Hydrogen in the Green Transition

SCIENCE SHEET

A snapshot of a phenomenon
and its societal significance

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JANE AND AATOS
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THE SCIENCE SHEET is a situation analysis of the phenomenon and its societal meaning. It is based on scientists' expertise and it is compiled for the policy-makers.

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1. WHAT IS HYDROGEN?

Hydrogen is the most common and the lightest element in the universe. Elsewhere in the universe, hydrogen is often gas, but on earth, it can be found in liquid and solid state, mostly bound with other elements, such as oxygen and carbon.

Considering its mass, hydrogen is energy-intensive. The energy is released during combustion, that is when hydrogen reacts with oxygen. In addition, the reaction leads to water but no carbon dioxide emissions. Especially the lightness of hydrogen and its zero-emission production and usage possibilities provide new insights in the context of the green transition and the energy transition.

However, separating hydrogen from compounds containing hydrogen is laborious. So, hydrogen as such is not an energy source, but also the production of hydrogen requires energy. The climate effect of hydrogen depends particularly on the method hydrogen is produced.

How is hydrogen produced?

Currently, hydrogen is produced in Finland and globally mainly with fossil fuels and fuels produced from fossil sources, but increasingly also with wind and solar power, where it is considered as clean hydrogen.

In Finland, hydrogen is mainly produced from natural gas. Hydrogen produced from natural gas can be low in emission, if the carbon dioxide produced during the production is sufficiently recovered and the production and the supply chains are low in emission.

In the future, small amounts of hydrogen can be produced also from other raw materials, such as biomass and industrial side streams. Clean, non-fossil hydrogen can also be produced from water consisting of hydrogen and oxygen atoms. In an electrolysis unit, water can be resolved down in elements, that is hydrogen and oxygen, by using electric power.

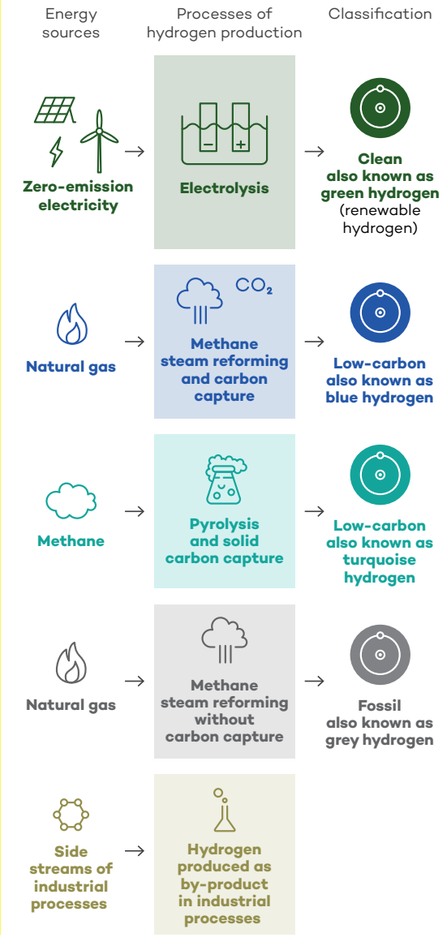
The International Energy Agency IEA estimates that in 2050, approximately three quarters of all clean and low-emission hydrogen will be produced by electrolysis.

The main challenge related to electrolysis is that it requires a high amount of electricity. Water-to-hydrogen conversion's coefficient of efficiency is over 65%. The number describes how much recoverable energy is produced comparing to the energy that is used to produce hydrogen.

Even though the basic idea of electrolysis is not new, remarkable potential is seen in the technical development of electrolysis units. The expectations focus particularly on the units' increasing mass production, which could significantly decrease the investment costs of hydrogen production. This is fundamental for the economic implementation of hydrogen production.

Producing hydrogen by electrolysis is an important sub-process when different chemical compounds, such as synthetic fuels, are produced with electrical energy. This production method is generally called "power-to-x technology", as it changes electric energy to another form x. For example, combining hydrogen and carbon dioxide in synthesis, synthetic methanol is produced, and it can be used as raw material for traffic or industry. This synthetic process further decreases the efficiency of energy consumption.

