HYDROGEN RESEARCH FORUM FINLAND

STRATEGIC RESEARCH AGENDA FOR FINNISH HYDROGEN RESEARCH:

INSIGHTS FROM THE HYDROGEN RESEARCH FORUM FINLAND

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HYDROGEN RESEARCH FORUM FINLAND

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BACKGROUND: HYDROGEN AS A DRIVER FOR A CLEAN INDUSTRIAL REVOLUTION

The goal of The Paris Agreement is to limit the temperature increase due to climate change to 1.5°C. Reaching this goal requires drastic reductions in fossil fuel emissions, which must occur in the energy sector, industry, heating, transportation and the other sectors of society. This can be accomplished either through direct electrification or through the hydrogen economy, both of which offer emission-free or low-emission solutions for various applications, including industry, transportation, and heating.

Hydrogen economy focuses on clean hydrogen that will replace fossil energy carriers and enable the reduction of climate emissions on sectors where direct use of electricity is challenging. In recent years, the cost of producing renewable electricity has decreased to a level competitive with fossil-fuel-based energy production. Due to this development, electricity production is becoming cleaner faster than other forms of primary energy. Hydrogen can store this renewable electricity for use in locations where direct electrification is difficult. Renewable energy, hydrogen and hydrogen derivatives promote societal stability, sustainability, self-sufficiency, safety, security of supply, economic growth and employment.

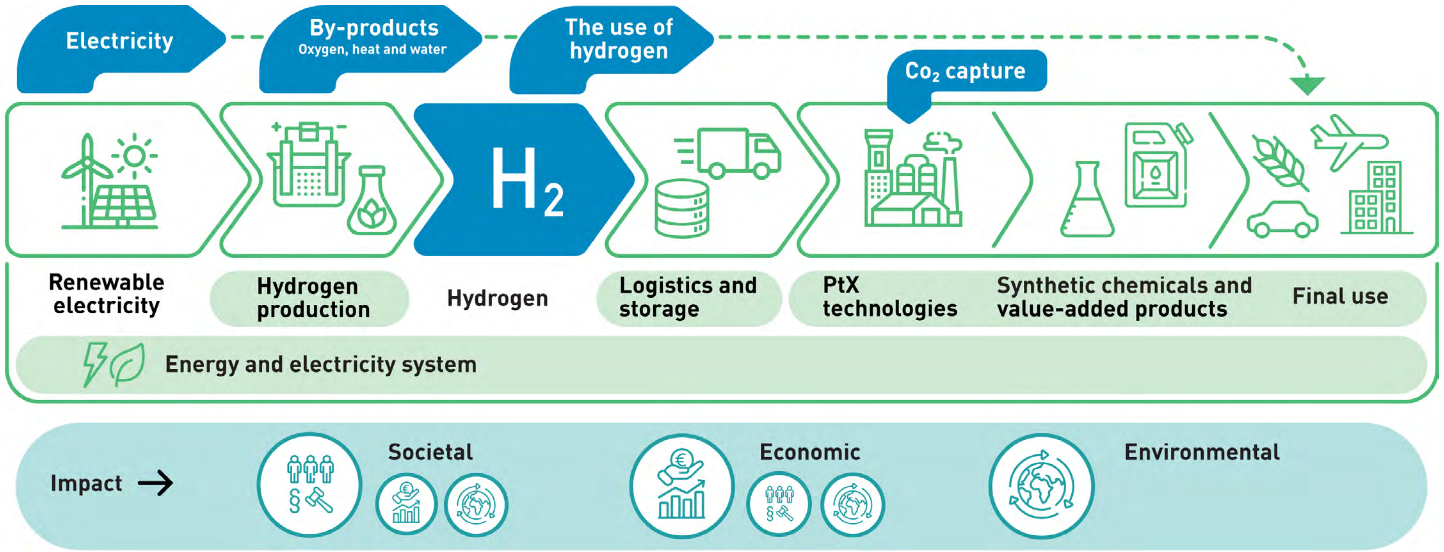
Finland's role in the EU will be strengthened thanks to the production potential of renewable energy and bio-based carbon dioxide. Finland's potential to produce renewable electricity (from onshore and offshore wind or solar power) exceeds domestic consumption tenfold. Finland also boasts a significant amount of bio-based carbon dioxide, which enables further processing of hydrogen to generate even higher added value products. Realizing these opportunities requires substantial investments in electricity production, hydrogen production, storage and processing, as well as for political acts to create a market for hydrogen. Research will also require investments to increase Finland's know-how and resilience in a changing global energy system.

This report focuses on key research topics within hydrogen economy and Power-to-X (PtX) technologies. To summarize PtX briefly, the term refers to transforming renewable electricity into various fuels or chemicals using hydrogen, carbon dioxide and nitrogen. PtX technologies are key to sustainable electrification that is meant to replace fossil fuels and processed fossil products.

"Renewable energy, hydrogen and hydrogen-derived products advance societal stability, sustainability, self-sufficiency, safety, security of supply, economic growth and employment."

PTX TECHNOLOGIES AND HYDROGEN ECONOMY: THE VALUE CHAIN OF MULTIPLE STAKEHOLDERS

The Hydrogen Value Chain



PtX technologies and hydrogen economy consist of various solutions, stakeholders and elements.The hydrogen value chain consists of hydrogen production, transportation, storage and use. A key concept in hydrogen production is clean primary energy, which will be an essential part for the energy system. Hydrogen can be utilized directly or as part of various processed raw materials across different sectors. This integration connects various parts of society, such as the energy, metal, forestry, chemical, steel and processing industries and sustainable traffic as parts of the hydrogen value chain. The viewpoints of markets, society, the environment and sustainability are intrinsically related to the use of hydrogen and processed hydrogen. Understanding these viewpoints in the upcoming energy transition requires research.

In Europe, the development of hydrogen value chains progresses through so-called hydrogen valleys. These are geographical areas where various hydrogen applications are combined into an ecosystem that advances hydrogen initiatives. As this technology is in transitional phase, each valley faces significant research, development and innovation (RDI) needs.

At the European level, the primary entity supporting research, development and innovation in hydrogen technologies is the Clean Hydrogen Partnership undertaking to support the research and innovation of hydrogen technologies. The activities are further supported by CETP, Processes4Planet and Horizon Europe.

Clean Hydrogen Partnership:
This partnership between the public and private sectors focuses specifically, on researching and developing fuel cells and hydrogen technologies in Europe.

Clean Energy Transition Partnership (CETP):
A multinational partnership that brings together governments, industries and research institutions from various countries to promote the research and development of clean energy and technologies. The partnership aims to accelerate the transition to sustainable energy system, including hydrogen technologies.

Horizon Europe:
The European Union's research and innovation key funding programme that promotes hydrogen research and development.

Processes4Planet:
Part of the EU Horizon Europe programme. Focuses on R&D to promote low-carbon technologies in industry, including hydrogen technologies.

