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The role of hydrogen and electrofuels in implementing the carbon neutrality targets of the Finnish energy system and their integration into national statistics

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Enni Sanasvuori

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Author Enni Sanasvuori

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Thesis supervisor Prof. Risto Lahdelma

Thesis advisor Ville Maljanen, MSc

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Abstract

According to the Intergovernmental Panel on Climate Change (IPCC), global carbon neutrality should be achieved around 2050 to stop global warming from exceeding 2 degrees Celsius. The European Commission has set a goal to reduce emissions by at least 55 % (compared to 1990 levels) by 2030, and to reach climate neutrality by 2050.

Low-carbon or carbon neutral hydrogen can be produced from water and renewable electricity, biomass, or fossil sources utilising Carbon Capture and Storage (CCS). It can be combusted directly for energy, converted into electricity using fuel cells, or combined with carbon and other compounds to produce other fuels (electrofuels) and chemicals. Hydrogen could also be used to store renewable electricity in chemical form at times of high supply and low demand.

A hydrogen strategy for the European Union (EU) was adopted in 2020. The strategy emphasises hydrogen's role as a key element in achieving the goals of the European Green Deal. Hydrogen was also included into the amended energy statistics regulation framework in 2022 as a new energy product of which data reporting will become a legal obligation in the EU.

The objective of this thesis is to conduct a literature review on hydrogen production technologies, storage and distribution methods, and applications, as well as to develop a new national data collection for hydrogen data, so that the new statutory reporting requirements can be fulfilled. In addition, the current situation and future potential of the hydrogen industry in Finland are researched.

It was found out that Finland could produce enough renewable hydrogen and/or electrofuels to cover domestic demand and in addition produce enough for export, due to renewable wind power potential and abundant freshwater resources. However, the hydrogen field is at a very initial stage of development and is highly uncertain to what extent it will develop. The new data collection survey form enables production of new hydrogen statistics to aid public decision making and research on the current state of hydrogen production and consumption in Finland.

Keywords hydrogen, power-to-x, national statistics, carbon neutrality, energy transition, synthetic fuels, electrofuels

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Aalto University

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Tiivistelmä

Hallitustenvälisen ilmastonmuutospaneelin (IPCC) mukaan globaali hiilineutraalius tulisi saavuttaa vuoteen 2050 mennessä, jotta ilmaston lämpeneminen ei ylittäisi kahta celsiusastetta. Euroopan komissio on asettanut tavoitteekseen vähentää EU:n päästöjä vähintään 55 % (verrattuna vuoden 1990 tasoon) vuoteen 2030 mennessä ja saavuttaa ilmastoneutraalius vuoteen 2050 mennessä.

Vähähiilistä tai hiilineutraalia vetyä voidaan tuottaa vedestä ja uusiutuvasta sähköstä, biomassasta tai hiilidioksidin talteenottoa ja varastointia (CCS) hyödyntäen fossiilisista lähteistä. Vety voidaan polttaa ja hyödyntää suoraan energiana tai muuntaa sen sisältämä energia sähköksi polttokennossa. Vety on mahdollista myös syntetisoida hiilen tai muiden yhdisteiden avulla muiksi polttoaineiksi tai kemikaaleiksi. Vetyä voitaisiin myös käyttää uusiutuvan sähkön varastoimiseen kemiallisessa muodossa.

Euroopan unionin vetystrategia julkaistiin vuonna 2020. Strategiassa korostetaan vedyn roolia keskeisenä elementtinä Euroopan vihreän kehityksen ohjelman tavoitteiden saavuttamisessa. Energiatilastoasetuksen päivityksen yhteydessä 2022 vety liitettiin osaksi energiatilastokehystä uutena energiatuotteena, josta tietojen raportoiminen tulee EU:n jäsenmaille lakisääteiseksi tehtäväksi.

Tässä diplomityössä tehdään kirjallisuuskatsaus vedyn tuotantotekniikoista, varastointi- ja jakelumenetelmistä ja sovelluksista, sekä kehitetään uusi kansallisen tason tiedonkeruu vedylle uusien lakisääteisten raportointivaatimuksien toteuttamiseksi. Lisäksi työssä selvitetään Suomen vetyteollisuuden nykytilannetta ja tulevaisuuden potentiaalia.

Työssä saatiin selville, että Suomen tuulivoimapotentiaalin ja runsaiden vesivarojen ansiosta Suomella olisi mahdollisuus tuottaa riittävästi vetyä ja/tai sähköpolttoaineita kotimaisen kysynnän kattamisen lisäksi vientiin. Vetytalous on kuitenkin vielä hyvin alkuvaiheessa ja sen kehittyminen epävarmaa. Uusi tiedonkeruu mahdollistaa uusien vetytilastojen laatimisen, mikä puolestaan mahdollistaa uusien tietojen tuottamisen yhteiskunnalle, tutkijoille ja päätöksentekijöille julkisen päätöksenteon ja vedyn tuotannon ja kulutuksen nykytilan tarkemmaksi selvittämiseksi.

Avainsanat vety, power-to-x, kansallinen tilastointi, hiilinteuraalius, energiasiirtymä, synteettiset polttoaineet, sähköpolttoaineet

Contents

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Espoo, 22 October 2022
Enni Sanasvuori

Abbreviations

AEL	Alkaline Electrolysis
ATR	Autothermal Reforming
BAU	Business As Usual
BEV	Battery Electric Vehicle
CC	Carbon Capture
CCS	Carbon Capture and Storage
CCUS	Carbon Capture Utilisation and Storage
CHP	Combined Heat and Power
DAC	Direct Air Capture
DRFC	Discrete Regenerative Fuel Cell
DTL	Direct Transmission Line
EEA	European Environment Agency
E-fuels	Electrofuels
EHB	European Hydrogen Backbone
ESI	Energy Strategy Integration
EU	European Union
FC	Fuel Cell
FCEV	Fuel Cell Electric Vehicle
GHG	Greenhouse Gas
HTEL	High Temperature Electrolysis
ICE	Internal Combustion Engine
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
LOHC	Liquid Organic Hydrogen Carrier
NACE	Nomenclature statistique des activités économiques dans la Communauté européenne
PEM	Proton Exchange Membrane
POX	Partial Oxdiation
P2G	Power-to-Gas
P2L	Power-to-Liquid
P2X	Power-to-X
RFC	Regenerative Fuel Cell
RFNBO	Renewable Fuels of Non-Biological Origin
SOEC	Solid Oxide Electrolysis
SR	Steam Reforming
UN	United Nations
UNECE	United Nations Economic Commission for Europe
URFC	Unitised Regenerative Fuel Cell
WGS	Water Gas Shift

1 Introduction

To prevent the worst climate change scenarios from becoming a reality and to stop the global mean temperature from rising above 2 degrees Celsius, the Paris Agreement was signed in 2015 by 196 countries (European Commission, 2022a). Stopping global warming at 1.5 or 2 degrees Celsius, according to the Intergovernmental Panel on Climate Change (IPCC) requires that global carbon neutrality (net zero) should be reached around 2050 (IPCC, 2018a). Thus, the European Commission has adopted as its official target to reach climate neutrality by 2050 (European Commission, 2022b).

Reaching these goals requires technological and social changes across all sectors of the economy, but since about 75 % of all anthropogenic Greenhouse Gas (GHG) emissions are caused by the energy sector, fuel combustion, and transportation, the decarbonisation of the entire energy system is at the core of reaching these goals (EEA, 2022).

Renewable hydrogen (H_2) as a potential and versatile fuel has become the subject of high academic and political interest, the direct use of which could be used to decarbonise especially certain hard-to-electrify sectors, such as heavy-duty truck transport, maritime transport, aviation or some carbon intensive industrial processes such as steel production (IEA, 2021b). In addition to the direct use of hydrogen, using Power-to-X -technologies (P2X) hydrogen could be further transformed to other low-carbon or carbon neutral energy products and raw material chemicals, or used to store renewable electricity in chemical form at times of high supply and low demand (European Commission, 2020a). However, largely due to the properties of hydrogen, the widespread adoption of hydrogen technologies requires extensive investments in new infrastructure.

The current energy crisis in Europe stems from Russia cutting its natural gas supplies to Europe. It remains to be seen if the energy crisis will result in such a change in the public perception of energy sources, that growing demand for energy security lead to faster adoption of renewable energy sources and new technologies to phase out Russian gas. Osička and Černoch (2022) state aptly that “Rather paradoxically, the Russians have managed to make natural gas what renewable energy used to be: expensive and unreliable“ (Osička and Černoch, 2022).

Official national statistics are used to monitor politically set official targets, and the 2022 amended energy statistics regulation (2022/132) is aimed at national statistics being able to support the monitoring of measures of the European Green Deal. It adds hydrogen into the list of existing energy products, of which data will need to be annually reported to Eurostat, the statistical authority of the European Union.

This thesis is conducted for Statistics Finland. The goal of the thesis is to prepare for the upcoming statutory national hydrogen reporting by planning how the required data should be collected so that the reporting can be done

(chapter 5). Generic Statistical Business Process Model (GSBPM) is used to support the planning of the new data collection (chapter 5). The scope of the thesis does not include the planning of how the collected data will be analysed, aggregated, or publicised. A challenge regarding this work is that the final reporting hydrogen questionnaire, its full definitions and filling instructions have not yet been finalized. For this reason, a hydrogen questionnaire draft provided by Eurostat (attachment A) at the time of writing is used.

Since the amended energy statistics regulation (regulation 2022/132) includes only hydrogen as a new mandatory fuel to be included into the energy statistics framework, this thesis focuses on hydrogen. However, it is possible that other new fuels with a strong connection to hydrogen will be added to the scope later. For this reason, P2X fuels in general are included in the scope and briefly discussed as well.

The most relevant policy context and terminology will be presented in chapter 2, and a literature review on the most important currently used and potential future production technologies, storage and distribution methods, and applications for hydrogen is conducted (chapter 3). The literature review focuses on research published in recent years, as information can quickly become outdated with emerging and maturing technologies. The aim of the literature review is to support the production of completely new statistics by providing background information on the current state and prospects of the hydrogen field.

Chapter 4 focuses on Finland to provide further background information to aid the design of new national statistics. The aim of chapter 4 is to form an image of the potential role of hydrogen in Finland. This is done by compiling the main results of studies conducted so far about the hydrogen economy in Finland. Chapter 4 also aims to discover how much hydrogen is currently produced and consumed in Finland based on publicly available information.

2 Policy context and terminology

The terminology, legislation, and regulations related to the hydrogen industry and P2X are currently in the process of being written and thus, the policy context is changing rapidly (Prime Minister's Office, 2022). This chapter expands on the introduction by presenting more context information of the field from the policy perspective and defines important terminology used in this thesis.

At present on the European Union (EU) level the most important policy documents related to hydrogen and P2X are: The Paris Agreement (UN, 2015), European Green Deal (European Commission, 2019), EU hydrogen (European Commission, 2020a) and energy system integration (European Commission, 2020b) strategies, the fit-for-55 package (European Commission, 2021a), hydrogen and gas markets decarbonisation package (European Commission, 2021b) and the revised Renewable Energy Directive (directive 2018/2001).

On a national level, the regulations and directives related to these documents will be transposed into Finnish legislation. Finland has not published its own national hydrogen strategy. However, it is currently being prepared as a part of a yet unpublished climate and energy strategy (Prime Minister's Office, 2022). Business Finland (2020) has published a national hydrogen roadmap for Finland, but this is not an official legislative document.

At the Paris Climate Conference in 2015, 196 countries including the EU agreed to limit global warming to below 2 and preferably below 1.5 degrees Celsius compared to pre-industrial levels (UNFCCC, 2022; European Commission, 2022a). Following this, the European Green Deal was released in 2019, which is a package of measures in which EU set a goal to be the world's first climate neutral continent by reaching net-zero GHG emissions by 2050 (European Commission, 2022c; European Commission, 2022d). The European Commission refers to this as "achieving climate neutrality". This target has been written into the European Climate Law (regulation 2021/1119) and is thus legally binding. The intermediate target of reducing GHG emissions by at least 55 % by 2030 is also set in this law (European Commission, 2022e).

According to modelled pathways by IPCC preventing the 2 °C increase requires the world to reach net zero carbon dioxide (CO_2) emissions around 2070 and preventing the 1.5 °C increase means global net zero carbon dioxide emissions should be reached around 2050, while non-carbon dioxide emissions also need to be radically decreased (IPCC, 2018a). IPCC's definition for net zero carbon dioxide emissions is given as: "Net zero carbon dioxide emissions are achieved when anthropogenic carbon dioxide emissions are balanced globally by anthropogenic carbon dioxide removals over a specified period. Net zero carbon dioxide emissions are also referred to as carbon neutrality." (IPCC, 2018b).

It is important to note that “net zero carbon dioxide emissions” is a different term from “net zero emissions” that refers to climatic neutrality of all anthropogenic GHGs and not only carbon dioxide: “Net zero emissions are achieved when anthropogenic emissions of greenhouse gases to the atmosphere are balanced by anthropogenic removals over a specified period. Where multiple greenhouse gases are involved, the quantification of net zero emissions depends on the climate metric chosen to compare emissions of different gases (such as global warming potential, global temperature change potential, and others, as well as the chosen time horizon).” (IPCC, 2018b). The target of EU is to reach net zero emissions (climate neutrality) by 2050, not just carbon neutrality (European Council, 2022).

The energy system integration strategy (European Commission, 2020b) was published alongside the hydrogen strategy (European Commission, 2020a) for the EU. In the ESI strategy (European Commission, 2020b), the use of hydrogen is emphasised especially for sectors which are hard to decarbonise or electrify, such as buses and heavy-duty road transport, non-electrified rail and maritime transport and refining, steel and the chemical industries. Priority is placed on developing production of hydrogen using renewable electricity, while low-carbon hydrogen (see Table 1) is mentioned to be required during the transitional phase to kick-start economies of scale.

