around 1 mg/W of PGM, while PEM electrolysers use 2-3 times more. By 2030, the global electrolyser manufacturing capacity will reach 66 GW/year, necessitating 83.5 tonnes of PGM at today's levels. Alkaline cells would require 41 tonnes. Using PGM-free exsolution perovskites could significantly reduce this pressure.

A long-awaited improvement in diaphragm performance for alkaline electrolysis has arrived, potentially increasing its market share to over 40 GW/year by 2030. This would create a yearly diaphragm demand of 500,000 to 1,000,000 m². The CCD design will enable new alkaline electrolyser concepts, with an estimated 4% of EU alkaline electrolysers using CCD by 2030, representing a market potential of 2400 MW and EUR120 million in CCD turnover.

Implementing EXSOTHyC's diagnostic tools could extend electrolyser stack lifetimes by 1 year (~10%). By 2030, this could amount to a combined extension of 24,000 years across 60 GW of EU electrolysers, with an average stack size of 2.5 MW.

Stargate aims to become a leading EU electrolyser manufacturer by 2030. The 500-kW stack system developed from the EXSOTHyC prototype is expected to be a key product, generating EUR 91 million in revenue, with a headcount of 45-50 people and an R&D budget of EUR 4.5 million annually.

EXSOTHyC-derived products are projected to produce 42,000 tons of H_2 per year, avoiding around 500,000 tons of CO_2eq annually. The increased efficiency of the stack will reduce the need for 110 MW of renewable power to produce the same amount of green H_2.

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