Besides these, the most important established networks for hydrogen research are:

EERA JP Fuel Cells & Hydrogen:
European Energy Research Alliance's joint programme that focuses on researching and developing fuel cells and hydrogen technologies.

SET Plan Green Hydrogen IWG:
A workgroup under the EU's Strategic Energy Technology (SET) Plan focuses on researching and developing green hydrogen technologies.

IEA Hydrogen TCP:
International Energy Agency's collaboration programme for hydrogen technologies that promotes hydrogen research and global development.

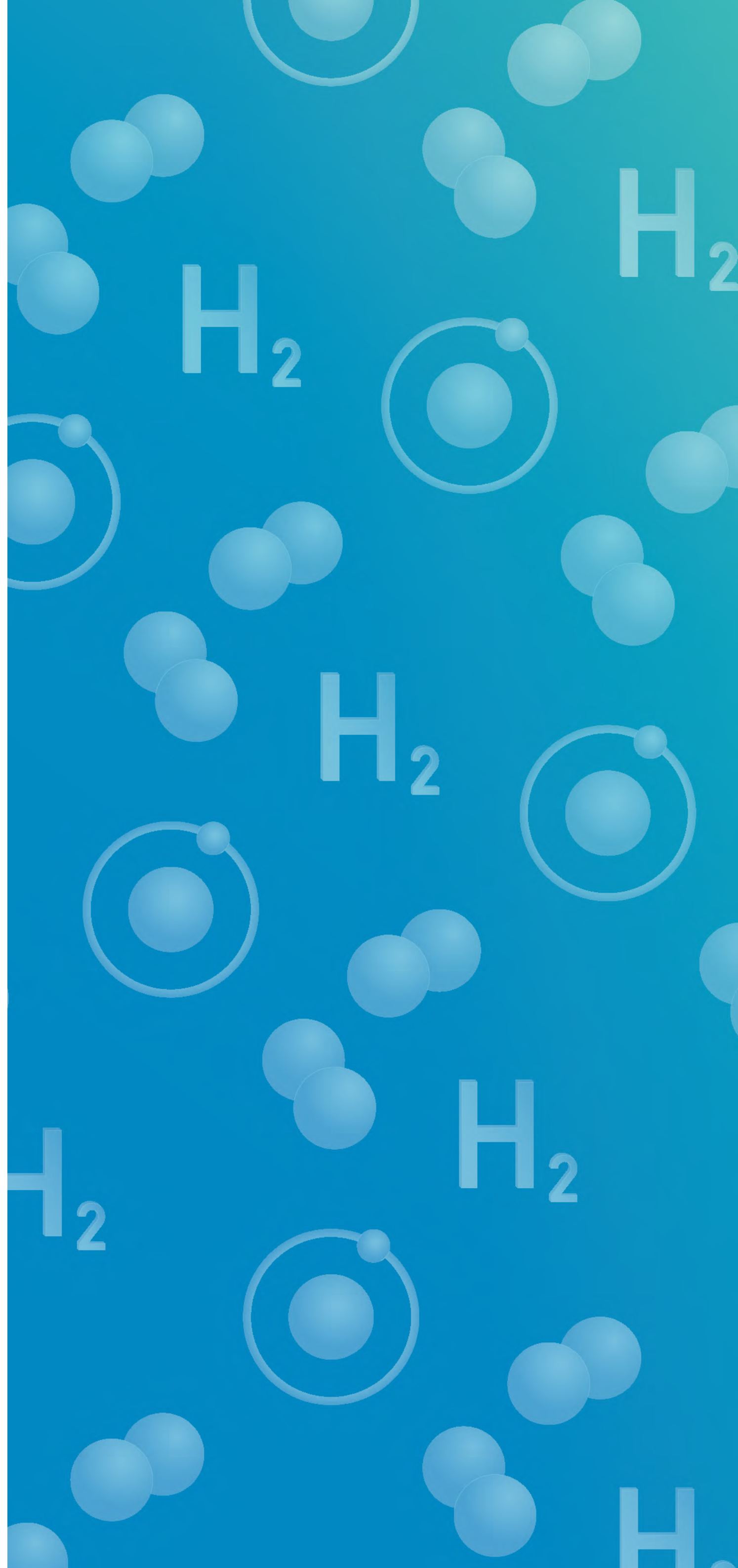
Hydrogen Europe:
A European organization that endorses carbon neutrality by advancing the European hydrogen industry.

Hydrogen Europe Research:
The research division of the Hydrogen Europe network that promotes and supports hydrogen R&D in Europe.

European Clean Hydrogen Alliance:
An alliance established the EU initiative that promotes the development of hydrogen economy, including research and development within Europe.

International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE):
This international collaborative body advances hydrogen research and development worldwide.

In addition to these hydrogen-specific networks, there are several international networks focusing on e.g. renewable fuels. Among the RDI initiatives closest to commercialization are the Innovation Fund which supports the first commercial facilities, and Business Finland's Energy Aid at the national level.



KEY RESEARCH AREAS RELATED TO PTX TECHNOLOGIES AND HYDROGEN ECONOMY

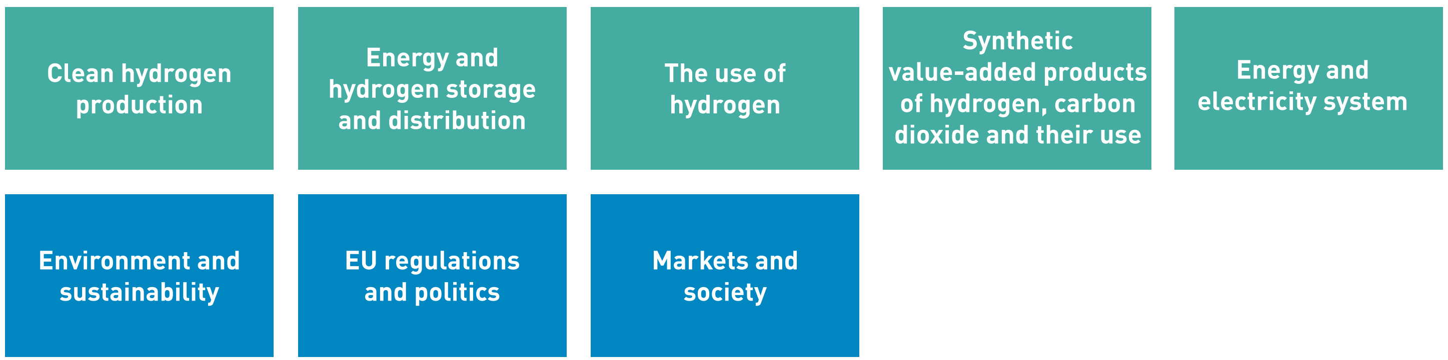
The following chapters outline research needs regarding the various facets of hydrogen economy value chain, which in this document are categorized as follows:

- Clean Hydrogen production
- Energy and hydrogen storage and distribution
- Use of hydrogen
- Synthetic value-added products of hydrogen, carbon dioxide and their usage
- Energy and electricity systems

In addition to the value chain, research must support the hydrogen economy and the implementation of PtX technologies by providing information about environmental impacts, sustainability and general acceptability. Research must also continuously provide information to decision-makers and companies on EU regulations and the development of domestic industrial policies, which can be used to promote Finland's hydrogen economy and PtX technologies. Additionally, research results must support the development of hydrogen economy markets, reinforcing economic growth in Finland and supporting the development of a welfare society.