Energy System Integration (ESI), sometimes also referred to as energy sector coupling, refers to the linking of different energy sectors in a more interconnected manner, considering both the supply and user sides of the economy, across multiple different energy carriers. It is seen as an important step in building a more efficient, affordable, and climate-friendly energy system (European Commission, 2020b). The overall goal of ESI is to increase flexibility and integration between different modes of production of energy and different uses of energy, utilising the different components of ESI which according to European Commission (2020b), include electrification, smart grids and meters, flexibility markets, digitalisation and hydrogen. The ESI strategy (European Commission, 2020b) for EU outlines an action plan for improving the integration of the energy system.

The European Commission (2020b) defines three different aspects to be a part of its ESI Strategy for the upcoming five-to-ten-years and beyond: developing a more circular energy system, greater direct electrification of end-use sectors, and the use of renewable and low-carbon fuels (including hydrogen) on those end-use applications where direct electrification is not feasible. A more circular energy system refers to a system in which the most energy efficient technologies are prioritised, waste streams are reused, and cross-sectoral synergies taken advantage of. Better utilisation of Combined Heat and Power (CHP), reuse of waste heat from e.g. data centers and industrial processes, and energy produced from bio-waste are mentioned (European Commission 2020b) as associated examples.

Renewable and low-carbon liquid and gaseous fuels (including hydrogen) are mentioned (European Commission 2020b) to provide energy solutions for applications which cannot be feasibly or efficiently electrified. These fuels are thus seen as enablers for ESI, because using them synergies between electricity, gas and end-use sectors can be taken advantage of (European Commission 2020b). The diagram in figure 1 presents the different sectors of ESI and aims to describe how, for example hydrogen, is seen as part of the different sectors of ESI supporting their deeper integration.

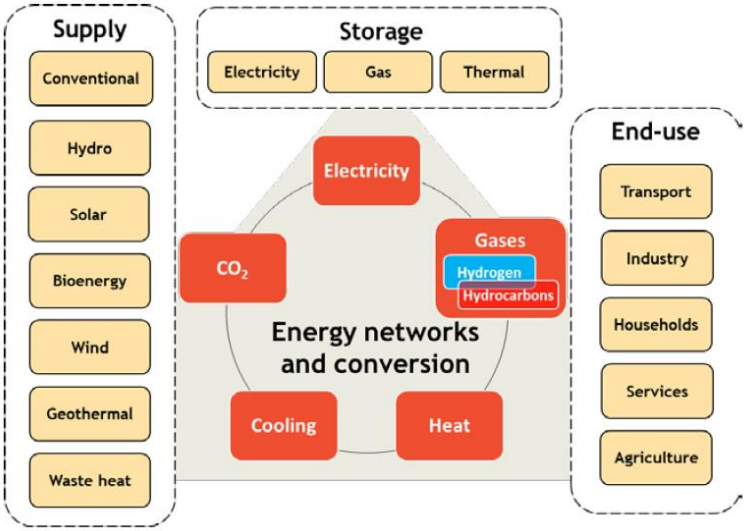


Figure 1: Schematic of energy system sectors' coupling (European Parliament, 2018).

The hydrogen strategy (European Commission, 2020a) envisions how clean hydrogen can be utilised in the EU to decarbonise different sectors. A legally non-binding goal of installing 6 GW of renewable hydrogen (see table 1) electrolysers by 2024 and 40 GW by 2030 is set. The strategy also lists some important hydrogen terminology which are also used in this thesis and compiled into table 1. More information about the production technologies referred in table 1, such as reforming or gasification, can be found in chapter 3.2. Hydrogen-derived synthetic fuels (table 1) can be referred to as Power-to-Gas (P2G), Power-to-Liquids (P2L) -fuels or electrofuels (e-fuels) (Brynolf et al., 2018). The term "e-fuels" is adopted in this thesis.

Table 1: Hydrogen terms and their definitions (adapted from European Commission, 2020a).

Term	Definition
Electricity-based hydrogen	Refers to hydrogen produced through the electrolysis of water (in an electrolyser, powered by electricity), regardless of the

	electricity source. The full life-cycle GHG emissions of the production of electricity-based hydrogen depends on how the electricity is produced.
Renewable hydrogen	Hydrogen produced through the electrolysis of water (in an electrolyser, powered by electricity), and with the electricity stemming from renewable sources. The full life-cycle GHG emissions of the production of renewable hydrogen are close to zero. Renewable hydrogen may also be produced through the reforming of biogas (instead of natural gas) or biochemical conversion of biomass, if in compliance with sustainability requirements.
Clean hydrogen	Refers to renewable hydrogen.
Fossil-based hydrogen	Refers to hydrogen produced through a variety of processes using fossil fuels as feedstock, mainly the reforming of natural gas or the gasification of coal. This represents the bulk of hydrogen produced today. The life-cycle GHG emissions of the production of fossil-based hydrogen are high.
Fossil-based hydrogen with carbon capture	Subpart of fossil-based hydrogen, but where GHG emitted as part of the hydrogen production process are captured. The GHG emissions of the production of fossil-based hydrogen with carbon capture or pyrolysis are lower than for fossil-fuel based hydrogen, but the variable effectiveness of GHG capture (maximum 90 %) needs to be taken into account.
Low-carbon hydrogen	Encompasses fossil-based hydrogen with carbon capture and electricity-based hydrogen, with significantly reduced full life-cycle GHG emissions compared to existing hydrogen production.
Hydrogen-derived synthetic fuels	Refers to a variety of gaseous and liquid fuels on the basis of hydrogen and carbon. For synthetic fuels to be considered renewable, the hydrogen part of the syngas should be renewable. Synthetic fuels include for instance synthetic kerosene in aviation, synthetic diesel for cars, and various molecules used in the production of chemicals and fertilisers. Synthetic fuels can be associated with very different levels of GHG emissions depending on the feedstock and process used. In terms of air pollution, burning synthetic fuels produces similar levels of air pollutant emissions than fossil fuels.

Carbon capture in table 1 refers to a group of technologies which are used to capture carbon dioxide emitted from point sources or directly from air using Direct Air Capture (DAC) (Osman et al., 2020). Carbon Capture Utilisation and Storage (CCUS) comprises of Carbon Capture and Storage (CCS) and Carbon Capture and Utilisation (CCU) – terms which are sometimes used independently. CCS is used to refer to long term underground storage of the captured carbon, while CCU refers to utilisation of the captured carbon, where the carbon is converted to some other commercial product (Wang and Oko, 2017).

Hydrogen colour terms presented in table 2 are sometimes used when referring to hydrogen produced from a specific source or by using certain technology. The definitions are not yet clearly defined and may vary between different sources, for example yellow hydrogen is sometimes used to refer to hydrogen produced via water electrolysis powered by grid or solar electricity.

Table 2 adopts the definitions given by Ustolin et al. (2022) and presents a carbon footrprint range for each colour of hydrogen. The carbon footprints are given in kilograms of carbon dioxide equivalent per produced kilogram of hydrogen (kg_{CO_2}/kg_{H_2}) to give an estimation on the global warming potential for the different hydrogen production routes (Ustolin et al., 2022). However, International Energy Agency (IEA) does not recommend the use of the colour terms (IEA, 2021b) because they deem them to be overly simplified, as they may not reliably describe the true environmental impacts of the produced hydrogen because of geographical variations in production conditions, different reactor technology set-ups and due to the multitude of different possible energy sources which can be used. Ustolin et al. (2022) also emphasises that assessing the carbon footprint is challenging as it is strongly dependent on the initial assumptions made, and as can be seen especially the carbon footprint value for blue hydrogen varies considerably from 2.6 kg_{CO_2}/kg_{H_2} to 16.2 kg_{CO_2}/kg_{H_2}.

Table 2: Table presenting the common definitions used when referring to coloured hydrogen (adapted from Ustolin et al., 2022).

Colour of hydrogen	Definition	Carbon footprint (kg_{CO_2}/kg_{H_2})
Black or brown	Hydrogen produced from black (bituminous) or brown coal (lignite).	21.8 – 51.9
Gray	Hydrogen produced from methane (natural gas) with steam reforming without CCUS.	10.9 – 18.4
Blue	Gray hydrogen coupled with Carbon Capture Utilisation and Storage (CCUS) technology.	2.6 – 16.2
Turquoise	Hydrogen produced using methane cracking/pyrolysis.	4.4
Green	Hydrogen produced using water electrolysis and renewable electricity.	0.63 – 6.6
Yellow	Water electrolysis using grid electricity.	28.6 – 32.0
Purple, pink, red	Hydrogen produced using nuclear energy: purple (electricity), pink (thermal + electric energy, red (thermal energy)	2.0 (purple), 0.4 – 2.0 (pink), 0.3 – 1.8 (red)

In the decarbonisation of gases -package published in December of 2021, a new organisation called the European Network of Network Operators for Hydrogen (ENNOH) is introduced. The role of ENNOH is to develop and manage transboundary hydrogen infrastructure and trade in the EU (Prime Minister's Office, 2022). In this package low-carbon gases are defined as gases that "produce at least 70% less greenhouse gas emissions than fossil natural gas across their full lifecycle" and renewable gases "are gases produced from biomass including biomethane, as well as hydrogen produced from renewable sources" (European Commission, 2021c).

The fit-for-55 package (European Commission, 2021a) proposes that the current Emissions Trading System is to be expanded to new sectors (maritime and road transport) and free allowances gradually removed from the system. Facilities producing renewable and low-carbon hydrogen could receive free emissions allowances. The proposals included in the package need to still be approved by the European Parliament and are thus still subject to changes (Prime Minister's Office, 2022; European Commission, 2021d).

According to European Commission (2021d) stricter average emission limits for new cars are defined (55 % reduction by 2030 and 100 % by 2035 compared to the level at 2021), a requirement for Member States to build hydrogen refueling stations for every 150 km and electricity charging stations every 60 km, and an Alternative Fuels Infrastructure Regulation including multiple targets for renewable and Renewable Fuels of Non-Biological Origin (RFNBO) in transportation are proposed. RFNBOs include hydrogen and e-fuels (European Commission, 2021d).

In relation to energy statistics, the amended energy statistics regulation (regulation 2022/132) entered into force in February 2022. It defines the common framework for how energy statistics are produced in the EU. This amendment was the most comprehensive energy statistics regulation amendment ever conducted and is aimed to support the European Green Deal so that new statistics to monitor the new decarbonisation policy initiatives can be produced in the EU (Eurostat, 2022).

The amendment includes new and more detailed data on for example hydrogen, decentralised production of electricity, large-scale batteries, energy consumption in data centres, the non-energy use of renewables and further breakdown of final energy consumption in transport and the services sector (regulation 2022/132; Eurostat, 2022a). This EU energy statistics regulation obliges Finland to provide the data specified in the regulation to the EU in the future. In Finland, the reporting of data is carried out by Statistics Finland, whose activities are regulated by the Statistics Act (280/2004). Chapter 5.3 goes into more detail about the new reporting requirements set for hydrogen.

3 Hydrogen technologies

3.1 Properties of hydrogen

Hydrogen is the lightest and most abundant element in the universe. The hydrogen atom consists of one proton and one electron, and under normal conditions forms diatomic hydrogen gas (H_2) which is colourless, odourless, tasteless and flammable gas that forms water (H_2O) when it burns with oxygen (O_2) (Jolly, 2022). Hydrogen is non-toxic; however, it can lead to asphyxiation in high concentrations (Calise et al., 2019). Upon ignition, hydrogen burns with a barely visible pale blue flame (Calise et al., 2019) and its combustion in vehicles or heating appliances does not produce carbon dioxide, particulates or sulphur oxides (IEA, 2019).

According to Zhang et al. (2014), if hydrogen is combusted in air or in the presence of nitrogen gas (N_2), nitrous oxides (NO_x) can form as a byproduct of the combustion process, but the amount of nitrous oxides -emissions heavily depend on the fuel-mix used: Higher hydrogen concentrations decrease the amount of formed nitrous oxides -emissions and with pure hydrogen combustion ultralow nitrous oxides -emissions occur. Catalysts can also be used to reduce the amounts of nitrous oxides -emissions (Zhang et al., 2014).

Jolly (2022) states that even though hydrogen is the most abundant element in the universe, it can mainly be found on Earth bound into other elements, especially in water and within hydrocarbons that form the basis for organic chemistry and life. Most elements can form compounds with hydrogen by sharing electrons through a covalent bond (Jolly, 2022).

Because of the light weight of the molecule, hydrogen gas can escape the atmosphere into outer space and thus hydrogen can only be found in very small concentrations (< 1 ppm by volume) in Earth's atmosphere (Calise et al., 2019). Hydrogen not forming any significant deposits in nature means that for human utilisation purposes it needs to be produced through a transformation process from some other compound containing hydrogen. This makes hydrogen a secondary energy source (energy carrier) (IEA, 2019).

The heating values of hydrogen are higher than those of any other known carbon-free fuel and higher than many of the currently used most important fuels, such as gasoline, diesel, methane (CH_4), or methanol (CH_3OH) as can be seen in table 3 (Nikolaidis and Poullikkas, 2017). However, the volumetric energy density of gaseous hydrogen is very low and pressurising or liquefying hydrogen is necessary to store and transport significant amounts of energy (Mertens et al., 2020). The boiling point of hydrogen is -252.77 °C (Jolly, 2022), meaning that storing and distributing hydrogen as liquid requires cryogenic equipment (see chapter 3.3).

Safety risks using hydrogen need to be carefully considered, since hydrogen can spontaneously explode by spark, heat, or sunlight in air at

concentrations 4 – 75 %. Thus, hydrogen is very flammable, and the odorless and colorless flame poses an additional safety hazard. (Nazir et al., 2020c; Zhang et al., 2014).

Table 3: Higher and lower heating values of hydrogen and other common fuels (adapted from Nikolaidis and Poullikkas, 2017).

Fuel	State at ambient temperature and preassure	Higher heating value (HHV) (MJ/kg)	Lower heating value (LHV) (MJ/kg)
Hydrogen	Gas	141.9	119.9
Methane	Gas	55.5	50
Ethane	Gas	51.9	47.8
Gasoline	Liquid	47.5	44.5
Diesel	Liquid	44.8	42.5
Methanol	Liquid	20	18.1

Due to its physical and chemical properties, abundance and technical versatility, hydrogen is currently receiving a considerable amount of attention as a new fuel which could help solve the biggest problems related to fossil fuels: global warming, air pollution, environmental pollution, and economic dependence on fossil fuels (Nazir et al., 2020a; IEA, 2019).