Here is how hydrogen is produced from various energy sources



2. WHAT DOES HYDROGEN ECONOMY MEAN AND WHY DO WE TALK ABOUT IT?

Currently, when hydrogen economy is being discussed, references are made to a large-scale usage of hydrogen as a part of the transition in the energy system. The decreasing production costs of renewable electricity and the need to withdraw from fossil economy have raised interest in using clean hydrogen.

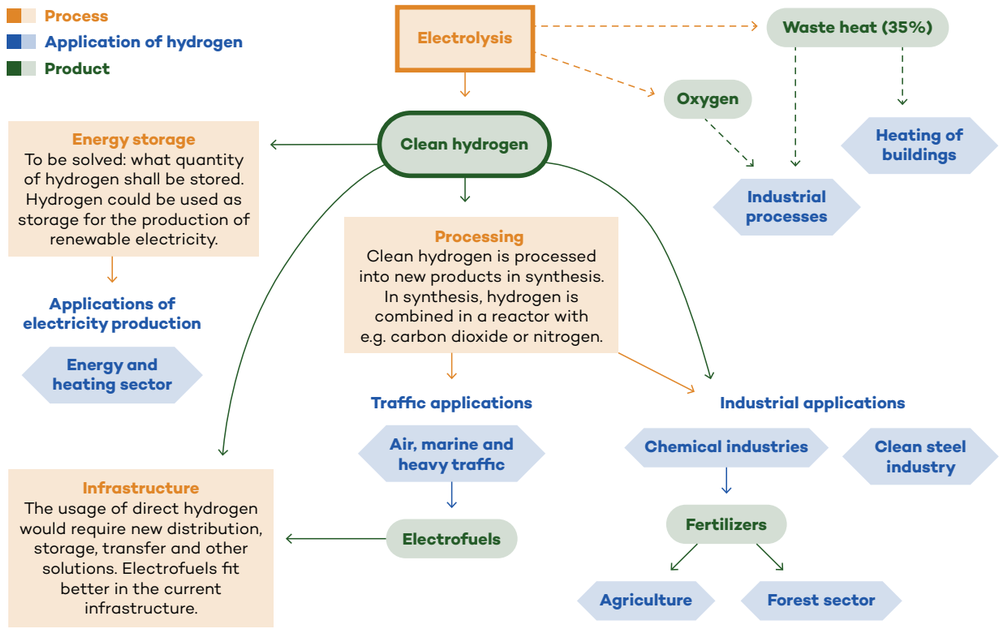
The carbon dioxide emissions produced by the energy production and use can be decreased by replacing fossil fuels with electricity. Climate scenarios (IPCC, IEA) see hydrogen as one way to decrease carbon dioxide emissions as of the 2030s, when the global production of clean hydrogen by electrolysis is expected to increase significantly.

Hydrogen can be used to replace the use of fossil raw materials by indirect electrification. This implies that hydrogen produced by renewable electricity is processed into other assets or used to store electricity.

Hydrogen economy or hydrogen solutions?

- The use of hydrogen is part of a broader energy transition. Clean hydrogen is one of the enablers of the green energy transition.
- To talk of the hydrogen economy can entail a risk of seeing the usage possibilities of hydrogen broader than its potential actually is.
- Hydrogen has many divergent concrete applications which can also be referred to as hydrogen solutions.

Applications of clean hydrogen
Clean hydrogen produced by electrolysis* offers different solutions for many sectors. Also the side streams from the production need to be taken into account.



*In Finland, alternatives to electrolysis to produce clean hydrogen are being developed. One of these is the production of clean hydrogen from water by photocatalysis, the implementation of which requires long-term research and development.

The usage of hydrogen as starting material of fuel for industry is particularly interesting to sectors, in which withdrawal from fossil energy sources is difficult. In the prospective scenarios, industry, heavy road traffic, marine traffic and air traffic are highlighted as the applications of hydrogen and the derivatives thereof.

Expectations of the industry towards hydrogen are solutions that allow metals and various chemical compounds, such as methanol and ammonia, to be produced in a more low-carbon manner. They are used for example in the production of plastics and fertilizers or as fuels.