- Environment and sustainability
- EU regulations and politics
- Markets and society

This report focuses on the above-mentioned topics as short-term, medium-term and long-term goals. A term in this case refers to the duration starting from initiating the research and the results being brought into wider use. Short-term goals emphasize finding solutions to industrial bottlenecks within research, development and innovation operations (RDI). RDI also plays an important part in educating future industrial experts who understand hydrogen economy and PtX technologies. Medium-term goals emphasize improvements to technological cost competitiveness and functionality, as well as applications that are not immediately applicable at an industrial scale. Long-terms goals focus on breakthrough technologies that can alter development roadmaps based on current solutions, as well as evaluating and predicting overall sustainability.



Clean Hydrogen production

Green hydrogen refers to hydrogen that has been produced using renewable energy, such as solar or wind power. Currently, production of green hydrogen requires a significant amount of renewable energy. As such, improving the efficiency of hydrogen production through research is important to make it competitive. Boosting the efficiency of hydrogen production also supports Finland's climate goals, as green hydrogen can replace fossil fuels. Key research focuses within hydrogen production are the scaling of electrolysis, investigating alternative raw materials to replace critical ones and removing production barriers. In addition, we must study how to improve the efficiency and automation of electrolysis systems, as well as new, efficient ways to produce hydrogen.

Short term, 1–3 years	Medium term, 3–5 years	Long term, 5–10 years
Development of commercial or near-commercial electrolysis technologies (alkaline and PEM): • Scaling up to a gigawatt capacity • Efficient and alternative materials for electrolysis • Removing production limitations of electrolysis technologies	Development of commercial or near-commercial electrolysis technologies (alkaline and PEM): • Improving the energy-efficiency of electrolysis • Development of manufacturing technologies and automation in electrolysis production Development of lower technology readiness levels: • SOEC, AEM • Methane pyrolysis (biomethane)	Alternative hydrogen production technologies: • Photocatalysis • Other alternative technologies, such as biomass conversion to hydrogen

Energy and hydrogen storage and distribution

Finland has significant renewable energy production potential in both onshore/offshore wind power and solar energy. Efficient storage and distribution methods enable renewable energy to be efficiently integrated into the energy system. Advanced storage and transfer solutions can improve the flexibility and reliability of the Finnish energy supply, especially in terms of the intermittency of renewable energy and electricity production. Key research areas include hydrogen pipeline distribution and storage, and comparison with other transport methods. Other topics calling for research include hydrogen's role as an energy storage, alternative hydrogen storage methods, materials studies on hydrogen components, and the transport of hydrogen by ship, liquid hydrogen and new hydrogen carriers.

Short term, 1–3 years	Medium term, 3–5 years	Long term, 5–10 years
Topics related to hydrogen pipeline transport: • Cost-efficiency • Technical implementation • Compression • Storage • Transfer losses • Safety Additional topics: • Comparison of hydrogen pipeline transport with alternatives, such as e-methanol and e-ammonia • Hydrogen storage	Hydrogen-related topics: • Materials research for hydrogen components • Technical implementation of hydrogen transport by ship • Liquid nitrogen • Alternative hydrogen storage methods, such as minerals • Hydrogen's role as an energy storage	New hydrogen carriers: • Liquid organic hydrogen carriers (LOHC)

The use of hydrogen

Hydrogen use is studied from various angles which allows it to be utilized on multiple sectors. Key research topics include the use of hydrogen in the production of clean steel, its application in engines and turbines, fuel cells and X2P technologies, as well as in in transportation. Other research needs include infrastructure related to hydrogen use, its application in maritime transportation, and utilizing hydrogen to produce clean steel from lower quality ores.

Short term, 1–3 years	Medium term, 3–5 years	Long term, 5–10 years
• Using hydrogen to produce clean steels • Using hydrogen in engines and turbines • Fuel cells and X-to-Power (X2P) cycles, incl. RESOC Using hydrogen for transportation: • Mobile work machines • Heavy-duty vehicles	• The use of hydrogen in maritime transport • Infrastructure required for hydrogen use	• Using hydrogen to produce clean steels from lower quality ores

Synthetic value-added products of hydrogen, carbon dioxide and their uses

Besides potential for renewable energy, Finland has a significant amount of biogenic carbon dioxide, which can be converted into synthetic value-added products together with hydrogen. These include synthetic fuels, chemicals and materials. These synthetic intermediate and value-added products can be utilized in various sectors, such as. raw materials for the chemical industry and as fuels for sustainable transportation. Key research areas include synthesis of derivative and value-added products, carbon dioxide capture, purification and logistics, as well as catal-ysis processes and materials.

Short term, 1–3 years	Medium term, 3–5 years	Long term, 5–10 years
Synthetic derivative products: • e-ammonia • e-methanol • e-methane • Fischer-Tropsch products • Sustainable aviation fuel (SAF) Carbon dioxide (CO2) sources: • Separation technologies • Direct air capture (DAC) • Purification • Logistics	• Catalysis processes and materials Value-added products: • e-plastics • e-chemicals • Use of hydrogen-derivative products in aviation	• *No identified areas of research*

Energy and electricity system

The transition of energy production towards renewable energy, such as solar and wind power, requires the electrical system to adjust to varying energy production and consumption. The system must be flexible and resilient to accommodate this variability. Additionally, the need to transfer power will multiply in the near future due to the shift to a hydrogen economy and PtX technologies, which will call for significant investments into national grids. As such, key research topics are the renewal of the electricity market, energy and electricity storages and their flexibility, as well as the flexibility of consumption and demand, electricity transfer needs and optimizations of electricity systems. Other important research consideration include energy and electricity system models, sector integration, value chains, business models and pricing mechanisms. The new system must account for new production side streams, such as heat, carbonl, oxygen, and their utilization.

Short term, 1–3 years	Medium term, 3–5 years	Long term, 5–10 years
• Renewal of the electricity market • Storage and flexibility of electricity and energy • Flexibility of electricity and energy consumption and demand • Enabling large-capacity electricity transfers • Analyses and process modeling of technical economy	• Sector integration • Optimizing the electricity system • Energy system value chains and business models • Pricing mechanisms • Utilization of by-products from hydrogen production (heat, coal and oxygen)	• Distributed off-grid energy solutions Development of new technologies for the electricity grid • Main grid, 750 kV

Environment and sustainability

Environmental and sustainability issues in a changing energy system are among key research areas, as the green transition and hydrogen economy impact climate change and biodiversity, among other factors. Because this, it must be ensured that the change does not endanger or further burden the environment or climate. Additionally, We must ensure the availability and suitability of critical raw materials and resources. The changes brought by the green transition and hydrogen economy also affect communities, employment and regional economies. This is why understanding the aforementioned effects is crucial, as is developing work methods that comprehensively support sustainable development, the just transition, and general acceptability of the change.