3.2 Production technologies

Hydrogen can be produced using multiple different technologies and sources, including natural gas, coal, biomass, biogas, and water. It should be noted that the use of fossil sources without the use of CCUS technology in hydrogen production leads to production of carbon emissions and thus the decarbonisation potential of hydrogen depends on the feedstocks used (Staffell at al., 2019). So, the renewability of the produced hydrogen is not technology specific but depends on the source fuels used in its production.

As stated by IEA (2019), renewable, carbon neutral, or low-carbon hydrogen can only be produced by using renewable energy sources, nuclear energy or fossil fuel plants equipped with CCUS. This also applies to the upstream energy input of electricity that is used to produce hydrogen (IEA, 2019). Figure 2 presents the different production process routes for hydrogen, divided into those utilising fossil fuels, renewable energy, or nuclear energy sources. In this chapter hydrogen production technologies are presented from a technical point of view.

Currently the most important production technologies are reforming methods, which consist of Steam Reforming (SR), Partial Oxidation (POX) and Autothermal Reforming (ATR) (chapter 3.2.1). These processes utilise different hydrocarbon molecules, water or air, and heat, and process them

into hydrogen. Hydrocarbon cracking, including methane and ammonia (NH_3) pyrolysis, is discussed in chapter 3.2.2.

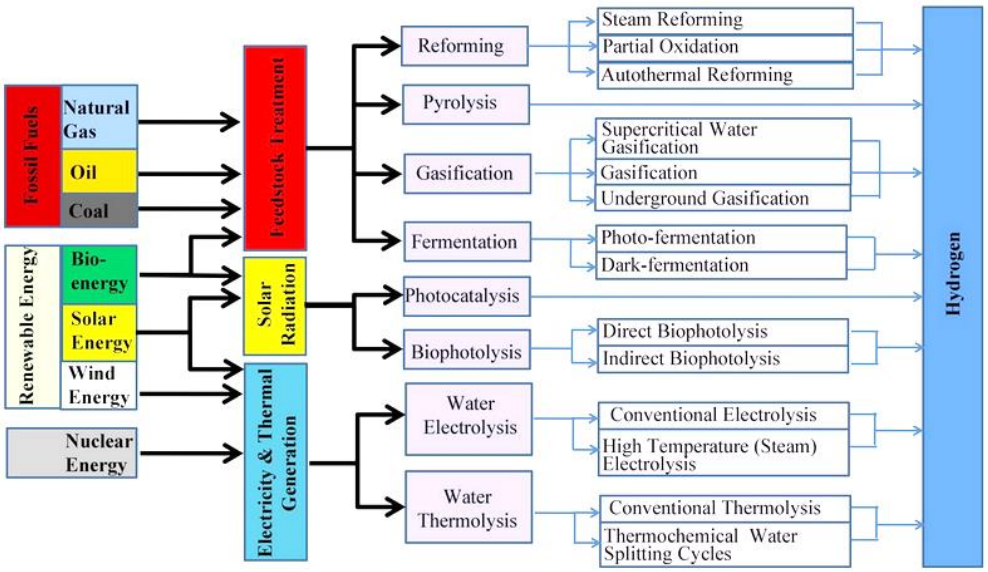


Figure 2: Hydrogen production routes from fossil, renewable or nuclear energy sources (Scipioni et al., 2017).

Water splitting methods (chapter 3.2.3) utilise electrolysis to produce hydrogen from water using electricity and/or heat. Photolysis utilises visible light energy in achieving water splitting, and thermolysis heat – these emerging technologies are included in chapter 3.2.4. Gasification, pyrolysis, combustion and liquefaction using biomass to thermochemically produce hydrogen are discussed in chapter 3.2.5.

Biological methods (3.2.6) take advantage of microbe-reactors and microbes' natural fermentation and photolysis reactions to produce hydrogen. These methods consist of bio-photolysis, dark and photo fermentation. Hydrogen produced using thermochemical or biological methods can be referred to as biohydrogen.

Figure 3 (IEA ,2021b) presents the breakdown of sources of global hydrogen production in 2020, when about 90 Mt of hydrogen was produced in total. Natural gas and coal were the biggest sources used and less than 0.7 % was produced from renewable sources or from fossil fuel plants equipped with CCUS. About 80 % of the hydrogen was dedicated hydrogen production, while the rest was produced as a byproduct. Byproduct hydrogen is produced mainly by chlor-alkali electrolysis in the chemicals industry (Nazir et al., 2020a). According to IEA (2021b), production of hydrogen is estimated to have produced approximately 900 Mt of carbon dioxide emissions in 2020.

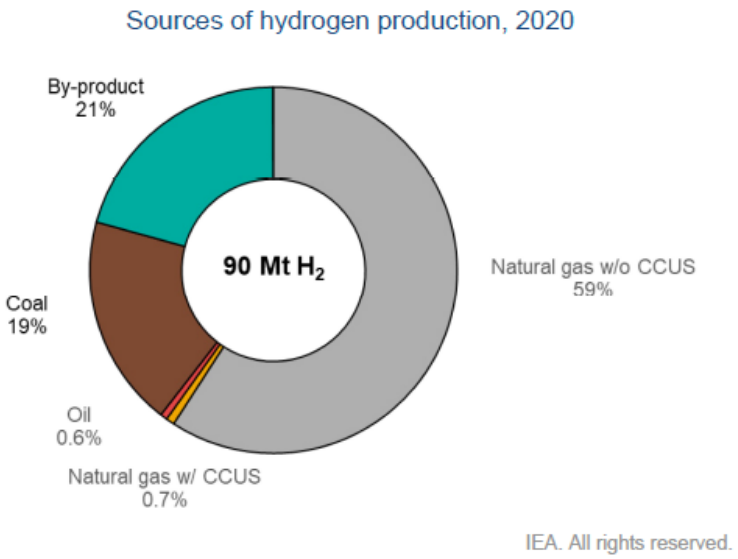


Figure 3: Hydrogen production in 2020 (IEA, 2021b).

3.2.1 Hydrocarbon reforming methods

Hydrocarbon reforming involves the conversion of a hydrocarbon molecule and an additional oxidant into hydrogen. If the oxidant used is steam (H_2O) the process is called SR. If instead oxygen is used, the process is called POX. A combinatory process of SR and POX is called ATR (Nikolaidis and Poullikkas, 2017).

SR is based on an endothermic catalytic equilibrium reaction

$$C_nH_m + n\,H_2O \rightleftharpoons n\,CO + (n + \frac{1}{2}m)H_2. \quad (1)$$

Basile et al. (2017) explains this reaction is strongly endothermic ($\Delta H° < 0$), which means the process requires an outside heat source, and high temperatures (800 – 1 100 °C) enhance the process. Even though in the temperature and pressure conditions used, the conversion of the hydrocarbon feedstock into hydrogen could be achieved without a catalyst, they are usually used to accelerate the reaction and to reduce the probability of unwanted side reactions from occurring. Hydrogen conversion efficiency of SR is 74 – 85 %, which is the highest of all currently known hydrogen production technologies (Nikolaidis and Poullikkas, 2017).

The main steps of the process are desulphurisation (if sulfur compounds are present in the feedstock), the generation of synthesis gas called syngas or reforming gas, water-gas shift reaction, and gas purification (Nikolaidis and Poullikkas, 2017). The three main technical components of the reforming process are the reformer unit, the water gas shift unit (WGS) and the oxidation or some other purification unit (Basile et al., 2017). Syngas produced in the reformer is a gas mixture containing mostly hydrogen (46 %) and carbon

monoxide (46 %), but also other compounds such as carbon dioxide (6 %), methane (1 %) and nitrogen gas (Nikolaidis and Poullikkas, 2017). The content and amount of impurities depend on the hydrocarbon used, its source and purity (Basile et al., 2017).

Based on Basile et al. (2017), the Water-Gas shift (WGS) reaction 2 usually takes place after the reformer reaction 1 in the WGS reactor:

$$CO + H_2O \rightleftharpoons CO_2 + H_2. \qquad \Delta H°_{298K} = -41\ \text{kJ/mol} \quad (2)$$

In the WGS reaction 2, the carbon monoxide (CO) in the syngas reacts further with steam to produce carbon dioxide and hydrogen. Thus, the WGS reaction increases the hydrogen yield of the process (Basile et al., 2017). This reaction is slightly exothermic ($\Delta H° < 0$) and is thus favored in lower temperatures than the reformer reaction. According to Basile et al. (2017), for this reason the WGS unit is separate from the reformer unit, as cooling may be needed to accelerate the WGS reaction.

An oxidation unit can be employed after the WGS unit if further purification of the output gas is required (Basile et al., 2017). The aim of the oxidation unit is to remove carbon monoxide from the formed syngas because carbon monoxide is highly detrimental to Proton Exchange Membrane (PEM) Fuel Cell (FC) applications. This can be achieved with oxidating the carbon monoxide into carbon dioxide as shown in reaction 3 (Basile et al., 2017).

$$CO + \frac{1}{2}O \rightleftharpoons CO_2 \qquad \Delta H°_{298K} = -283.0\ \text{kJ/mol} \quad (3)$$

The SR process can be replaced by a POX process if steam is replaced by a substoichiometric amount of oxygen. In this case the reformer reaction is (Nikolaidis and Poullikkas, 2017):

$$C_nH_m + \frac{1}{2}nO_2 \rightleftharpoons n\,CO + \frac{1}{2}mH_2. \quad (4)$$

Using a substoichiometric amount of oxygen leads to only partial oxidation of the hydrocarbon feedstock into mainly carbon monoxide and hydrogen (syngas) according to Zhang et al. (2014). The reaction is then followed by WGS reaction 2 and further purification similarly as in SR. The main components in a POX plant are a partial oxidation reactor, a shift reactor, and hydrogen purification equipment (Zhang et al., 2014). The efficiency of POX (60 – 75 %) is slightly lower than that of SR (Nikolaidis and Poullikkas, 2017).

Since the reaction is exothermic ($\Delta H° < 0$), this process does not require an outside heat source and due to the high temperatures used, the reaction does not require the use of a catalyst (Zhang et al., 2014). However, the use

of a catalyst significantly increases the hydrogen yield; Nickel compounds, nickel-modified hexa-aluminates or platinum group metals are commonly used catalysts for the POX process (Zhang et al., 2014). As for SR, a challenge for the POX process is catalyst deactivation caused by carbon monoxide and coke deposition (Godula-Jopek et al., 2012). Figure 4 presents a flow chart comparison of the SR and POX processes side-by-side.

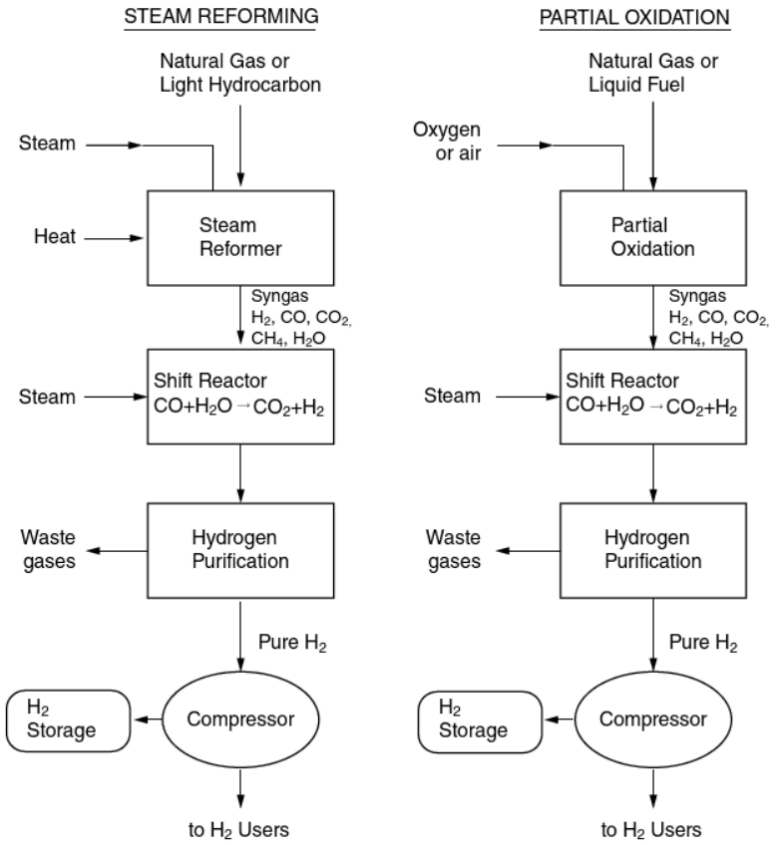


Figure 4: Flow chart comparison of SR and POX methods (Zhang et al., 2014).

When natural gas or methane is used to produce hydrogen with SR, n = 1 and m = 4 can be inserted into reaction (1) and the reformer reaction becomes

$$CH_4 + H_2O \rightleftharpoons CO + 3\,H_2. \qquad \Delta H°_{298K} = +206.0\ \text{kJ/mol} \quad (5)$$

And inserting methane into the POX reaction the reformer reaction (4) becomes

$$CH_4 + \frac{1}{2}O_2 \rightleftharpoons CO + 2\,H_2. \qquad \Delta H°_{298K} = -35.6\ \text{kJ/mol} \quad (6)$$

From reaction 6 it can be seen, that per one methane molecule, two hydrogen molecules are produced. The H/C ratio (2/1 = 2) is lower than for the corresponding methane SR reaction 5, for which the H/C ratio is 3/1 = 3. Thus, the SR's hydrogen yield is inherently higher, which is a drawback to its utilisation (Basile et al., 2017).

The POX reaction is faster and requires a smaller plant size compared to SR (Basile et al., 2017; Godula-Jopek et al., 2012), but a cost increase related to the process is the required oxygen purification from air (Sankir and Demirci Sankir, 2017). According to Nikolaidis and Poullikkas (2017), POX is the best process to use if heavier hydrocarbon inputs such as heavy oil residues or coal (C) are used.