The potential demand for the usage of hydrogen derivatives in traffic is highest in air traffic and marine traffic. These applications require storing hydrogen on a large scale, but no such mature technology exists.

The transition in the energy system requires tighter connectivity between the energy usage sectors. Considering hydrogen, the sector integration could mean for example the following:

- Utilization of the waste heat produced in electrolysis in heat production
- Utilization of the oxygen produced in hydrogen production as industrial gas or as bleaching chemical for paper pulp industry
- Utilization of hydrogen production as regulating energy of electricity production: the temporary overproduction of electricity could be stored as hydrogen or in its carriers.

The production of clean hydrogen is about to start in Finland

Finland aspires to be the pioneer in the production of clean hydrogen. According to the decision of principle of the Finnish Government, Finland is well placed to produce at least ten per cent of the zero emission hydrogen of the European Union by 2030.

Currently, approximately 99% of the hydrogen produced in Finland is produced from natural gas, i.e. methane, which creates a source of carbon dioxide emissions. To increase the production of clean hydrogen in Finland means aiming to replace hydrogen's natural gas production with carbon neutral patterns of production, such as wind power and solar power.

Several hydrogen production projects are planned in Finland. Some of the projects are still at the planning stage, whereas in some of the projects, an investment decision has been taken. From the viewpoint of projects in the pipeline, Finland's hydrogen economy has progressed rapidly, although in concrete terms, the production of clean hydrogen is only about to start.

Hydrogen to reinforce energy self-sufficiency?

Many factors affect the speed of the production and deployment of clean hydrogen. These include the rate of fossil fuels and electricity, the access to low-emission electricity, political solutions globally and indirectly e.g. Russia's war of aggression to Ukraine.

In Europe, the interest in clean hydrogen has increased particularly by the need to withdraw from Russian fossil energy.

The use of hydrogen is seen as an opportunity to increase energy self-sufficiency.

Building the energy system of the future on hydrogen might however create new dependencies, with respect to e.g. the further increasing need for the production of renewable electricity and access to critical raw materials.

Finland does not have a national hydrogen strategy

In Finland, there are less clean hydrogen production and investments compared to Sweden and Denmark. Contrary to Finland, even hydrogen valleys are built elsewhere in Europe. This means projects, in which multiple hydrogen applications are combined to cover the entire hydrogen value chain to form an integrated hydrogen ecosystem.

In European countries, the development of the clean hydrogen production is driven by a strong public support. In Germany, France and Italy, for example, public investments are several times higher compared to EU's significant inputs.

As regards to hydrogen technology, Finland relies largely on import. From the perspective of the national economy, Finland does not benefit from hydrogen production as much as it would be possible if there were Finnish actors in every sector of the hydrogen value chain. Importing high-level processed products, such as fossil-free steel and methanol, and manufacturing of electrolysis units could promote the competitiveness of Finnish hydrogen industry.

However, there is strong hydrogen knowhow in Finland. The demand of hydrogen specialists in the energy sector continues to grow, and there is a shortage of specialists in higher education and research institutions. For example, a pressing need has been identified for polytechnic-level application and installation expertise in the development of electrolysis production.

How does the European Union promote the hydrogen economy?

- EU's hydrogen strategy aims to achieve an annual production of 20 million tons of renewable hydrogen by 2030.
- In the EU states, the development of the hydrogen economy is driven by billions of euros in support to channel especially through the recovery plan NextGenerationEU.
- Hydrogen solutions are included in the European Green Deal programme and in the Fit for 55 legislative proposal package, which aims to speed up climate action.
- RePowerEU energy plan aims to decrease the dependency to Russia's fossil fuels rapidly and to speed up the carbon neutral energy transition.
- EU plans extra investments in creating the hydrogen market through European Hydrogen Bank, which is in preparation.

Finland's strengths in clean hydrogen production

◆ A good level of access to renewable energy and clean water has been reached
Particularly onshore wind power is cost-effective and high in growth potential in Finland. The production of hydrogen with electrolytic processes requires clean fresh water, the reserves of which benefit Finland.