Short term, 1–3 years	Medium term, 3–5 years	Long term, 5–10 years
Climate change, land use, biodiversity and critical raw materials: • Evaluating the effects of the green transition and hydrogen economy • Life cycle analysis of various green transition and hydrogen economy scenarios • Certifying green hydrogen production • The effects of land use Additional topics: • Component-level life cycle studies	• Resources and critical raw ingredients • Evaluating and promoting the general acceptability of the green transition and hydrogen economy	• Evaluating and promoting the general acceptability of the green transition and hydrogen economy • Creation and distribution of welfare in the green transition and hydrogen economy • Monitoring, advancing and supporting industrial changes within hydrogen economy

EU regulations and politics

EU regulations and national politics have a crucial impact on the green transition and hydrogen economy. The study must delve into these themes to provide information to the government, municipalities and companies about what special conditions apply to Finland regarding EU regulations, and to highlight actions for advancing the transition. Clarifying and ensuring consistency in EU regulations concerning electricity, hydrogen and carbon dioxide is also important to assure investments. Geopolitical changes and security of supply must also be accounted for as key elements of the green transition and hydrogen economy. The study must also generate data on how soft law mechanisms, authorization processes and long-term agreements can be developed to support investments and the transition.

Short term, 1–3 years	Medium term, 3–5 years	Long term, 5–10 years
• Performing an impact evaluation to advance authorization processes • Evaluating the effects of key EU regulations and the options to impact them to promote Finland's green transition and hydrogen economy • Evaluating the lock-in-effects of long-term agreements and how to influence them	• Evaluating national legislation • Evaluating national politics • Assessment of the EU regulatory framework and influencing it • Monitoring soft law mechanisms • Geopolitics and security of supply	• Forming a situation picture of the EU regulation framework and promoting its effectiveness

Markets and society

Hydrogen economy and PtX technologies are going to revolutionize the entire energy system's value chain and the market. Demand for hydrogen will increase rapidly if emission goals and related EU regulations transpire as planned. This gives Finland a considerable economic opportunity that could enhance industry turnover and create an abundance of new jobs by 2035. It is particularly important for Finland to utilize its green hydrogen and biogenic carbon dioxide for domestic industrial needs, and to process the materials into higher value-added raw materials or products. Research must monitor and support the development of business models, the macro economy, Finland's competitiveness and market development to reinforce the country's position as a manufacturer of hydrogen-derived end-products, such as raw materials and products for the chemical industry and synthetic fuels for aviation and maritime transport.

Short term, 1–3 years	Medium term, 3–5 years	Long term, 5–10 years
• Monitoring and supporting the development of business models within the green transition and hydrogen economy	• Monitoring the macro economy and Finland's competitiveness within the green transition and hydrogen economy	• Monitoring the market developments of the green transition and hydrogen economy, and forming a situation picture

CONCLUSIONS AND RECOMMENDATIONS

This report was used as the basis for a questionnaire for inquiring about key research topics for the development of the hydrogen economy value chain. The questionnaire contained 83 research topics, divided into eight main categories based on this report's hydrogen value chain and three separate time periods. A total of 46 representatives from 12 Finnish universities and research institutes answered the questionnaire. The questionnaire highlighted 24 of the most important research topics. The main categories were arranged in an order of importance (1–8) based on how many of the afore-mentioned topics were included in each category: (1) the synthetic value-added products of hydrogen, carbon dioxide, and their use (2) the use of hydrogen (3) the environment and sustainability (4) storage and distribution of energy and hydrogen, (5) the energy and electricity system, (6) manufacture of clean hydrogen, (7) the markets and society, and (8) EU regulations and politics. Although the main categories of markets and society (7) and EU regulations and politics (8) were not among the most significant research topics, they were considered important by the Finnish Hydrogen Research Forum for the development of the hydrogen economy and PtX technologies. The Finnish Hydrogen Research Forum decided to highlight the three research topics deemed the most important from each main category based on the average results of the questionnaire. These topics are presented in the table below.

The goal of this report is to shed light on the most critical research needs, through which the development of hydrogen economy in Finland may be advanced. These results can additionally be utilized to guide the funding of the research on the hydrogen economy and PtX technologies, and to increase cooperation between Finnish researchers.

Key research areas pertaining to hydrogen economy

Research needs are divided into short-term, medium-term and long-term goals.

- 1-3 years: SHORT-TERM
- 3-5 years: MEDIUM-TERM
- 5-10 years: LONG-TERM

1 Synthetic value-added products of hydrogen, carbon dioxide and their use

- e-methanol
- e-ammonia
- Sustainable aviation fuel (SAF)

2 The use of hydrogen

- Using hydrogen to produce clean steel
- Fuel cells and X-to-Power (X2P) cycles, including RESOC
- The use of hydrogen in maritime transport

3 The environment and sustainability

- Evaluating the environmental impacts of the green transition and hydrogen economy
- Resources and critical raw materials
- Life cycle analysis in hydrogen economy
- Monitoring, advancing and supporting industrial changes in the green transition and hydrogen economy

4 Storage and distribution of energy and hydrogen

- Hydrogen storage
- Comparing hydrogen pipeline distribution to other alternatives
- Materials research on hydrogen components

5 Energy and electricity system

- Storage and flexibility of electricity and energy
- Utilization of by-products from hydrogen production
- Flexibility of electricity and energy consumption and demand

6 Production of clean hydrogen

- Finding efficient and/or alternative electrolysis materials
- Improving the energy efficiency of electrolysis materials (alkaline and PEM)
- Removing production limitations of electrolysis technologies (alkaline and PEM)

7 The markets and society

- Monitoring the development of business models and supporting them through the green transition and in hydrogen economy.
- Monitoring and supporting Finnish macro economy and competitiveness through the green transition
- –

8 EU regulations and politics

- Evaluating the effects of key EU regulations to promote Finland's green transition and hydrogen economy
- Geopolitics and security of supply
- Forming an overview of the EU regulation framework and promoting its effectiveness

ABBREVIATIONS AND GLOSSARY

AEM (Anion Exchange Membrane):
An anion exchange membrane is a membrane used in electrolysis that transfers anions (negatively charged ions) between electrodes. It enables water to be broken down into hydrogen and oxygen.

Alkaline electrolysis:
A hydrogen production method in which water is split into hydrogen and oxygen using an alkaline electrolyte solution, such as potassium hydroxide or sodium hydroxide. The process takes place within the electrolysis cell, in which the flow of electricity divides the water.

CO2 (Carbon dioxide):
A gaseous compound that is a major greenhouse gas. It is created by e.g. burning fossil fuels.

DAC (Direct Air Capture):
A technology that captures carbon dioxide directly from the atmosphere using chemical processes.