If coal is used as the hydrocarbon feedstock, n = 1 and m = 0 can be inserted into reaction 1. The process is then referred to as coal gasification (Nikolaidis and Poullikkas, 2017). Figure 5 below presents the process. Coal is estimated to be the production method for 19 % of the world's hydrogen in 2020 (IEA, 2021b, see figure 3).

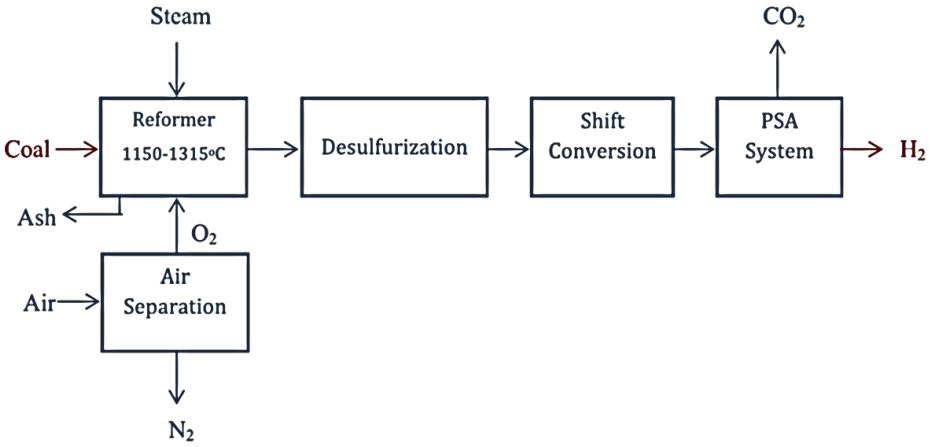


Figure 5: Coal gasification process in the production of hydrogen (Nikolaidis and Poullikkas, 2017).

ATR is a sequential combination of SR and POX processes; it takes advantage of the exothermicity of POX to provide the heat needed for the endothermic SR reaction and the higher hydrogen yield of SR (Basile et al., 2017). In ATR both steam and oxygen are fed as reactants into the process along with the hydrocarbon and the reforming and oxidation reactions occur simultaneously as can be seen in reaction 7 (Nikolaidis and Poullikkas, 2017). The hydrogen yield depends largely on the ratio on which steam and oxygen are fed into the process (Basile et al., 2017). The hydrogen conversion efficiency of ATR is 60 – 75 % according to Nikolaidis and Poullikkas (2017). Advantages to ATR are its fast start-up time and lower temperature requirements (Godula-Jopek et al., 2012). The ATR reaction is

$$C_nH_m + \frac{1}{2}nH_2O + \frac{1}{4}nO_2 \rightleftharpoons n\,CO + \left(\frac{1}{2}n + \frac{1}{2}m\right)H_2. \quad (7)$$

Reforming methods are used to produce hydrogen mainly using fossil fuels, and currently most of global hydrogen is produced from natural gas using SR, while liquefied petroleum gas and naphtha are used in smaller amounts (IEA, 2019). According to Nikolaidis and Poullikkas (2017) POX can be used to process heavy fuel oil or coal into hydrogen, as well as gas mixtures containing methane and other light hydrocarbons such as ethane (C_2H_6), propane (C_3H_8), butane (C_4H_{10}), and pentane (C_5H_{12}).

Methanol, ethanol (C_2H_5OH), glycerol ($C_3H_8O_3$) and other bio-oils or hydrogen peroxide (H_2O_2) have also been demonstrated as plausible reforming feedstocks for hydrogen production (Zhang et al., 2014). Methanol can be acquired from biomass or carbon dioxide (Martino et al., 2021), ethanol from different agricultural streams and glycerol synthetized from propylene oxide, sorbitol, glucose or as a by-product from e.g. soap manufacturing or biodiesel production (Zhang et al., 2014).

Zhang et al. (2014) state that theoretically one could obtain 7 moles of hydrogen per each one mole of glycerol, and this and glycerol's renewability and other beneficial qualities make it an attractive possible alternative to natural gas or coal, as glycerol is also edible, biodegradable, non-flammable and non-toxic. However, byproduct formation, catalyst deactivation and high energy requirements remain the biggest challenges yet to be resolved.

By incorporating CCUS technology the carbon dioxide produced in the process can be captured, stored and/or utilised to prevent its entry into the atmosphere (Nikolaidis and Poullikkas, 2017). Hydrogen produced with SR utilising Carbon Capture (CC) technology can be referred to as "low-carbon" hydrogen, if the process produces at least 70 % less GHG emissions than if natural gas was used instead (European Commission, 2021c).

3.2.2 Methane and ammonia cracking

Decomposing organic or inorganic compounds containing hydrogen under high heat is referred to as cracking or pyrolysis (biomass pyrolysis included in chapter 3.2.5). In this process, the hydrocarbon feedstock is broken down into solid coal and hydrogen gas (Zhang et al., 2014). The reaction can be written as:

$$C_nH_m \rightarrow nC + \frac{1}{2}mH_2. \quad (8)$$

Inserting methane, n = 1 and m = 4 into the reaction, the methane cracking reaction becomes:

$$CH_4 \rightarrow C + 2\,H_2. \qquad \Delta H°_{298K} = +74.8\ \text{kJ/mol} \quad (9)$$

Zhang et al. (2014) writes that used non-catalytically, the endothermic reaction requires a temperature above 1 000 °C to be achieved but using a catalyst it can be lowered to about 500 °C. However, higher temperatures are said to help in reaching higher hydrogen yields as the reaction is very temperature dependent. The most active catalyst discovered is nickel, but also other iron group metals can be used as well as activated carbon or metal oxides (Zhang et al., 2014). Figure 6presents a flow chart showing the methane cracking process (Nikolaidis and Poullikkas, 2017).

Methane cracking produces only hydrogen and solid carbon as a byproduct as can be seen in reaction 9. According to Zhang et al. (2014), the carbon can hinder catalyst activity, but the catalyst can be purified and re-activated with steam or air. The produced carbon mainly consists of filamentous carbon or carbon nanotubes, of which nanotubes can be sold commercially. The unreacted gaseous methane can be easily separated from hydrogen with adsorption or membrane technology, and high-purity hydrogen (up to 99 V-%) can be produced with methane cracking (Zhang et al., 2014).

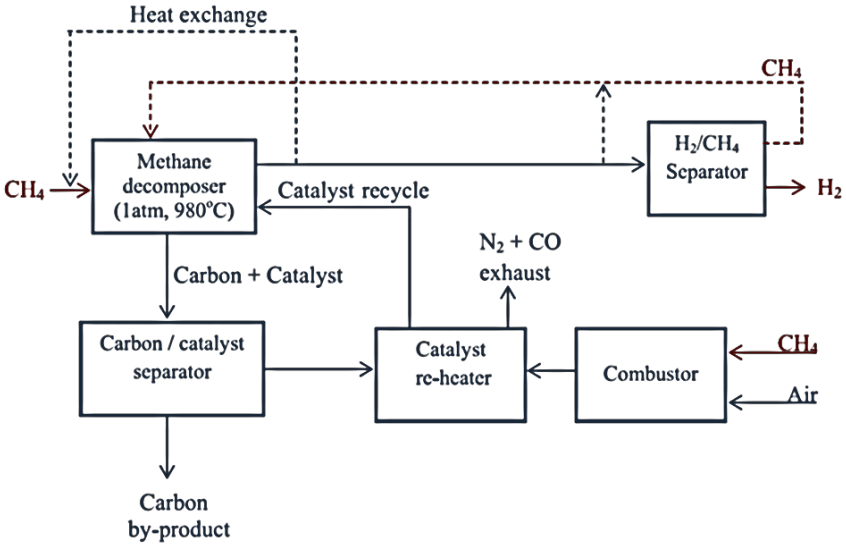


Figure 6: Methane cracking process flow chart (Nikolaidis and Poullikkas, 2017).

Even though the byproduct solid carbon presents a challenge – as currently there does not exist enough commercial demand for it, large methane cracking plants are told by Nikolaidis and Poullikkas (2017) to be able to reach 25 – 30 % cheaper hydrogen production costs than those of SR or POX plants. This being due to the simpler reaction conditions and process steps required: 980 °C at atmospheric pressure, with about 1.5 times smaller energy requirement per hydrogen mole produced and with no carbon dioxide - removal or WGS unit required (Nikolaidis and Poullikkas, 2017).

Ammonia cracking reaction is:

$$2\ NH_3 \rightarrow N_2 + 3\ H_2. \qquad \Delta H°_{298K} = +46.22\ kJ/mol \quad (10)$$

As with methane cracking, high purity hydrogen can be reached with ammonia cracking with high thermal efficiency (Zhang et al., 2014). The reaction rate depends on the used catalyst and pressure: porcelain and silica glass, iron (Fe), tungsten (W), molybdenum (Mo), nickel (Ni), noble metals and metal oxides can be used as catalysts for ammonia cracking (Zhang et al., 2014). An advantage of the method is that the produced nitrogen gas can be released into the atmosphere without negative environmental impacts, and that the method does not require other reactants, such as oxygen or water (Zhang et al., 2014).

3.2.3 Water splitting using electrolysis

Water splitting refers to an endothermic process in which the water molecule is broken down into its components, oxygen and hydrogen (see reaction 11). These methods consist of electrolysis, thermolysis (chapter 3.2.4) and photo-electrolysis (chapter 3.2.4). Electrolysis relies on electricity, thermolysis on heat and photo-electrolysis on light energy (photons) to achieve the splitting of water. Conversion efficiencies of electrolysis vary from 40 to 60 % (Nikolaidis and Poullikkas, 2017).

The carbon neutrality of these processes depends on the source of electricity and/or heat used. If the energy is produced with renewable sources such as hydro, wind or solar power, the produced hydrogen can be considered renewable (European Commission, 2020a) and can be produced with minimal to zero GHG emissions (Martino et al., 2021; Safari and Dincer, 2020; IEA, 2019). The renewability of electricity used can be verified using a Direct Transmission Line (DTL) or official green certificates (guarantees-of-origin) (Energy Authority, 2022).

The water splitting reaction is:

$$H_2O \rightleftharpoons H_2 + \frac{1}{2}O_2. \qquad \Delta H°_{298K} = +285.840\ kJ/mol \quad (11)$$

At temperature T = 298 K (25 °C) and pressure of p = 1 bar, the reaction's entropy change is $\Delta S°_{298K}$ = +163.15 kJ/(mol K) and Gibb's energy $\Delta G°_{298K}$ = +237.22 kJ/mol (Godula-Jopek and Stolten, 2015). Since the Gibb's energy change is positive ($\Delta G° > 0$) the reaction is non-spontaneous and requires outside energy to occur in the form of electric energy and/or heat (Godula-Jopek and Stolten, 2015). Figure 7 presents the total energy

required (ΔH) for achieving water splitting at different temperatures at 1 bar pressure. The total energy required is the sum of electrical energy (ΔG) and thermal energy ($T\Delta S$) required for the reaction to take place, as shown in equation 12:

$$\Delta H = \Delta G + T\Delta S. \quad (12)$$

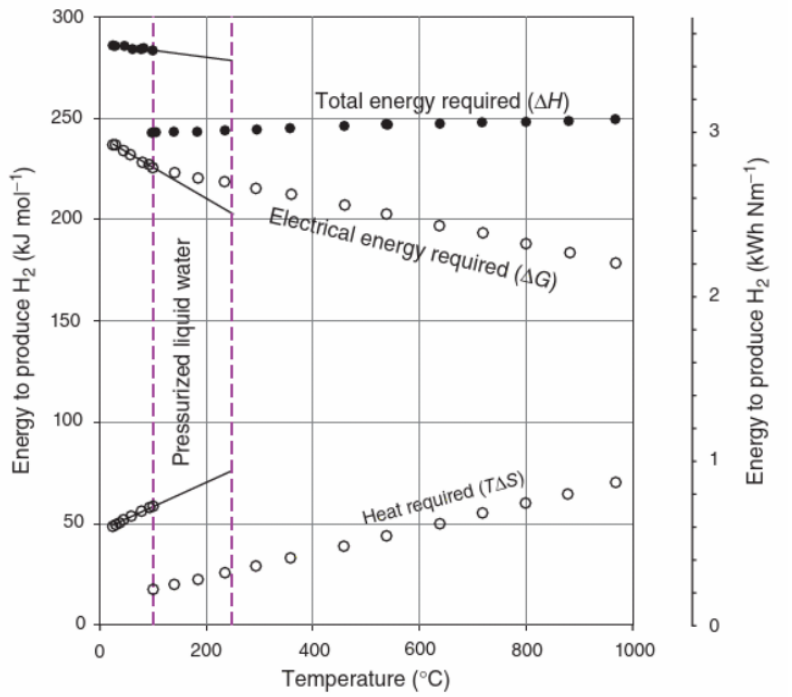


Figure 7: Electrical energy required (ΔG), heat required (TΔS) and the total energy required (ΔH) for water electrolysis at different temperatures at 1 bar preassure (Godula-Jopek and Stolten, 2015).

From figure 7 it is noteworthy to notice, that while the total energy required does not significantly change with temperature, the share of electrical energy (voltage) required decreases when more heat is applied into the system and temperature increases (Godula-Jopek and Stolten, 2015). Because Gibb's energy remains positive until temperatures reach higher values than 2 227 °C (2 500 K), the reaction does not become spontaneous until extremely high temperatures. For this reason, the utilisation of the spontaneity of water splitting in hydrogen production is not considered practical (Godula-Jopek and Stolten, 2015).

However, arccording to Godula-Jopek and Stolten (2015), since the required electrical energy decreases in higher temperatures it means that high-temperature electrolysis could be used to reduce production expenses of water splitting, as heat is stated to generally be less expensive than electricity. Unfortunately, high-temperature electrolysis technologies have not yet

reached a mature stage and especially materials technology -related problems such as high degradation rates still need to be resolved (Godula-Jopek and Stolten, 2015; Smolinka and Garche, 2021).