◆ Research base and businesses have sound expertise
Finnish universities and research institutions have long been active in researching hydrogen and its use. There is also strong expertise in hydrogen production and processing in the businesses, with regards to the manufacturing technology of electrolysis units, among others.

◆ A functioning and a rule-based authorization system
As of 2023, Finland adopted a priority procedure to speed up the authorization process of hydrogen investments by offering them priority in the authorization procedure for a set period.

◆ Opportunities to further process hydrogen
Strong chemical industries, as well as knowhow in electrical engineering, energy technologies and chemical technologies and in assembly sector and electrochemistry promote the development of further processing clean hydrogen. Energy production generates large amounts of biogenic carbon dioxide that can be utilized as raw material for power-to-x processes.

The development of the legislation supporting the production of clean hydrogen

December 2019
The European Green Deal is published

2020
EU's hydrogen strategy is published

2020
National hydrogen strategies in Germany and Norway

June 2021
EU's recovery plan is adopted. Through the plan, hydrogen investments are being supported significantly

July 2021
Fit for 55 climate package is published

November 2021
National hydrogen and electrofuel strategy in Sweden

December 2021
The European Commission publishes a framework to promote the use of hydrogen and decarbonisation in the gas market as a part of the Fit for 55 climate package

December 2021
National hydrogen strategy in Denmark

December 2022
The European Union adopted the funding for REPowerEU energy plan, setting the goal for hydrogen's annual production

February 2023
The Finnish Government publishes its decision of principle on hydrogen

February 2023
The European Union specifies the definition of green hydrogen to include nuclear power (directive RED II)

The end of 2023
European Hydrogen Bank will be opened

2030
Finland aims to produce 10% of the clean hydrogen in the European Union

2019 — 2020 — 2021 — 2022 — 2023 — 2030

Hydrogen projects in Finland

2021
Finnish companies founded a national hydrogen cluster to speed up the development of hydrogen economy and the competitiveness of the businesses

2022
Substantial EU funding is granted to Neste's clean hydrogen production project

Autumn 2022
PX2 Solutions begins to build a production facility of clean hydrogen and synthetic methane in Harjavalta, Finland

2023
The estimated completion of Hycamite's pilot facility for low-carbon hydrogen in Kokkola, Finland

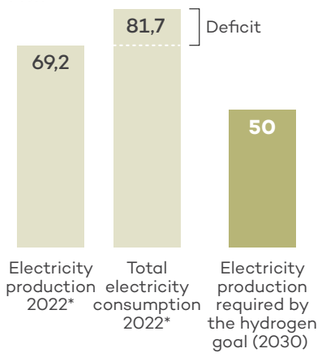
Spring 2024
The estimated launch of PX2's production facility for clean hydrogen

3. FOUR CENTRAL THEMES OF CLEAN HYDROGEN FOR FINLAND

1 National hydrogen goals require a rapid increase in the production of renewable electricity

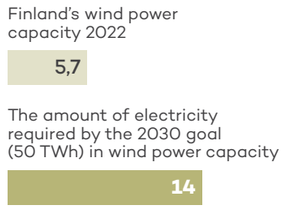
National clean hydrogen production goals require rapid and strong increase in zero emission electricity production. Using clean hydrogen in for example steel reducing would decrease carbon dioxide emissions significantly, but at the same time the demand for electricity would increase over tenfold. Potential solutions can be found in additions in wind power and solar power. From the viewpoint of hydrogen production, the construction of nuclear power is expensive and slow.

Proportions of electricity demand
Finland's hydrogen goal would require an increase in the production of renewable electricity



*Anticipated numbers. Source: OSF

How much wind power would the hydrogen goal require?
Achieving Finland's 2030 goal by wind power would require a largely greater wind power capacity than today



watt-hour (Wh) = unit of energy, one watt of power for an hour
watt (W) = unit of power
Source: VTT and the Finnish Wind Power Association

Trend:
If the wish is to increase the production of renewable electricity, solutions are needed:

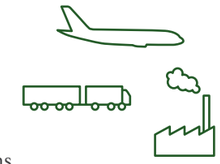
◆ To increase the number of wind power units
Regional targets for use must by law take the complete safety into account, particularly the needs of national defence and borders. Wind power projects are limited by the large restriction zones set by the Finnish Defence Forces for air-surveillance radars along Finland's eastern border. Unless the radar issue is solved, the number of onshore wind power units cannot in practice be increased in the western parts of the country, which affects the production potential of wind power. Additions in the offshore wind power require a decrease in the cost level and the development of the technology, but numerous projects are being planned. Additions in the production of renewable electricity could be enhanced by simplifying and accelerating the authorization processes and by investing in building transfer connections for electricity. When the share of alternating energy production grows, new solutions to store energy and to take care of a sufficient regulating energy are needed.

◆ To engage local communities sufficiently
The acceptance of wind power projects can be enhanced by strengthening the engagement of the local communities. To speed up the authorization processes for wind power investments, a priority procedure has been adopted in Finland. The risk is that local communities' engagement might become secondary and for example the possibilities to appeal might become weaker.

◆ To define the role of solar power
In theory, solar power can be scaled well to meet the growing demand for renewable electricity. However, strong annual variation in the production would make the solar-power-produced hydrogen significantly more expensive than that produced by wind power. For this reason, the industrial production of clean hydrogen cannot exclusively be based on solar power.

◆ The sustainability of the supply chains
For both wind and solar power, the construction shall consider the environmental load and the ethics of the supply chains. As the wind power production increases, solutions for the access of critical raw materials and recycling are needed. The production of solar power's raw material components is currently being concentrated in China, and human rights violations, such as forced labour, has been identified in the production processes.

2 The use of clean hydrogen requires development



The use of clean hydrogen in new industrial-scale applications requires solutions to many technological and production-related questions that are specific to each application. In Finland, new key applications for clean hydrogen could be fertilizer and steel production and electrofuels for traffic. Each application has their own challenges to solve.

Trend:
To use clean hydrogen in traffic, solutions are needed:

◆ To develop the direct and indirect electrification in parallel
The direct electrification of the traffic is currently happening rapidly. The challenge in the direct electrification of heavy private transports and freight transport however, is the vast amount of critical raw materials and minerals needed for the batteries. Hydrogen and the further processed synthetic fuels thereof could be part of the solution, which would, considering hydrogen, require developing the distribution network further alongside with the electric charging system. Hydrogen's use in traffic could also be developed for city-specific entities.

◆ To use hydrogen in air and marine traffic
The direct use of clean hydrogen in air and marine traffic would require significant structural development in hydrogen storage, transfer and refuelling technologies. Clean hydrogen could be further processed as kerosene for fuel in air traffic. In the marine traffic, ammonia and methanol processed from hydrogen could also be widely used.

Trend:
In order to use clean hydrogen widely in the industry, solutions are needed:

◆ To develop the production processes
Hydrogen reducing in steel production and power-to-x methods are examples of clean hydrogen applications still requiring technical development. Industrial demonstration projects are needed to ensure the functionality of new power-to-x methods in large size. The only difference in the production of methanol and ammonia is how the hydrogen and the carbon dioxide used in the process are sourced. The processes of steel production require significant changes in order to allow the use of clean hydrogen in them. It would be possible to implement new technology in industrial-scale applications in research, product development and demonstration projects requiring long-term funding.

◆ For storage problems
The use of hydrogen as raw material in for example steel and chemical industries requires consistent access to hydrogen, which is why new technological solutions to transfer and store hydrogen are needed. The most advanced experiments, such as the Swedish Hybrit project, are however still pilots and not yet for industrial production.

◆ To secure investments and research to strengthen hydrogen economy
The use of clean hydrogen widely in the Finnish industry requires readiness for risk-taking among the industrial actors. Investments in the downstream parts of the value chain, especially in the higher processed activity, would create a demand for the hydrogen production and processing. New hydrogen production processes, such as hydrogen's photocatalytic production from water, and hydrogen storage and further processing require constant inputs in the research.