LOHC (Liquid Organic Hydrogen Carriers):
organic hydrogen carriers that enable safe and efficient storage of hydrogen using organic liquids.

Off-grid energy solutions:
Independent energy systems that are not connected to a centralized electrical grid. They use locally produced energy, such as solar or wind power and may involve battery storages.

PEM (Proton Exchange Membrane Electrolyzer):
Proton exchange membrane electrolysis is a technology in which water is broken down into hydrogen and oxygen using a proton exchange membrane.

PtX (Power-to-X):
A technology that converts hydrogen produced using renewable energy into various energy sources or chemicals, such as synthetic fuels or methanol.

RESOC (Reversible solid oxide cells):
Reversible solid oxide cells are devices that can operate as both fuel cells and electrolysis cells. Fuel cells convert chemical energy directly into electricity, while electrolysis cells use electricity to produce chemical compounds, such as hydrogen.

SAF (Sustainable Aviation Fuel):
Aviation fuel made from renewable or recycled raw materials and which reduces greenhouse emissions compared to traditional fossil fuels.

SOEC (Solid Oxide Electrolysis Cell):
Solid oxide electrolysis cells are electrolysis devices that break down water or carbon dioxide using oxide material at high temperatures.

Soft law mechanisms:
Regulatory or instructional methods that are not legally binding but offer guidance and recommendations. These may include international agreements, recommendations, instructions or practices that contribute to shaping policy and practices without formal legal obligation.

X2P (X-to-Power):
Technology that converts various energy sources, such as chemical and heat back into electricity.

APPENDICES

Strategic Research Agenda for Finnish Hydrogen Research
– The Finnish Hydrogen Research Forum's views

Strategic Research Agenda for Finnish Hydrogen Research
- Comparison of Research Needs in Finland's Hydrogen Economy from the Perspectives of Industry and Academia

The state of Finnish hydrogen economy research

STRATEGIC RESEARCH AGENDA FOR FINNISH HYDROGEN RESEARCH
- INSIGHTS FROM THE HYDROGEN RESEARCH FORUM FINLAND

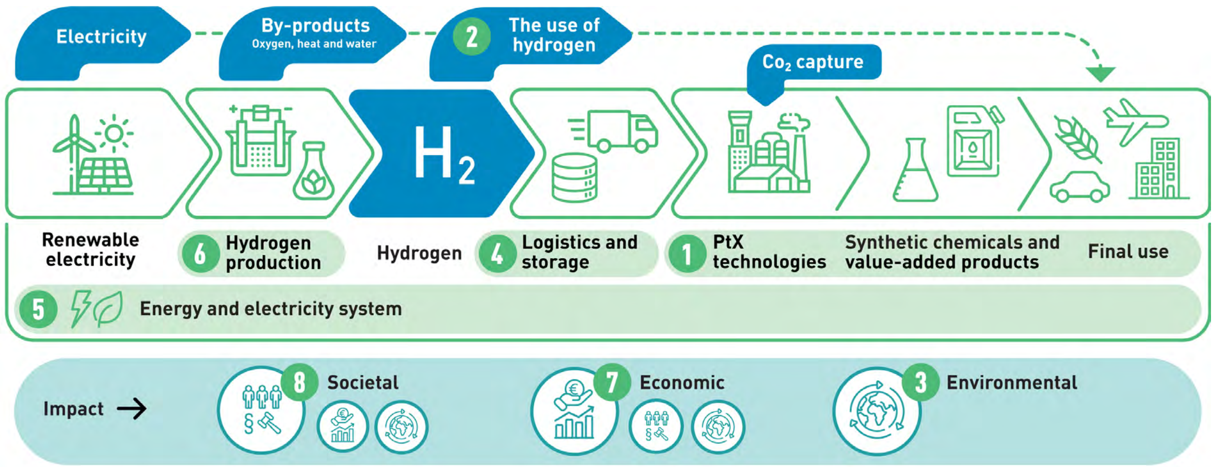
HYDROGEN RESEARCH FORUM FINLAND

Hydrogen drives a clean industrial breakthrough

The goal of the Paris Agreement is to limit the temperature increase due to climate change to 1.5 °C. This calls for a drastic reductions in fossil fuel emissions, primarily through the use of clean electricity in transportation, heating and industry. Clean hydrogen is a key element here, as it can replace fossil fuels and promote emissions on sectors where the direct use of electricity is challenging.

Other additional factors in the energy transition are the self-sufficiency of energy, security of supply and safety, all of which contribute to a stable and sustainable society. In recent years, the production costs of clean electricity have come down to a level that is competitive with fossil electricity production. This accelerates the transition to clean electricity production, enabling the use of hydrogen for energy storage and distribution in areas where direct electrification is difficult. Finland's potential for renewable energy (onshore wind, offshore wind, and solar power) exceeds our domestic consumption tenfold. Finland also has a significant amount of biogenic carbon dioxide at a European scale, giving Finland a unique position to reinforce its role within the EU's energy system.

Key research areas pertaining to hydrogen economy



1 Synthetic value-added products of hydrogen, carbon dioxide and their use

- e-methanol
- e-ammonia
- Sustainable aviation fuel (SAF)

2 The use of hydrogen

- Using hydrogen to produce clean steel
- Fuel cells and X-to-Power (X2P) cycles, including RESOC
- The use of hydrogen in maritime transport

3 The environment and sustainability

- Evaluating the environmental impacts of the green transition and hydrogen economy
- Resources and critical raw materials
- Life cycle analysis in hydrogen economy
- Monitoring, advancing and supporting industrial changes in the green transition and hydrogen economy

4 Storage and distribution of energy and hydrogen

- Hydrogen storage
- Comparing hydrogen pipeline distribution to other alternatives
- Materials research on hydrogen components

5 Energy and electricity system

- Storage and flexibility of electricity and energy
- Utilization of by-products from hydrogen production
- Flexibility of electricity and energy consumption and demand

6 Production of clean hydrogen

- Finding efficient and/or alternative electrolysis materials
- Improving the energy efficiency of electrolysis materials (alkaline and PEM)
- Removing production limitations of electrolysis technologies (alkaline and PEM)

7 The markets and society

- Monitoring the development of business models and supporting them through the green transition and in hydrogen economy.
- Monitoring and supporting Finnish macro economy and competitiveness through the green transition

8 EU regulations and politics

- Evaluating the effects of key EU regulations to promote Finland's green transition and hydrogen economy
- Geopolitics and security of supply
- Forming an overview of the EU regulation framework and promoting its effectiveness

Research needs are divided into short-term, medium-term and long-term goals.

1-3 years	SHORT-TERM
3-5 years	MEDIUM-TERM
5-10 years	LONG-TERM

STRATEGIC RESEARCH AGENDA FOR FINNISH HYDROGEN RESEARCH

- INSIGHTS FROM THE HYDROGEN RESEARCH FORUM FINLAND

PtX technologies transform renewable electricity into various fuels and chemicals, often utilizing carbon dioxide and hydrogen. They are key technologies in electrification that can replace fossil fuels and derivative products. The value chain of hydrogen economy consists of the production, storage and direct use of hydrogen. Boosting the efficiency of hydrogen production requires clean primary energy production and water resources, which will be essential to the energy system in the future.