Smolinka and Garche (2021) explain the basic structure and function of an electrolysis cell: The cell consists of a voltage source connected to two electrodes and an electrically conductive liquid or solid electrolyte. The other electrode is negatively charged (cathode) and the other one positively charged (anode). The electrolyte connects the cathode to the anode and allows for electrically charged particles to flow and create an electric current. Electrons and negative ions in the electrolyte are attracted to the positively charged anode and repelled by the cathode, and electrons flow from the anode towards the cathode where an oxidation reaction occurs and negatively charged electrons are produced. The electrons travel via a conductor to the cathode attracted by the positive charge. In water electrolysis hydrogen gas is produced at the cathode when water undergoes a reduction reaction. The half-cell reaction occurring at the cathode is referred to as hydrogen evolution reaction and the reaction at the anode as the oxygen evolution reaction.

Different electrolysis cell types are defined by the type of electrolyte used. table 4 lists the different cell types and their main characteristics. The most used electrolysis cells are the Alkaline Electrolysis (AEL), PEM and Solid Oxide Electrolysis (SOEC) (Nikolaidis and Poullikkas, 2017).

Table 4: Different water electrolysis methods and their main characteristics (compiled from Smolinka and Garche, 2021).

Common abbreviations	Name	Electrolyte	Temperature range (°C)	Charge carrier
AEL or AEC	Alkaline Electrolysis	Liquid electrolyte	70 – 90	OH^-
AEM, AEMEC or AEMEL	Anion exchange membrane water electrolysis	Solid polymer electrolyte	50 – 70	OH^-
PEM, PEMEC, PEMEL or SPE	Proton exchange membrane water electrolysis	Acidic solid ionomer electrolyte	50 – 80	H^+
PCCEL	Proton conductive ceramic electrolysis	High temperature process	450 – 600	H^+
SOEC or SOEL	Solid oxide steam electrolysis	High temperature process with a solid oxide electrolyte	650 – 850	O^{2-}
CoSOEL	High temperature co-electrolysis process of water and carbon dioxide	Solid oxide electrolyte	700 – 900	O^{2-}

According to Smolinka and Garche (2021), AEL cell technology is fully developed and has been commercially available for decades since the late 1960's and currently AEL cells can be purchased on a MW scale. AEL cells operate usually in a temperature range of 50 – 80 °C, even though higher temperature would increase the water splitting efficiency. However, higher temperatures are stated to start to increase the material degradation and corrosion rates (Smolinka and Garche, 2021). AEL has especially been used in industry to produce hydrogen needed for ammonia synthesis (Godula-Jopek and Stolten, 2015).

The main advantages of AEL are its use of abundant and inexpensive materials (mainly nickel and iron) (Godula-Jopek and Stolten, 2015), longevity and operability under different pressure conditions (up to 30 bar) (Smolinka and Garche, 2021). Its main disadvantages according to Smolinka and Garche (2021) are material degradation (corrosion) problems and relatively low current density when compared to PEM cells. AEL is not suitable for conditions were sudden current changes take place, as in this case a sudden large amount of produced gases can cause the liquid electrolyte to spray and damage the system (Godula-Jopek and Stolten, 2015). Figure 8 shows the technical structure of an AEL unit.

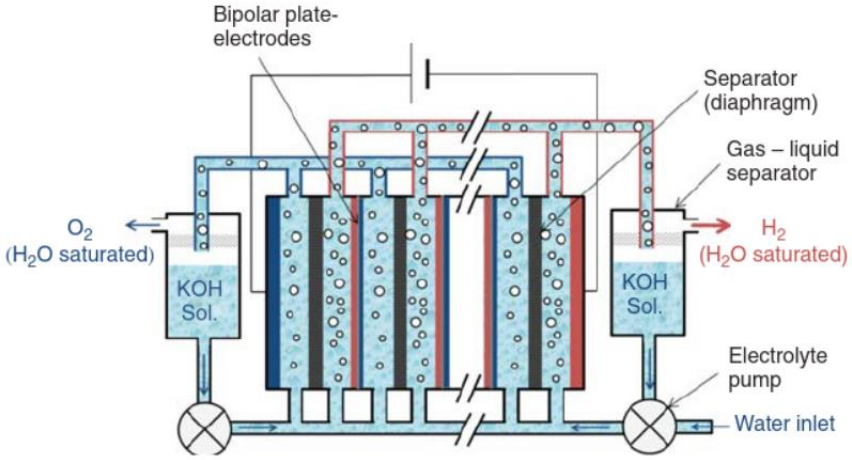


Figure 8: Structure of an AEL unit (Godula-Jopek and Stolten, 2015).

In PEM a solid acidic polymeric electrolyte is used instead, and water is supplied to the cell on the anode side where it is broken down into its components (Smolinka and Garche, 2021). Protons are then transported to the cathode whereas the electrons travel through an external circuit. Hydrogen gas is produced at the cathode, and a solid membrane separating the electrodes is used, with high proton conductivity and low gas permeability. The operating temperature for a PEM cell is 50 – 80 °C (Smolinka and Garche, 2021).

Smolinka and Garche (2021) mention advantages of a PEM cell to be its more flexible operating conditions, as a power input ranging from watts to

megawatts and high pressures can be applied on the system. In addition, due to hydrogen's low specific volume, the possibility to produce pressurised hydrogen is considered a great advantage to PEM cells. Also, very high purity hydrogen gas (up to 99.999 vol-%) can be produced with a PEM cell (Smolinka and Garche, 2021).

Based on Godula-Jopek and Stolten (2015), high current densities can be used with a PEM cell, which makes these electrolysers more compact in size. Also, due to the solid electrolyte, the improved safety aspects are told to make PEM cells more operable in onboard technologies. Unlike AEL, PEM cells can sustain a transient power input without damage and for this reason, Godula-Jopek and Stolten (2015) mention that PEM could be coupled with intermittent power sources or off-peak nuclear electricity. According to Smolinka and Garche (2021) PEM electrolysis cell efficiency is slightly lower than that of AEL cells, but their efficiency is expected to improve as larger cell plants will be constructed.

High-cost materials such as the membrane materials, noble metal catalysts and titanium-based components are required, which significantly increases the costs of a PEM electrolysis cell and this has remained as the biggest challenge for larger PEM utilisation, even though technologically PEM has already been demonstrated to be an efficient process (Smolinka and Garche, 2021; Godula-Jopek and Stolten, 2015). So far PEM has been utilised mainly to produce oxygen (Godula-Jopek and Stolten, 2015).

High Temperature Electrolysis (HTEL) processes use a solid oxide electrolyte, where steam is supplied to the cathode, and a reduction reaction leads to the production of oxygen and hydrogen ions (Smolinka and Garche, 2021). SOEC is operated at a temperature range 650 – 850 °C and its advantage is the lower electrical energy requirement, as more of the energy required for the water splitting reaction can be replaced with heat. Industrial waste heat with a temperature slightly above 100 °C can be used to heat an HTEL process (Smolinka and Garche, 2021). Another option discussed by Sahin and Sahin (2021) would be to use nuclear heat. Higher efficiencies can be reached using HTEL compared to low temperature electrolysis, but material degradation in HTEL cells such as in SOEC remain a big issue limiting their commercial viability according to Martino et al. (2021).

Seawater would be an essentially endless source of hydrogen, but seawater electrolysis remains at an early stage of development (Smolinka and Garche, 2021). The varying levels of different ions and other impurities present in seawater are stated (Smolinka and Garche, 2021) to present problems for the technology, as SOEC and PEM require the use of ultrapure water. Especially chloride (Cl^-), magnesium (Mg^{2+}) and calcium ions (Ca^{2+}) are problematic and should be removed from seawater prior to electrolysis. Chloride forms toxic chloride gas (Cl_2), and magnesium and calcium precipitate at the cathode inhibiting the water splitting process (Smolinka and Garche, 2021).

3.2.4 Water splitting using thermolysis and photolysis

Thermolysis is a process in which water molecules are decomposed into hydrogen and oxygen using heat (reaction 11). The temperature required for thermolysis is about 2 500 °C (about 2 700 K) (Funk, 2001). According to Nikolaidis and Poullikkas (2017), the hydrogen conversion efficiency of thermolysis is 20 – 45 % (Nikolaidis and Poullikkas, 2017).

Thermolysis consists of either a one-step process or a multi-step cycle in which a repeating series of chemical reactions leads to the production of hydrogen. Multi-step cycles' advantage is their lower operating temperature (below 2 000 °C), as such a high temperature is difficult to achieve using renewable sources of heat. Multiple metal oxides can be used for this, but the additional chemical requirements also increase the costs of these multi-step processes according to Safari and Dincer (2020) and Nikolaidis and Poullikkas (2017).

Photo-electrolysis (photolysis) uses visible light energy to split water, aided by a catalyst. Semiconductors are used to absorb photons that create electron-hole pairs. The hole splits water into oxygen and protons (H^+) that travel through an electrolyte to the cathode. At the cathode electrons react to produce hydrogen gas. According to Nikolaidis and Poullikkas (2017) the conversion efficiency of photolysis is only 0.06 %, lowest of all the hydrogen production technologies.

3.2.5 Thermochemical methods

Thermochemical methods consist of pyrolysis, gasification, liquefaction, and combustion. Hydrogen produced either by thermochemical methods using biomass, or biological methods can be referred to as biohydrogen (Zhang et al., 2014). Thermochemical methods can utilise versatile biomass feedstocks as the hydrocarbon (C_nH_m) source and lower temperature and preassure conditions as compared to the conventional reforming methods can be used (Zhang et al., 2014; Nikolaidis and Poullikkas, 2017).

In pyrolysis biomass decomposes under high heat (600 – 950 K) and in the absence of oxygen into hydrogen, carbon monoxide, carbon dioxide, methane and other hydrocarbon gases (syngas) as shown in reaction 13 (Zhang et al., 2014). Liquid tar and solid char are also formed in the process. Different pyrolysis methods can be divided into slow, fast, or flash pyrolysis (Zhang et al., 2014). The pressure conditions range between 0.1 – 0.5 MPa (Nikolaidis and Poullikkas, 2017).

$$\text{biomass} \rightarrow H_2 + CO + CO_2 + \text{hydrocarbon gases} + \text{tar} + \text{char} \qquad (13)$$

The composition of the reaction products depends on the type of biomass and process technique used (Zhang et al., 2014). According to Nikolaidis and

Poullikkas (2017) solid char content is generally decreased by using higher temperature and shorter residence time, but consequently this increases the liquid tar content. The amount of gases in the products varies from 25 – 48 % for slow pyrolysis and 12 – 24 % for fast pyrolysis (Zhang et al., 2014). Pyrolysis can be chained with SR and WGS to transform the syngas into more hydrogen as shown in reactions (1) and (3) with increased investment costs (Nikolaidis and Poullikkas, 2017). According to Zhang et al. (2014) in practice gasification units need to be coupled with SR and WGS to further transform the methane and CO into hydrogen and inorganic impurities and tar need to be purified out of the process.

Unlike pyrolysis, gasification is conducted under oxidising high heat (at about 770 K – 1 600 K) conditions using for example air, oxygen and/or steam (Nikolaidis and Poullikkas, 2017). It is stated (Nikolaidis and Poullikkas, 2017) that the pressure can range more than with pyrolysis, from atmospheric to about 35 bars. In addition to the product gases that form in pyrolysis (reaction 13), in pyrolysis steam and nitrogen gas are produced (Nikolaidis and Poullikkas, 2017).

A big challenge regarding processes using biomass is the often-large variability in quality and moisture content of the biomass, since the particle size of the biomass, temperature, heating rate, residence time, preassure and reactor configuration all affect the final product composition of pyrolysis (Zhang et al., 2014). Metal catalysts can be used to increase the yield and reduce unwanted reactions from occurring (Zhang et al., 2014).

According to Zhang et al. (2014) the scaling up of biohydrogen remains an issue. A challenge complicating the scaling-up of these technologies is stated to be the lower hydrogen content and smaller yield when biomass is used as fuel as for example when compared to methane. Also, the availability of biomass restricts the construction of large-scale plants and their location (IEA, 2019).

Even though carbon dioxide is released using biomass, biohydrogen production can be assessed to be carbon neutral, as the emitted carbon dioxide includes carbon which has been absorbed in plants by photosynthesis rather than carbon from fossil sources (Nikolaidis and Poullikkas, 2017; Zhang et al., 2014). If these technologies are coupled with Carbon Capture and Storage (CCS), negative emissions could be achieved (IEA, 2019, Ustolin, 2022).

According to Nikolaidis and Poullikkas (2017), out of thermochemical methods pyrolysis and gasification are the most preferable hydrogen production technologies to use, while liquefaction and combustion are less attractive options due to their lower hydrogen yields, emissions of polluting byproducts and more difficult operating conditions (anaerobic high preassure conditions). Very limited amount of literature is available concerning these hydrogen production methods.

3.2.6 Biochemical methods

Biochemical and biological methods consist of photolysis using green and blue-green algae (cyanoacteria), photo fermentation, dark fermentation, carbon monoxide gas fermentation and hybrid reactor systems. Hydrogen production using bacteria and algae is dependent on enzymes (hydrogenases and nitrogenases) which act as a catalyst in biological production of hydrogen (Zhang et al., 2014).

In photolysis cyanobacteria break down water into oxygen and hydrogen using photosynthesis (Zhang et al., 2014). According to Zhang et al. (2014), both photolysis and photo fermentation require light energy, but photo fermentation uses organic chemicals as substrates for hydrogen production. Dark fermentation occurs in the dark with anaerobic bacteria whose energy to produce hydrogen comes from breaking down organic molecules. Different dark fermenting bacteria require different optimal temperature and pH-conditions (Zhang et al., 2014). Dark fermentation produces a mixture of hydrogen, carbon dioxide, methane, carbon monoxide and hydrogen sulfide (H_2S) gases of biological origin (biogas), while with photolysis the only reaction products are oxygen and hydrogen (Zhang et al., 2014).

Zhang et al. (2014) state that photo fermentation is deemed a more attractive hydrogen production process out of the other biological methods, because of the higher substrate-to-hydrogen ratio, the possibility to use more versatile organic waste materials and use a wider spectrum of visible light wavelengths. However, its drawbacks are told to be related to its low solar energy conversion efficiency, high land area and special bioreactor-technology requirements. Also, photosynthetic microbes are not able to continuously produce hydrogen, but can only do so in short intervals (Ghirardi, 2015). Hybrid systems combine photo and dark fermentation to take advantage of both processes' advantages and to increase the hydrogen yield (Zhang et al., 2014).