3 The benefits of hydrogen economy are unevenly distributed

The access to renewable electricity drives regional investments in hydrogen infrastructure and industry. In Finland, the production of renewable electricity is being concentrated particularly in the western parts of the country and in Lapland because of the restriction zones set by the Finnish Defence Forces for the air-surveillance radars. The first clean hydrogen value chains are most likely to be created especially in the Bothnian Bay area.

Trend:

When the hydrogen economy is geographically centralized, solutions are needed:

◆ To support the equitable development of the regions
The geographical centralization of clean hydrogen's value chains can lead to the pile-up of the benefits of the hydrogen economy. Minimizing the negative impacts of the development requires that the regions' different starting points and local needs are taken into account.

◆ To develop decentralized energy solutions
The uneven centralization of hydrogen production can be alleviated by supporting local energy solutions. In some parts of Finland, the production could base on the use of wood or other biomass or on solar power and small nuclear plants. The promotion of bio-based raw materials can on the other hand increase the demand of domestic wood and intensify the logging pressure. In addition, the costs of bio-based raw materials most probably drive the hydrogen production towards solar power and wind power production.

4 Hydrogen production must be assessed in the context of natural resources and environmental sustainability

Hydrogen production requires plenty of energy with the current methods. Some clean hydrogen solutions, such as the indirect electrification of the traffic, have poor cost-benefit ration in terms of energy consumption. At the same time, the EU's energy efficiency goals oblige Finland to decrease its energy consumption significantly by 2030. In addition, the production of clean hydrogen requires several critical raw materials which are of great economic importance but also challenging to access.

Trend:

In the context of sustainability, solutions are needed:

◆ For adequacy and availability of critical raw materials
In the technologies of hydrogen economy, many critical and strategic raw materials, such as rare earth metals, are used. The most accessible of the electrolysis processes (PEM) is based on the use of rare platinum group metals, which are finite natural resources. There are also geopolitical challenges concerning the availability and supply chains of critical raw materials. Also the environmental and societal impacts of the supply chains need to be looked at in their entirety.

◆ To put hydrogen production in proportion as a part of the transition in the energy system
Hydrogen and its secondary products can be a useful part of the method range of the green transition, but they alone are not an adequate solution to the challenges of the transition in the energy system and the green transition. Aiming for a hydrogen economy that is too broadly sized can even slow down the withdrawal from fossil fuels, if the availability of hydrogen or electrofuels remains lower than the set goals or if there is a shortage of low-emission electricity available.

◆ To integrate circular economy with hydrogen production
20-30% of the energy used in hydrogen production is lost as waste heat that could be utilized in district heating network, e.g. in the heating of buildings and in industrial use. The oxygen generated in hydrogen's production process can in turn be utilized in industrial processes. When increasing hydrogen production, it is important to integrate the production energy with the system as a whole.

◆ For the land-use changes caused by hydrogen production
Replacing fossil fuels with hydrogen and its secondary products changes the land use, which has impacts on the functioning of the local ecosystems. Studies have shown for example that the extractive industry ensuring the availability of the critical raw materials and large wind parks have a negative impact on biodiversity.

4. THE GOVERNMENT'S ROLE IN THE DEVELOPMENT

At EU-level, Finland is committed to many agreements and regulations considering hydrogen production, processing and use. These agreements and regulations form the framework for the development of hydrogen economy. National instruments can in turn be used to strengthen the incentive of the environment.

The production of clean hydrogen and the development of the market can be promoted by legislation supporting the development and implementation of new solutions and ensuring the safety of the projects. For example, when developing the future regulation of locating the hydrogen storages, it would be good to carry out discussion of the appropriate extent of the catchment areas. Directive-based hydrogen use could in turn be aimed to secure the cash flow of the investing companies.

Hydrogen knowhow can be strengthened by investing in continuous learning, particularly considering further training for people working in energy, electricity and chemical technology. Knowledge can be intensified also with national training projects and by increasing the number training places in vocational schools, polytechnics and universities. By investing in research, development and innovation, strong networks between companies, universities and research institutions can be supported, while promoting the technological development of clean hydrogen applications.