Research Time Frames and Needs

The research needs are categorized into short-term (1–3 years), medium-term (3–5 years), and long-term (5–10 years) goals. Short-term goals center around overcoming industrial bottlenecks. Medium-term goals focus on improving the cost-competitiveness of technologies and the long-term goals center around developing breakthrough technologies and evaluating sustainability.

Key research areas

- **Clean hydrogen production:** Development and commercialization of more effective electrolysis systems.
- **Storage and distribution of energy and hydrogen:** Researching optimal distribution and storage methods.
- **Use of hydrogen:** Development of hydrogen fuel cells and manufacture of clean steel.
- **Synthetic value-added products of hydrogen, carbon dioxide and their use:** Development of synthetic fuels and chemicals out of hydrogen.
- **The energy and electricity system:** Adaptability of the energy system to renewable energy sources and flexible solutions.
- **Markets and society**
- **EU regulations and politics**
- **Environment and sustainability**

Method and results

The Finnish Strategic Hydrogen involved 12 Finnish universities and research institutes, including Aalto University, University of Helsinki, University of Jyväskylä, Natural Resources Institute Finland, LUT University, University of Oulu, Tampere University, University of Turku, University of Eastern Finland, University of Vaasa, VTT Technical Research Centre of Finland and Åbo Akademi. The collaboration collected and evaluated 83 research topics, which were narrowed down into 24 of the most important ones that are crucial for Finnish competitiveness.
"The synthetic value-added products of hydrogen, carbon dioxide and their use" ranked as the most important category. The second most important was "The use of hydrogen" and the third one "The environment and sustainability". Other important categories included "Storage and distribution of energy and hydrogen", "The energy and electricity system", and "Manufacture of clean hydrogen". The lowest-scoring categories were "The markets and society" and "EU regulations and politics". From the perspective of the most important research category, "Synthetic value-added products of hydrogen, carbon dioxide, and their use," it is essential to study the entire hydrogen value chain and its various components. Understanding the changes in the value chain and their impacts is crucial for implementing these changes as efficiently as possible.

Summary

Hydrogen and PtX technologies are key factors as Finland moves towards a more sustainable and self-sufficient energy system. The goal of the Finnish Strategic Hydrogen Study is to reinforce Finland's position as a pioneer of hydrogen economy and to make use of the country's unique renewable electricity resources and biogenic carbon dioxide. This calls for extensive research and development cooperation and significant investments. Cooperation between Finnish universities and research institutes is crucial for realizing this strategy.

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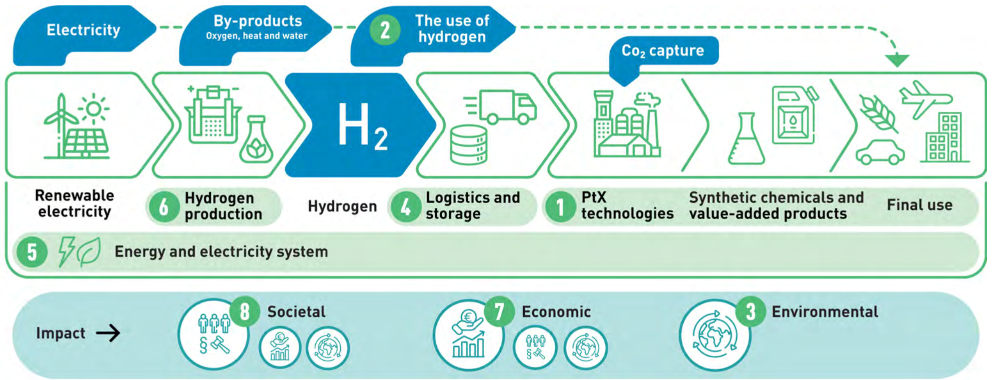
STRATEGIC RESEARCH AGENDA FOR FINNISH HYDROGEN RESEARCH

- COMPARISON OF RESEARCH NEEDS IN FINLAND'S HYDROGEN ECONOMY FROM THE PERSPECTIVES OF INDUSTRY AND ACADEMIA

HYDROGEN RESEARCH FORUM FINLAND

Key research areas pertaining to hydrogen economy



To understand the needs for research from the Finnish economy's viewpoint, one should also examine the industry's needs for research. The industrial viewpoint emphasizes practical solutions that support the rapid commercialization of hydrogen economy and strengthen competitiveness. Conversely, research organizations' focuses are more widely related to sustainability, innovations and long-term impacts. Combining these viewpoints creates a comprehensive and balanced understanding of what kind of research is needed to support both technological development and national economy goals in advancing the hydrogen economy.

Research area	Industry-specific research needs	Shared views of industry and academia on the research needs of Finland's hydrogen economy	Research needs by academia
1 Synthetic value-added products of hydrogen, carbon dioxide, and their use	–	e-methanol Sustainable aviation fuel (SAF) Carbon dioxide separation technologies	e-ammonia
2 The use of hydrogen	Infrastructure required for hydrogen use	Using hydrogen to produce clean steel Fuel cells and X-to-Power (X2P) cycles, including RESOC Using hydrogen in engines and turbines	The use of hydrogen in maritime transport
3 The environment and sustainability	–	Evaluating the environmental impacts of the green transition and hydrogen economy Resources and critical raw materials Life cycle analysis of various green transition and hydrogen economy scenarios	Monitoring, advancing and supporting industrial changes within hydrogen economy
4 Energy and hydrogen storage and distribution	–	Hydrogen storage Hydrogen's role as an energy storage Materials research for hydrogen components Safety of hydrogen pipeline distribution	Comparison of hydrogen pipeline distribution to other alternatives
5 Energy and the electricity system	–	Storage and flexibility of electricity and energy Utilization of by-products from hydrogen production Flexibility of energy and electricity consumption and demand	–
6 Clean hydrogen production	Development of electrolysis technologies (alkaline/PEM) Development of electrolysis technologies (SOEC/AEM)	Finding efficient and/or alternative electrolysis technologies Improving the energy-efficiency of electrolysis technologies (alkaline and PEM)	Removing production limitations of electrolysis technologies (alkaline and PEM)
7 The markets and society	Monitoring and supporting Finnish macro economy and competitiveness through the green transition	–	Monitoring the development of business models and supporting them through the green transition and in hydrogen economy.
8 EU regulations and politics	Assessment of the EU regulatory framework and influencing it	Evaluating the effects of key EU regulations and the options to impact them to promote Finland's green transition and hydrogen economy	Geopolitics and security of supply

Research needs are divided into short-term, medium-term and long-term goals.