Biological methods are less energy intensive than thermochemical biohydrogen production because generally the processes take place under atmospheric pressure and ambient temperatures (Nikolaidis and Poullikkas, 2017). However, the hydrogen yields are small (Zhang et al., 2014; Rodionova et al., 2017).

Table 5 presents an overall comparison of the different hydrogen production methods discussed in chapters 3.2.1 – 3.2.6.

Table 5: Comparison of hydrogen production methods. (Altered from Nikolaidis and Poullikkas, 2017).

Process	Efficiency (%)	Major advantages	Major disadvantages
SR	74 – 85	Most developed technology, existing infrastructure.	CO_2 byproduct, dependence on fossil fuels.
POX	60 – 75	Proven technology, existing infrastructure.	CO_2 byproduct, dependence on fossil fuels.
ATR	60 – 75	Proven technology, existing infrastructure.	CO_2 byproduct, dependence on fossil fuels.
Electrolysis	40 – 60	No pollution with renewable sources, proven technology, existing infrastructure, abundant feedstock, O_2 is the only byproduct, contributes to RES integration as an electricity storage option.	Low overall efficiency, high capital costs.
Thermolysis	20 – 45	Clean and sustainable, abundant feedstock, O_2 is the only byproduct.	Elements toxicity, corrosive problems, high capital costs.
Photolysis	0.06	Emission-free, abundant feedstock, O_2 is the only byproduct.	Requires sunlight, low conversion efficiency, non-effective photocatalytic material.
CHs pyrolysis	–	Emission-free, reduced-step procedure.	Carbon byproduct, dependence on fossil fuels.
Biomass pyrolysis	35 – 50	CO_2-neutral, abundant and cheap feedstock.	Tar formation, varying H_2 content due to seasonal availability and feedstock impurities.
Biomass gasification	–	CO_2-neutral, abundant and cheap feedstock.	Tar formation, varying H_2 content due to seasonal availability and feedstock impurities.
Bio-photolysis	10	CO2-consumed, O2 is the only byproduct, operation under mild conditions.	Requires sunlight, low H2 rates and yields, requirement of large reactor volume, O2 sensitivity, high raw material cost.
Dark fermentation	60 – 80	CO_2-neutral, simple, can produce H_2 without light, contributes to waste recycling, no O_2 limitation.	Fatty acids removal, low H_2 rates and yields, low conversion efficiency, requirement of large reactor volume.
Photofermentation	0.1	CO_2-neutral, contributes to waste recycling, can use different organic wastes and wastewaters.	Requires sunlight, low H_2 rates and yields, low conversion efficiency, requirement of large reactor volume, O_2 sensitivity

3.3 Distribution and storage of hydrogen

Hydrogen turns liquid at −259.29 °C (13.86 K) and gaseous at −252.77 °C (20.38 K) (Jolly, 2022), this poses a technical challenge to the distribution and storage of hydrogen. Currently, the most important hydrocarbon fuels used are mainly stored, transported and combusted in liquid form, but the liquid storage of hydrogen requires cryogenic conditions. Nonetheless, gaseous, liquid and solid forms of storing hydrogen exist. Currently the biggest challenge in developing storage technologies for hydrogen concern minimising the energy requirement of the storage system (Nazir et al., 2020b). Different distribution pathways for hydrogen include pipeline, road, rail and ocean transport (Nazir et al., 2020b).

Figure 9 (Nazir et al., 2020b) presents the categorisation of the main hydrogen storage options that can be divided into physical and material storage systems. In physical storage systems hydrogen is stored as hydrogen either liquefied or in compressed gaseous state, while in material storage systems hydrogen is chemically stored as another chemical compound, for example as ammonia, graphene, or metal hydrides (Nazir et al., 2020b). Hydrogen can then be consumed as the new chemical product or converted back into hydrogen.

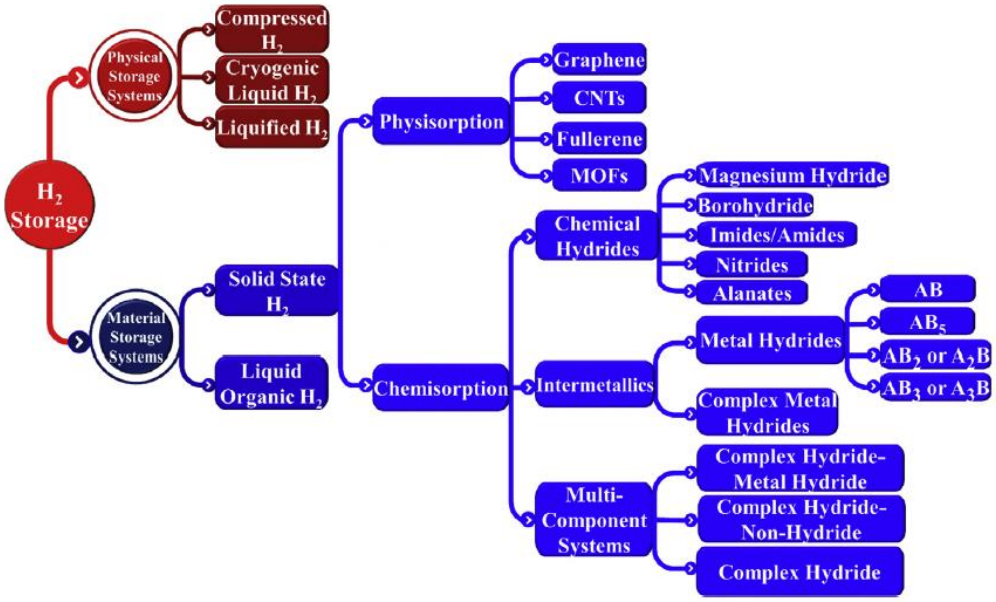


Figure 9: Different hydrogen storage technologies (Nazir et al., 2020b).

Physisorption refers to storing hydrogen by using another substance as an adsorbent to physically absorb hydrogen molecules without a chemical transformation of the hydrogen molecule taking place, whereas in chemisorption new chemical bonds by sharing electrons are formed (Nazir et al., 2020b). So far, these material storage methods are stated (ACER, 2021) to be at an initial

stage and ACER (2021) report mentions only ammonia and methanol as noteworthy options. Ammonia can be liquefied at ambient temperature below 8 bar of pressure with more than a twice higher volumetric energy density (10.5 MJ/L) than that for gaseous hydrogen at 700 bar pressure (5 MJ/L) – leading to lower storage and transportation costs than those for hydrogen (Jiao and Xu, 2018).

Nazir et al. (2020b) write, that due to the variability in production and demand, the need to store hydrogen would exist both at the production facilities and close to the end-user (figure 10) – the distance between the two may range from tens to thousands of kilometers and might require intercontinental transportation. Because of variable operating pressure requirements depending on end-use, compressors, pumps, pressure-reduction stations and liquefaction plants would be required in between different stages of the production-transport-user chain (Nazir et al., 2020b).

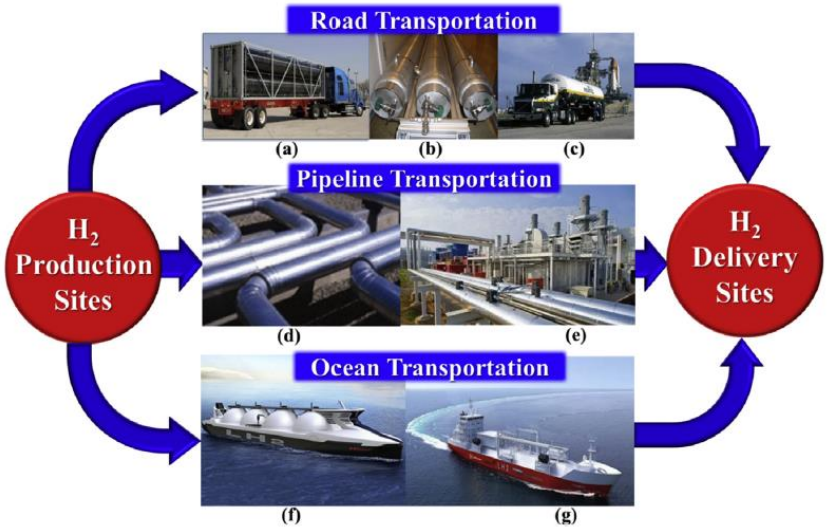


Figure 10: Compressed hydrogen in tube-trailers (a), metal hydrides hydrogen storage (b), liquid hydrogen storage (c), hydrogen transportation via pipeline (d and e), liquid hydrogen or Liquid Organic Hydrogen Carrier (LOHC) transportation via ocean (f and g) (Nazir et al., 2020b).

Storing hydrogen as compressed gas is the cheapest and technologically simplest method to store hydrogen. It is a mature commercially available method that only requires a compressor and a metal pressure vessel made usually of steel or carbon-fiber (Nazir et al., 2020b). Compressed gas hydrogen storages are stated (Nazir et al., 2020b) to be able to reach fast filling and discharge flow rates, but the storage tanks requiring a high amount of space. Natural gas storage tanks could be utilised as storing hydrogen instead when low atmospheric pressure levels of hydrogen are relevant (Elberry at al., 2021). Scipioni et al., (2017) points out in relation to hydrogen storage that leakage risks need to be considered. It is stated that the hydrogen molecule

is so small it can penetrate through some metals and other materials (Scipioni at al., 2017).

According to Elberry et al. (2021), when compressing hydrogen an important aspect is that the relative density of hydrogen gas is lower than that of other gaseous fuels and increasing pressure does not increase hydrogen density linearly. For this reason, it takes more energy to compress hydrogen than other gases – reaching a density of 70 kg/m3 for natural gas requires a pressure of 95 bars, when for hydrogen the pressure needs would need to be as high as 2 000 bars (in ambient temperature) (Elberry at al., 2021). Based on ACER (2021), to achieve the same energy flow capacity for a pure hydrogen pipeline network, it takes around three times more compressor power compared to a natural gas pipeline. However, to reduce the costs of hydrogen transport in the initial stages of the energy market transition, new hydrogen pipeline networks could be used at a smaller pressure-level and smaller capacity (ACER, 2021). Geological caverns such as depleted natural gas fields or oil reservoirs, are an alternative to having larger gaseous hydrogen storages, but their limited availability and location limits their use (Nazir, et al. 2020b).

Vacuum-insulated inner pressure vessels with external casings are used for liquid hydrogen storage (Nazir et al., 2020b). Liquefied storage of hydrogen requires 64 % more energy than compressed gas storage according to Elberry at al. (2021) but much more hydrogen can be stored in a same-sized tank in liquid form compared to compressed gas (29 700 kg gaseous hydrogen at 165 bars versus 142 000 kg of liquid hydrogen, both in a 2 000 m^3 tank) (Nazir et al., 2020b). Cryogenic liquefied hydrogen storages suffer from daily evaporation losses that correspond to a weight percentage loss of 0.5 – 1 % (Scipioni at al., 2017).

According to Nazir et al. (2020b), transport of hydrogen by road (trucks), railways, pipelines and ocean are possible, and depending on travel distance and volume the most suitable and economical best transport method varies. Nazir et al. (2020b) claim that for long range deliveries (> 3500 km), tanks on board ocean vessels are the least expensive option with a possible carrying capacity of about 9 000 m^3 of liquid hydrogen. Alternatively, liquid hydrogen could be transformed and transported as metal hydrides, Liquid Organic Hydrogen Carriers (LOHCs), ammonia or methane by ship.

However, according to ACER (2021), 25 to 35 % of the stored hydrogen's initial quantity would be required to maintain the cryogenic conditions required by the storage of liquid hydrogen at ambient pressure (compared to about 10 % for natural gas). This makes ocean transport a very expensive option. The ACER (2021) report also notes that currently commercial ships which can transport pure liquified hydrogen do not exist and that the transport of ammonia seems to be a much cheaper option. The chemical conversion of hydrogen into ammonia (and vice versa) is stated to consume 7 % to 18 % of the hydrogen's energy content.

Blending up to 15 % of hydrogen into existing natural gas networks would be possible and provide a way to utilise existing infrastructure according to Nazir et al. (2020b). Based on Elberry at al. (2021) higher blend percentages than 15 % start to cause compatibility issues on users' equipment and overall safety concerns. Another possibility is repurposing existing natural gas pipelines into dedicated hydrogen pipelines; this is cheaper than constructing completely new pipelines and existing routes and land rights can be taken advantage of (ACER, 2021). Pipelines can store tens of thousands of cubic meters of hydrogen per hour continuously, with typical flow rates between 310 – 8 900 kg/h at 10 – 30 bars (Nazir et al., 2020b). A challenge related to both hydrogen pipelines and tanks is stated to be metal (steel) embrittlement, which is enhanced in higher pressures and can lead to hydrogen leakage and pipeline failures due to cracking (Nazir et al., 2020b; Elberry at al., 2021). Elberry et al. (2021) points out that hydrogen pipelines are already in use at chemical and petrochemical industrial sites and thus, the technology is already mature, and that this theoretically enables the construction of new hydrogen pipelines with a relatively fast timeline.

3.4 Utilisation of hydrogen

Consumption of hydrogen has been steadily growing since 1975 as can be seen in figure 11 (IEA, 2019). In figure 11, refining, ammonia and "other pure" refer to consumption of pure hydrogen, while methanol, DRI and "other mixed" refers to uses of hydrogen where hydrogen consumed as a part of a gas mixture, such as syngas. The biggest user sector according to IEA (2019) has been fertilizer (ammonia) production, but significant amounts are also used in oil refining.