We need societal dialogue about the importance of clean hydrogen

The benefits, risks and general societal impacts of hydrogen production involve many value judgements, which in turn are closely connected with the role the government takes during the development. Societal discussion would be good to take place for example about the following subjects:

- In Europe, a significant amount of public support is directed towards hydrogen economy. Experts argue about whether this is efficient in the context of the green transition comparing to targeting the public support for example in general development and implementation of clean energy.
- Clean hydrogen raises new kinds of questions in the context of sustainability. In hydrogen production, the environmental load is focused on the upstream parts of the supply chain, geographically likely very far from the application sites. For this reason, the sustainability and the carbon neutrality of the production shall be assessed overall.

We need a more shared understanding of clean hydrogen's role as a part of a broader transition in the energy system and withdrawal from fossil economy.

To establish dialogue, the government could bring together actors to discuss the strategic orientation of the development and the importance of hydrogen. This would provide an opportunity to establish a shared understanding among the policy-makers, the industry and the research community about the importance of clean hydrogen in Finnish society.

LITERATURE

Carrara S, Bobba S, Blagoeva D, Alves Dias P, Cavalli A, Georgitzikis K, Grohol M, Itul A, Kuzov T, Latunussa C, Lyons L, Malano G, Maury T, Prior Arce Á, Somers J, Telsnig T, Veeh C, Wittmer D, Black C, Pennington D, Christou M (2,023). ***Supply chain analysis and material demand forecast in strategic technologies and sectors in the EU – A foresight study***. Office of the European Union: Luxembourg.

European Commission (2020). ***Communication from the Commission to the European Parliament, the European Council, the European Economic and Social Committee and the Committee of the Regions: A hydrogen strategy for a climate-neutral Europe COM(2020)301 final***. 8 July 2020.

European Commission (2023a). ***Communication on the European Hydrogen Bank (COM(2023)156)***. 16 March 2023.

European Commission (2023b). ***Regulation of the European Parliament and of the Council establishing a framework for ensuring a secure and sustainable supply of critical raw materials and amending Regulations (EU) 168/2013, (EU) 2018/858, 2018/1724 and (EU) 2019/1020***. Brussels, 16 March 2023. COM(2,023) 160 final, 2023/0079 (COD).

Huhta R, Heininen A, Mäntynen J & Pajarre M (2023). ***Report on hydrogen-powered aviation. Potential uses of hydrogen as an energy source in aviation and the role of hydrogen-powered aviation in the transport system***. Traficom Research Reports 2/2023 Finnish Transport and Communications Agency Traficom.

Intergovernmental Panel on Climate Change IPCC (2022). 'Summary for Policymakers', Teoksessa Shukla P R, Skea J, Slade R, Al Khourdajie A, van Diemen R, McCollum D, Pathak M, Some S, Vyas P, Fradera R, Belkacemi M, Hasija A, Lisboa G, Luz S & Malley J, (Ed.). ***Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change***. Cambridge University Press, Cambridge, UK and New York, NY, USA.

International Energy Agency, IEA (2019). ***The Future of Hydrogen: Seizing Today's Opportunities***. OECD: Paris.

International Energy Agency, IEA (2022). ***World Energy Outlook 2022***. International Energy Agency: Paris.

Räty, A. (2023). ***Itäisen Suomen tuulivoimarakentamisen tehostaminen***. Rapporteur Arto Räty's report. 15 March 2023.

Sivill L, Bröckl M, Semkin N, Ruismäki A, Pilpola H, Laukkanen O, Lehtinen H, Takamäki S, Vasara P, & Patronen J (2022). ***Hydrogen economy – Opportunities and limitations***. Publications of the Government's Analysis, Assessment and Research Activities 2022: 21.

Official Statistics of Finland (OSF). ***Energy supply and consumption***. Helsinki: Statistics Finland.

Finnish Wind Power Association (2023). ***Tuulivoimalat Suomessa: Toiminnassa olevat ja puretut voimalat***.

Ueckerdt F, Bauer C, Dirnaichner A, Everall J, Sacchi R, Luderer G (2021). ***Potential and risks of hydrogen-based e-fuels in climate change mitigation***. Nature Climate Change 11, 384-393.

Finnish Government (2023). ***Valtioneuvoston periaatepäätös TEM/2023/14***. 9 February 2023.

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