1-3 years	SHORT-TERM
3-5 years	MEDIUM-TERM
5-10 years	LONG-TERM

HYDROGEN RESEARCH FORUM FINLAND

STRATEGIC RESEARCH AGENDA FOR FINNISH HYDROGEN RESEARCH

- COMPARISON OF RESEARCH NEEDS IN FINLAND'S HYDROGEN ECONOMY FROM THE PERSPECTIVES OF INDUSTRY AND ACADEMIA

PtX technologies transform renewable energy into various fuels and chemicals, often utilizing carbon dioxide and hydrogen. They are key technologies in electrification that can replace fossil fuels and derivative products. The value chain of hydrogen economy consists of the production, storage and direct use of hydrogen. Boosting the efficiency of hydrogen production requires clean primary energy production and water resources, which will be essentials to the energy system in the future.

Research Time Frames and Needs

The research needs are categorized into short-term (1–3 years), medium-term (3–5 years), and long-term (5–10 years) goals. Short-term goals center around overcoming industrial bottlenecks. Medium-term goals focus on improving the cost-competitiveness of technologies and long-term goals center around developing breakthrough technologies and evaluating sustainability.

Key research areas

- **Clean hydrogen production:** Development and commercialization of more effective electrolysis systems.
- **Storage and distribution of energy and hydrogen:** Researching optimal distribution and storage methods.
- **Use of hydrogen:** Development of hydrogen fuel cells and manufacture of clean steel.
- **Synthetic value-added products of hydrogen, carbon dioxide and their use:** Development of synthetic fuels and chemicals out of hydrogen.
- **The energy and electricity system:** Adaptability of the energy system to renewable energy sources and flexible solutions.
- **Markets and society**
- **EU regulations and politics**
- **Environment and sustainability**

Method and results

The industry's views on the research needs of Finnish hydrogen economy were surveyed with a questionnaire. The questionnaire was based on research topics surveyed from Finnish universities and research organizations. The same questionnaire was sent to both universities and companies. A total of 23 representatives from Finnish companies responded to the survey. Based on the questionnaire, the highest averages – and thus the highest emphasis in terms of companies' research priorities – were related to the synthetic value-added products of hydrogen, carbon dioxide, and the manufacture of clean hydrogen. The next most important research categories were the use of hydrogen, storage and distribution of energy and hydrogen, and the energy and overall electricity systems. Companies were less likely to emphasize the evaluation of the markets and society, or environmental considerations in improving hydrogen economy and sustainability. Questions related to EU regulations and politics were the least important to companies from a research perspective.

Both companies and academia prioritized the category synthetic value-added products of hydrogen, carbon dioxide and their use as the most important research area Both sectors also considered the direct use of hydrogen important. Energy and hydrogen storage and distribution, and the energy and electricity system ranked fourth and fifth, respectively, for both groups.

Major differences could be seen within the categories of clean hydrogen production, and the environment and sustainability. For industry, the production of clean hydrogen was ranked as the second most important while academia ranked it only sixth. In contrast, universities ranked the environment and sustainability the third most important, while companies considered it among the two least important categories.

Summary

In conclusion, even though the views of industrial companies, universities and research institutes emphasize the significance of hydrogen economy for building a sustainable and self-sufficient energy system, they emphasized different focuses in terms of research. Industrial operators emphasize immediate and practical applications, such as clean hydrogen production and the development of synthetic value-added products. Universities on the other hand emphasize sustainability and environmental impacts in a larger context, thus reflecting the longevity and multidisciplinary nature of research.

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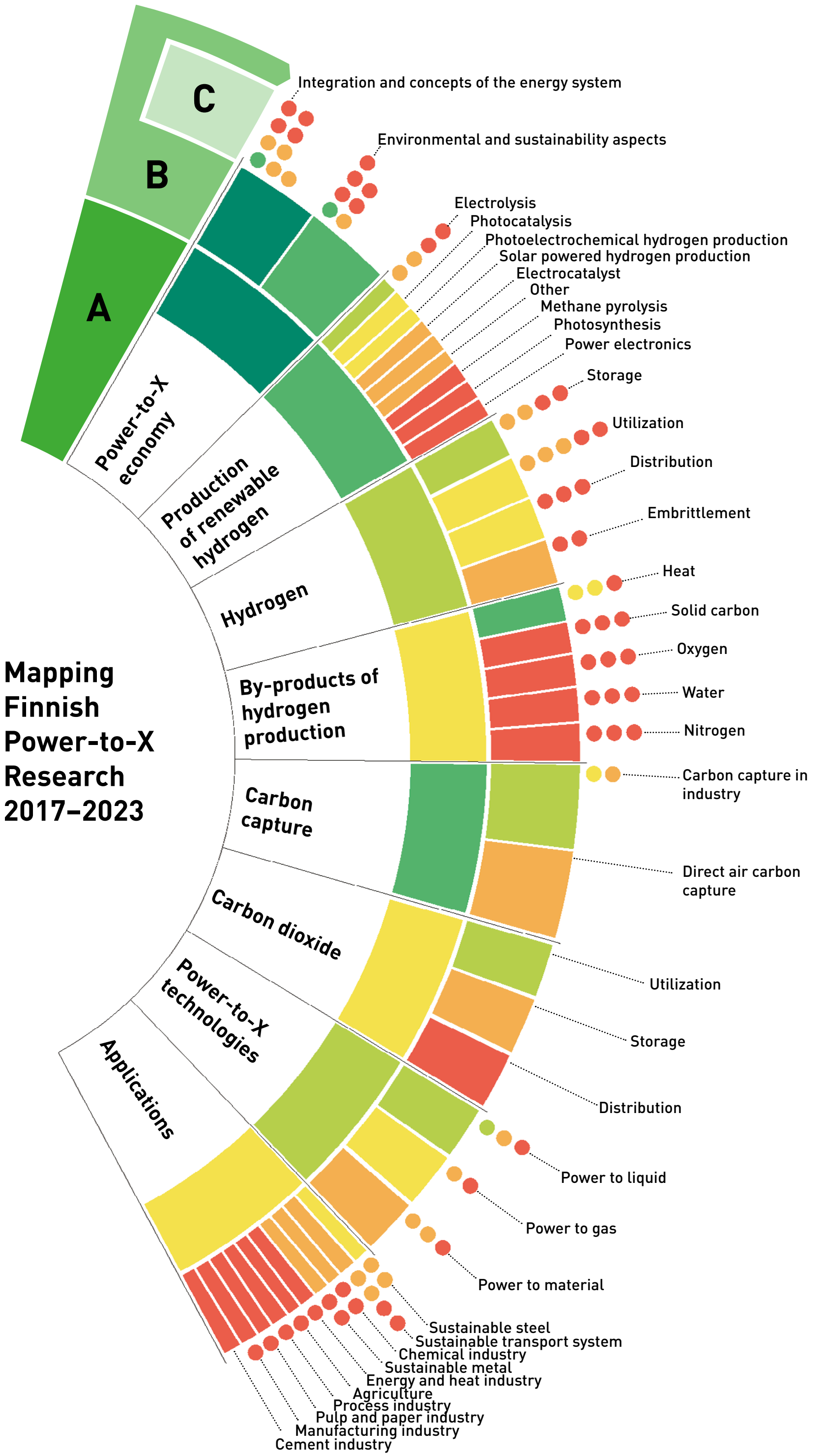
THE STATE OF FINNISH HYDROGEN ECONOMY RESEARCH

Power-to-X (PtX) technologies are essential for combating climate change and increasing energy self-sufficiency. This summary provides an overview of Finnish PtX research in recent years. The study was based on a bibliometric analysis and interviews and survey conducted for Finnish research institutions.