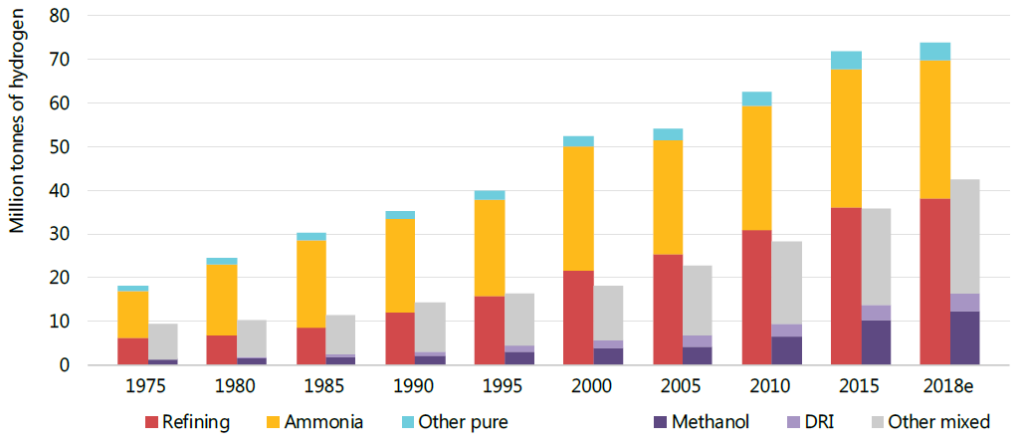


Figure 11: Consumption of global hydrogen 1975 – 2018e (IEA, 2019).

According to IEA (2021c), almost 70 MW of new electrolysis capacity was installed globally in 2020. This, in addition to two new CCUS-equipped fossil fuel facilities producing hydrogen corresponded to a global 15 % production capacity increase (IEA, 2021c). A growing demand is further indicated by the growing number of hydrogen policies related to supporting hydrogen investments, and national hydrogen roadmaps published by multiple countries in recent years (IEA, 2019).

IEA's global Net Zero Emissions scenario (IEA, 2021c) estimates that global hydrogen demand should rise to about 210 Mt by 2030 (figure 12). The scenario models what achieving net-zero emissions by 2050 would require from the energy sector (IEA, 2021a). According to IPCC industries account for about 25 % of global emissions and will require hydrogen among other measures to reach net zero (IPCC, 2022).

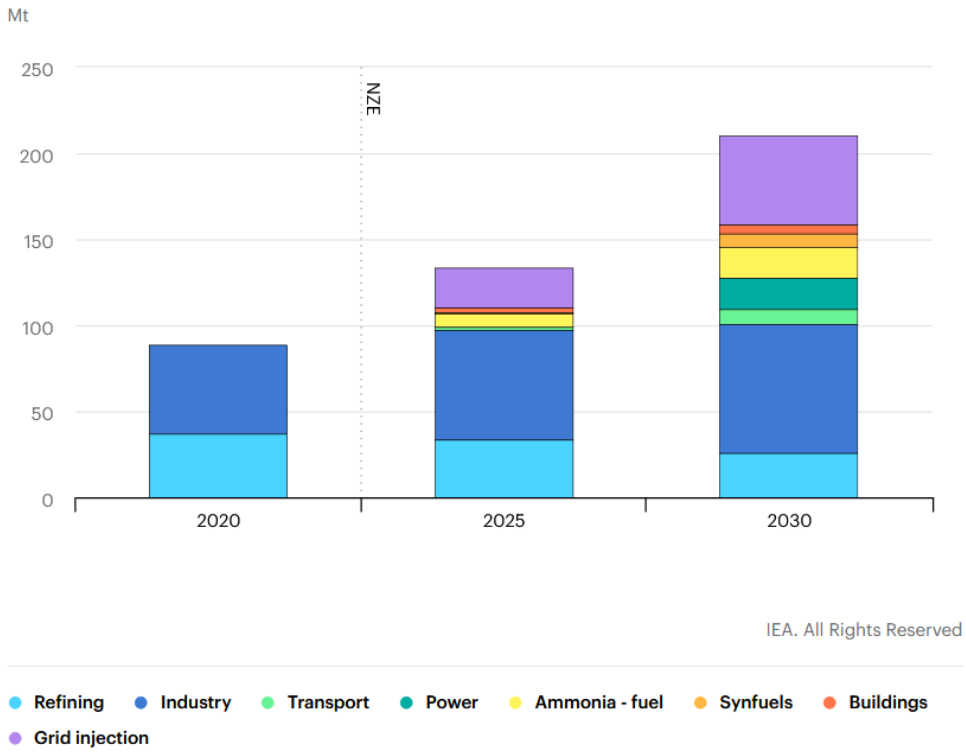


Figure 12: Global hydrogen demand by sector in the Net Zero Emissions (NZE) scenario 2020-2030 (IEA, 2021c).

Hydrogen can be used in many different applications, as depicted in Figure **13** figure 13. End-uses for hydrogen in the image have been grouped into transport, buildings and industry. Hydrogen can be combusted directly in burners, boilers, Internal Combustion Engines (ICEs), gas turbines or used in a FC where hydrogen is electro-chemically converted to electricity (Azzaro-Pantel, 2018). In figure 13 buildings, cogeneration and "turbines, internal combustion engines" for industry refer to energy use of hydrogen – where

hydrogen is used to produce electricity and/or heat in stationary applications. “Process synthesis, etc.” refers to industrial non-energy or raw material use of hydrogen (chapter 3.4.2). In mobile applications (chapter 3.4.3), hydrogen can be used directly by using FCs or indirectly in ICEs if hydrogen is first synthetised into other transportation fuels such as synthetic gasoline (Azzaro-Pantel, 2018).

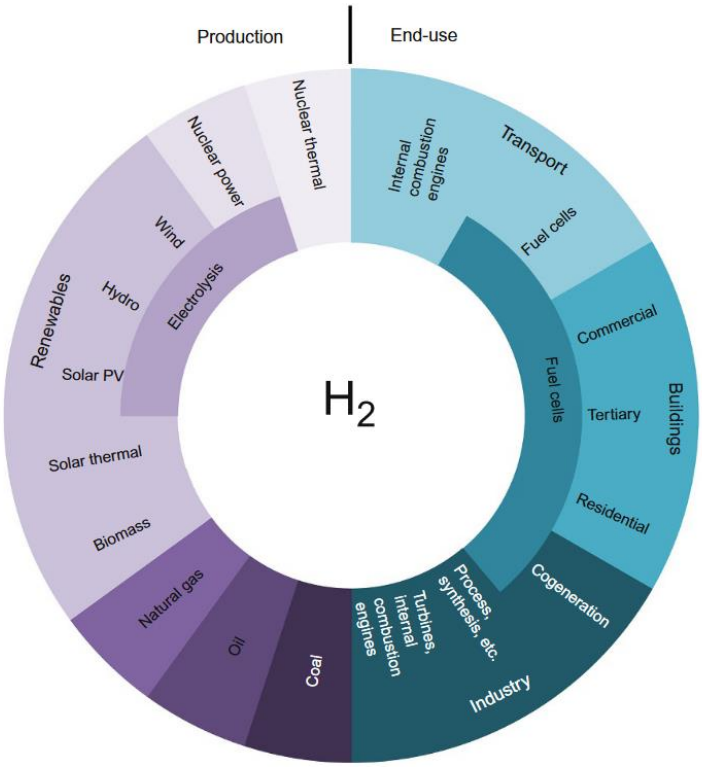


Figure 13: Sources and end-uses of hydrogen (Azzaro-Pantel, 2018).

These technological chains which utilise the transformation of renewable electricity into hydrogen and/or other chemicals or energy products are referred to as P2X -technologies. The “X” in the term can be replaced with the name of the end product, such as “heat”, “gas”, “liquids”, “methane”, or “ammonia”. Ammonia produced from electrolytic hydrogen is usually also included in this category (Ababneh and Hameed, 2022). The role of P2X -technologies is seen in their ability to advance and deepen the integration of renewable energy sources into the world economy, “displacing the requirement of fossil fuels” as stated by Daiyan et al. (2020).

3.4.1 Energy uses of hydrogen

Hydrogen could be used to decarbonise transportation, heating and power in buildings, industrial heat and used directly as a renewable feedstock material in the chemical industry as shown figure 14 (Hydrogen Cluster Finland,

2021). Since hydrogen can be produced via electrolysis using renewable electricity, hydrogen could also be used to stabilise the electric grid: electricity can be transformed and stored as hydrogen when the supply of renewable electricity exceeds electricity demand. This way, hydrogen would help in storing the available renewable electricity, keeping the electric grid in balance, and helping in alleviating the line congestion and electricity market disturbances caused by hard-to-predict solar and wind power (Elberry at al., 2021). The hydrogen can then either be used as hydrogen or transform it into electricity or other chemicals.

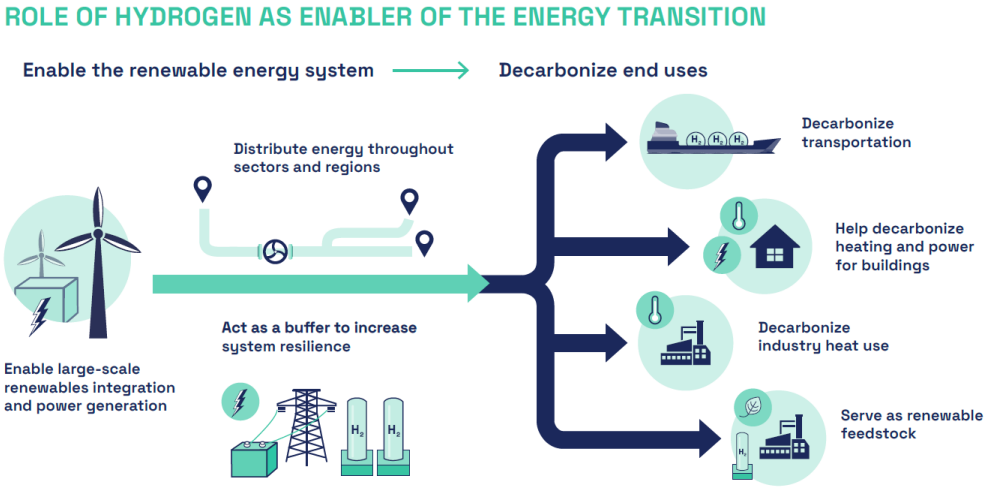


Figure 14: Hydrogen's role in the energy transition (Hydrogen Cluster Finland, 2021).

Because of the high heat of hydrogen flame (2 045 °C), hydrogen combustion can be used to produce high-grade heat needed in for example in many industrial processes (Nazir et al., 2020c). In ICEs or gas turbines, hydrogen can be combusted as a fuel alone or blended with other fuels such as gasoline, diesel, or natural gas (Zhang et al., 2014; Nazir et al., 2020c). Thus, hydrogen could be used to replace natural gas in gas turbines for example for peak electricity generation or in backup Fuel Cell (FC) power-only systems (Staffell at al., 2019).

Staffell at al. (2019) explain the structure of a FC. It consists of an anode, electrolyte, and a cathode. Chemical reactions which occur at the anode and the cathode produce water or carbon dioxide and electricity while a fuel that is continuously supplied is consumed. The produced electricity can then be used to power electrical devices, such as vehicles or stationary power generation applications, such as micro-CHP units (Zhang et al., 2014). The electrochemical conversion that occurs in FCs has higher energy conversion efficiency (40 – 60 %) than that of hydrogen combustion (34 – 40 %) (Staffell at al., 2019).

Regenerative Fuel Cells (RFC) are technical systems which can be used as an electrolyser to produce hydrogen using electricity and as a FC to produce electricity from hydrogen (Smolinka and Garche, 2021). They can also be called reversible FCs or secondary FCs. In charging mode, RFC consumes electricity and water and produces hydrogen and oxygen according to reaction 11. The hydrogen is stored in a tank as a pressurised gas while the oxygen most often is released into the atmosphere according to Smolinka and Garche (2021). When discharging the RFC, the reversible reaction of reaction 11 takes place and electricity and water are produced.

The main components of an RFC system are the water electrolysis stack, hydrogen and oxygen tanks and a power generator (FC stack). A regular heat engine or a gas turbine can be coupled into an RFC system as the power generator and any electrolysis cell type can be used. However, according to Smolinka and Garche (2021) currently the most developed RFC systems rely on PEM technology with two different main types of RFCs available.

The two main types of RFCs are Unitised RFCs (URFC) and Discrete RFCs (DRFC): DRFCs consists of two separate cell stacks – one electrolysis cell stack and one fuel cell stack. URFCs consist of a single cell stack which can be either run in electrolysis or fuel cell mode (Smolinka and Garche, 2021). DRFCs are larger and more expensive, but in operation more efficient and reliable than the single stack URFCs. An advantage to UFRCs is that they can reverse their mode of operation almost instantly, whereas DRFCs may require a battery backup to power the system during the transition period (Smolinka and Garche, 2021). Smolinka and Garche (2021) write that URFCs are currently mainly used in niche space and military applications, and that DRFC systems are more likely to be used for seasonal energy storage in the future.

Residential hydrogen boilers or FC micro-CHP units are available and have been deployed especially in Japan (Nazir et al., 2020c). According to Staffell at al. (2019), these FC micro-CHP systems have improved to an equivalent technical level as modern gas boilers in terms of product lifetime and reliability. However, they are still stated to be expensive. Currently residential gas boilers and furnaces mostly use natural gas and can only withstand low levels of blended hydrogen, but it is possible to convert them to run on pure hydrogen (Staffell at al., 2019). Catalytic boilers which produce lesser amounts of nitrous oxides -emissions are also in development (Staffell at al., 2019).

3.4.2 Industrial and non-energy use of hydrogen

Azzaro-Pantel (2018) explains that the refining industry consumes hydrogen in complex processes into which hydrogen is either provided externally as an input or as a produced byproduct. Hydrogen processes which involve hydrogen as an external input are said to include hydrocracking, hydrotreating and

desulphurization. Processes in which hydrogen is produced as a byproduct include catalytic or thermal hydrocracking and catalytic reforming. However, even in the processes where byproduct hydrogen is produced and consumed, the global hydrogen balance of the process is negative, which means that hydrogen needs to be fed into the system to feed these processes (Azzaro-Pantel, 2018).