Mapping Finnish Power-to-X Research 2017–2023



Category A
Research areas and processes within the hydrogen value chain

Category B
Research topics on Products, technologies and methods within the hydrogen value chain

Category C
Sub-categories and components of hydrogen value chain technologies and methods

Research status

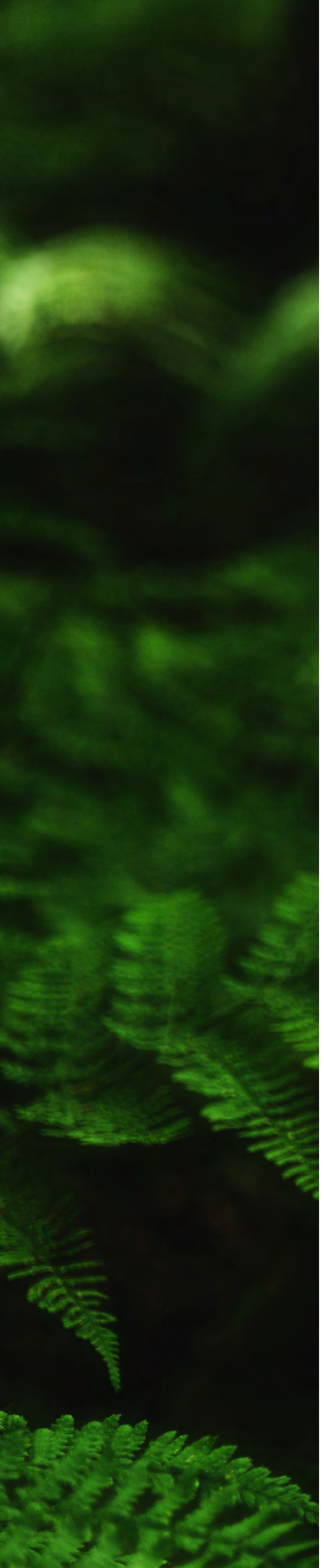
- Very strong
- Strong
- Established
- Somewhat
- Limited
- None

Legislative, material and safety perspectives

Legislation and politics
- Legislation and EU regulations
- Political actions and support
- Licensing
- Lock-in-effects of long-term agreements
- Soft law mechanisms

Raw materials and other materials
- Critical raw materials
- Raw material independence
- 3D printing
- Material characterization

Quality and safety
- Safety
- Quality



The state of Finnish hydrogen economy research

Power-to-X (PtX) technologies are essential for combating climate change and increasing energy self-sufficiency. This summary provides an overview of Finnish PtX research in recent years. The research is based on bibliometric analysis and interviews and survey conducted for Finnish research institutions.

The bibliometric analysis covered all Finnish articles about PtX technologies published between 2017–2023 as identified in the the Scopus database. Twelve Finnish universities and research institutes participated in the survey and interviews. These included Aalto University, University of Helsinki, University of Jyväskylä, Natural Resources Institute Finland, LUT University, University of Oulu, Tampere University, University of Turku, University of Eastern Finland, University of Vaasa, VTT Technical Research Centre of Finland and Åbo Akademi.

The study established a framework for delineating PtX economy-related research and created a structure for future research activities. The framework consists of three categories: main category A describes research areas and processes within the hydrogen value chain. Category B contains products, technologies and methods of the hydrogen value chain research. Finally, the more detailed category C contains the subclasses and components of the hydrogen value chain technologies and methods.

Key findings

The focus of Finnish PtX research lies in the PtX economy, particularly in the study of energy systems. Environmental and sustainability aspects, especially climate change, are key research topics, often studied together with energy system integration and concepts. Popular topics also include renewable hydrogen production through electrolysis, as well as carbon capture from industrial sources. Additionally, research on e-methanol within Power-to-Liquid (PtL) technologies is well established. Research into hydrogen storage, the utilization of carbon dioxide, and heat generated from hydrogen production side streams is also well developed. The results indicate that legislative and materials research are significant areas in Finnish PtX research. Legislative research focuses on the PtX economy at a general level, while materials research emphasizes renewable hydrogen production and electrolysis technologies.

Future trends and gaps in research

There are numerous research gaps in Finland's PtX research. In terms of PtX economy, there are deficiencies in the research of energy system integration and concepts, energy transitions, value chains, business models, life cycle assessments, security of supply, infrastructure, hydrogen valleys, machine learning, artificial intelligence, and information technology. There are also gaps in environmental and sustainability aspects related to wealth creation, circular economy, biodiversity, land use, sustainability, and general acceptability.

In the production of renewable hydrogen, there are shortcomings in the research of photosynthesis, solar hydrogen, PEM, AEM, and SOEC technologies, power electronics, and methane pyrolysis. There is little research on carbon dioxide capture, both from direct air and industrial sources, particularly from biogenic sources. Less studied topics concerning carbon dioxide include its storage and transportation.

There are many research gaps regarding hydrogen. Its utilization has mainly been studied in the context of heat production, where heat generated from hydrogen production is captured and utilized. However, there are still research gaps in areas such as electricity, fuel cells, gas turbines, and internal combustion engines. There is no research on hydrogen transportation regarding compression, pipelines, or maritime transport. In hydrogen storage, there is no research on the storage of gases, liquids, and metals, nor on compression. Research on hydrogen embrittlement is also limited. Regarding by-products of hydrogen production, research on solid carbon, oxygen, and nitrogen is lacking.

Research on PtX technologies is limited, particularly in PtL technology regarding e-fuels, PtG technology regarding e-ammonia and e-methane, and PtM technology regarding e-food and e-cement. There are deficiencies in application areas such as sustainable transportation systems, sustainable metals, chemical industry, agriculture, cement industry, manufacturing industry, process industry, paper and pulp industry, and electrical and thermal industries.

There are also significant research gaps in legislation, materials, and quality issues. Legislative and policy research has not addressed topics outside the PtX economy, which is a notable research gap. Additionally, quality and safety aspects are absent from Finland's PtX research. Material and raw material research could be expanded from renewable hydrogen production to carbon dioxide capture and hydrogen, including aspects like embrittlement, transportation, and storage

Summary

Finnish PtX research has developed greatly in recent years, although challenges remain to address. International cooperation plays an important part in improving the efficiency of research. Furthermore, collaboration between domestic research organizations and across different disciplines should be encouraged. Research results may also be used as a basis for national and international comparison, as well as to support the development of PtX technologies and PtX economy globally.

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