As figure 11 showed, one of the biggest consumers of hydrogen is the fertilizer (ammonia) industry (IEA, 2019). The Haber-Bosch process is used in ammonia production, where nitrogen captured from air and hydrogen are synthetised together using an iron catalyst (Nazir et al., 2020c):

$$N_2 + 3\,H_2 \rightleftharpoons 2\,NH_3. \tag{14}$$

Recently ammonia has also been considered a potential carbon-free fuel or as a solution to store and distribute hydrogen. Combusting ammonia, however, does produce pollutants (NO_x), and very small (below 100 ppm) amounts of GHG nitrous oxide (N_2O) have also been observed (Mounaim-Rousselle and Brequigny, 2020). Currently no vehicles operating on ammonia as a fuel are commercially available and the authors Mounaim-Rousselle and Breguiqny (2020) note that so far there is a significant lack of studies conducted on the matter. However, Wärtsilä has announced that they are developing and testing an ammonia marine engine (Wärtsilä, 2022).

Hydrogen can be synthetised with carbon to produce a multitude of different hydrocarbon chemicals as shown in figure 15, through the beforementioned P2G or P2L -processes (Azzaro-Pantel, 2018). The carbon can be supplied for these processes either by CC of flue gases from industrial or energy production sites, or by capturing carbon from air via DAC (Mertens et al. 2020).

When these synthetic hydrocarbon fuels are combusted, carbon dioxide is emitted into the atmosphere. Thus, carbon neutrality of these fuels should be ensured by using carbon from biogenic sources or air (Mertens et al. 2020). Biogenic sources of carbon include biogas, biofuel production, and wastewater treatment plants (Ababneh and Hameed, 2022; Mertens et al. 2020). According to Ababneh and Hameed (2022) CCS technologies could be used to capture 50 – 94 % of carbon dioxide emitted by these industries. They also mention that CCUS of carbon dioxide emitted by combusted biomass would lead to negative carbon emissions.

DAC technologies include high and low temperature processes, both of which are at an early stage of development and mentioned by Ababneh and Hameed (2022) to be more expensive than the industrial flue gas CC technologies due to their 2 – 4 times higher energy consumption.

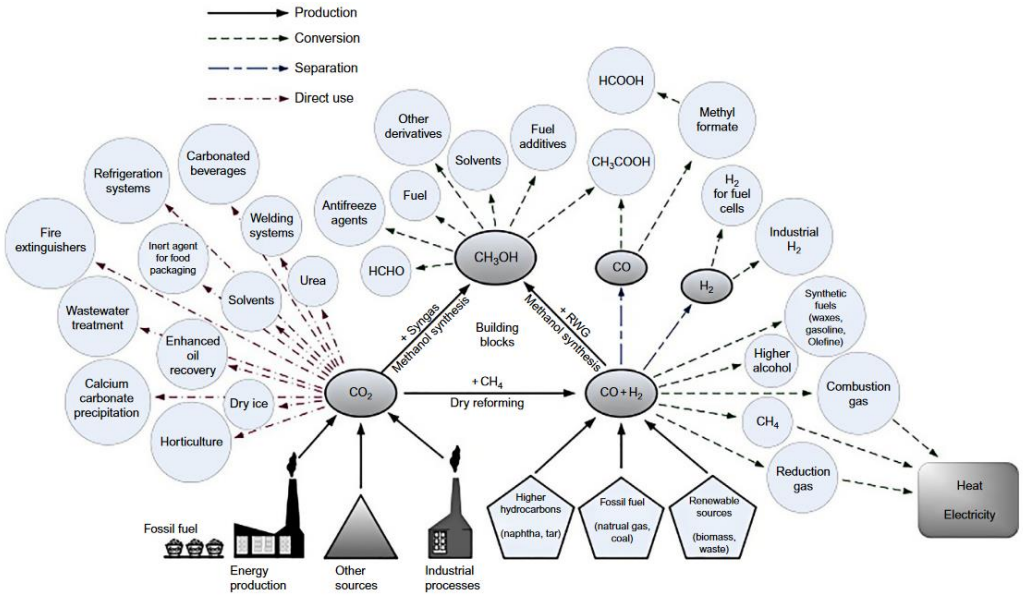


Figure 15: Hydrogen and carbon synthetic chemicals pathways (Azzaro-Pantel, 2018).

Other industrial consumers of hydrogen include metallurgy, glass industry, semiconductor industry and food industry (production of hydrogenated fats) (Azzaro-Pantel, 2018). Hydrogen can also be used as a coolant for example in power stations, aviation, aerospace applications or in the superconductor industry (Zhang et al., 2014). According to Zhang et al. (2014), in metallurgical industry hydrogen is used to reduce metallic ores to their pure metallic forms, and that especially tungsten and molybdenum are reduced using hydrogen, while carbon and carbon monoxide are other commonly used alternative materials. Hydrogen is also used as a welding gas (Zhang et al., 2014). The chemical industry produces hydrogen as a byproduct in the chlor-alkali industry (Nazir et al., 2020c) in chlor-alkali electrolysis, which is used to produce chlorine (Cl_2) and sodium hydroxide (NaOH) (Smolinka and Garche, 2021).

Currently the steel sector produces about 7 % of all anthropogenic carbon dioxide emissions, and the increasing demand for steel is projected to increase steel production further by 25 % – 30 % by 2050. According to Holappa (2020), modernising steel production facilities and improving their energy efficiency could accomplish an emissions reduction of 15 – 20 %, but further emissions reductions could only be achieved by replacing the fossil coal products and natural gas currently used with low carbon or carbon-free fuels, such as hydrogen. Industrial-scaled pilot projects in Austria (H_2FUTURE), Germany (GrInHy2.0) and in the Nordic countries (HYBRIT) are currently underway aiming to develop steelmaking using hydrogen (Holappa, 2020).

3.4.3 Hydrogen in transport

Currently hydrogen demand in transport applications is insignificant in comparison to its demand in oil refining and the chemicals industry (see figure 11) (IEA, 2021b). In the future, hydrogen could be used more as a transportation fuel, either directly by utilising ICEs or FCs, or indirectly using e-fuels (Staffell, at al. 2019).

Both for Fuel Cell Electric Vehicles (FCEVs) and FC trucks and buses the lack of refueling stations infrastructure is a major limiting factor to their wider deployment as stated by Nazir et al. (2020c). FCEVs fueled with hydrogen are commercially lacking behind and facing high competition from Li-ion Battery Electric Vehicles (BEVs), even though FCEVs driving range and refilling time compete well with BEVs according to Nazir et al. (2020c). So far, Toyota, Honda, and Hyundai have commercially released FCEV models (Nazir et al., 2020c).

According to Staffell et al. (2019), FCEVs might be the best decarbonisation technology available for heavy-duty buses and trucks, the costs of which have been reducing significantly during the last decade (Nazir et al., 2020c). Nazir et al. (2020c) lists that Toyota, Hino, Daimler, Volvo, Hyundai, Hyzon Motors, and Nikola Motor company are developing FC trucks, and that Nikola Motor company has received at least 13 000 preorders for their FC trucks. The amount of FC buses in Europe has been increasing from less than 50 units in 2012 to about 400 units in 2019, and China is also mentioned to have planned for the deployment of hundreds of FC buses (Nazir et al., 2020c).

In railway transport hydrogen can be burned in an ICE or used in a FC (Ustolin et al., 2022). Hydrogen was first deployed in railway transport in 2002 in Canada, after which multiple hydrogen train projects have been initiated: A FC train started its operation in Germany in 2017 (Ustolin et al., 2022), UK and France have planned to replace their diesel trains with FC trains by 2035 and 2040 respectively, Swedish and Polish actors (Inlandsbanan and Pesa Bydgoszcz SA) have signed letters of intent to start developing FC powered freight trains in their countries, and Japan has planned a FC train to operate between Yokohama and Kawasaki (Nazir et al., 2020c). A FC tram is expected to start operating in St. Petersburg Russia in 2022/2023 (Nazir et al., 2020c) and FC trams are also being developed and operated in China (Staffell at al., 2019).

Aviation is considered one of the most difficult sectors to decarbonize; biofuels and hybrid electric systems have been researched but would not lead to full decarbonisation or suffer from limited availability (biofuels) according to Staffell at al. (2019). In 2020, Airbus revealed three concepts of new zero-emission commercial aircrafts (designed for 100-200 passengers), which could enter service by 2035 (Airbus, 2020). However, Airbus emphasises in their press release that the scale-up of hydrogen to become a primary aviation

fuel requires “significant hydrogen transport and refueling infrastructure” at the airports (Airbus, 2020).

In a study by Goldmann et al. (2018), the use of five e-fuels (n-octane, methanol, methane, hydrogen, ammonia) as possible carbon-neutral replacement fuels for the aviation industry were analysed, n-octane was found to have very similar physical properties to existing jet fuel. The study concluded that synthetic n-octane could potentially be used as a drop-in replacement fuel for conventional jet fuel, possibly requiring small amounts of other hydrocarbons to be mixed in to adjust some of the fuel properties. The other e-fuels’ properties were found to differ to an extent that their use would require more technical modifications to be made to the engine, fuel supply and tank system.

For maritime transport, Nazir et al. (2020c) bring up hydrogen-fueled ships and boats are being developed and built in several countries: Powercell Sweden Ab and Havyard Group are developing a FC power system into an existing maritime vessel, in France inland waterway boats are under development as well as megawatt-scale FC powered ships (by ABB and Hydrogène de France). In addition, Hyundai is said to be developing FC powered fishing boats. It is noted by (Staffell at al., 2019) that due to the long lifetimes of marine vessels, the adoption of hydrogen or other new propulsion systems may be slowed down and traction for hydrogen is not expected until after 2030.

Material handling equipment such as forklift trucks powered by FCs are another mobile application for hydrogen. Staffell at al. (2019) state that their advantage over electric forklifts is faster refueling, and compared to diesel units, they can be operated safely indoors due to lack of emissions. Over 20 000 FC powered forklifts have already been sold in the USA by Plug Power, and multiple companies (Toyota Motor Corporation, BMW Manufacturing Co., Coca-Cola, FedEx Freight, Mercedes, Procter and Gamble, IKEA, Sysco, etc.) have indicated their interest in these products according to Nazir et al. (2020c). In addition, Hyundai Motor Group is said to be developing mass production of FC powered excavators to start in 2023. Other agricultural and recreational machinery could also adopt FC technology in the future (Staffell at al., 2019).

4 Role of hydrogen in Finland

This chapter examines assessments published so far about the role of hydrogen in Finland. The goal of this chapter is to form a picture of the potential role of hydrogen in Finland in the coming decades. It is to be noted that in this thesis the focus was on scenarios that specifically focus on hydrogen or the hydrogen economy in Finland. The chapter presents and summarises the main findings of the following assessments:

- Vetytalous – mahdollisuudet ja rajoitteet (Prime Minister's Office, 2022)
- A systemic view on the Finnish hydrogen economy today and in 2030 – Our common playbook for a way forward (Hydrogen Cluster Finland, 2021)
- Hydrogen development in Finland (Gasgrid Finland Oy and Guidehouse, 2021)
- National hydrogen roadmap for Finland (Business Finland, 2020)
- Hiilineutraali Suomi (LUT University et al., 2020)

Three of these assessments include results of modelled hydrogen scenarios (Prime Minister's Office, 2022; Gasgrid Finland Oy and Guidehouse, 2021; LUT University et al., 2020) – the main results of these scenarios are examined in chapter 4.3. The other two (Hydrogen Cluster Finland, 2021 and Business Finland, 2020) focus more on an assessment of Finnish strengths and weaknesses, key players, and the hydrogen value chain – the main findings of which are presented in chapter 4.2.

4.1 Hydrogen production and consumption in Finland

Little public data or statistics about hydrogen production or consumption in Finland can currently be found. However, hydrogen is included in the fuel classification (OSF, 2022a) used to produce statistics about the use of fuels in energy production and industries in Finland.

According to Statistics Finland's energy supply and consumption statistics (OSF, 2022b), the consumption of hydrogen in 2020 was 401 GWh, which corresponded to a 0.1 % share of total energy consumption in Finland. Figure 16 presents the data showing how hydrogen consumption has developed in Finland 1995 – 2020. The data includes only direct combustion of hydrogen for energy and thus does not include hydrogen used as a raw material (non-energy use of hydrogen) (OSF, 2022c).

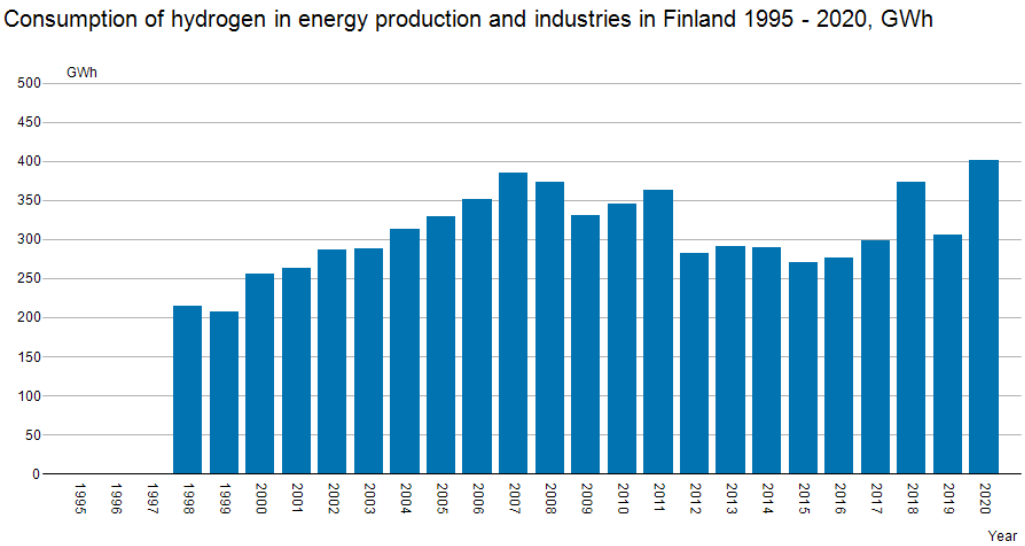


Figure 16: Consumption of hydrogen in energy production and industries in Finland from 1995 to 2020 in GWh (OSF, 2022b).

According to the national hydrogen roadmap by Business Finland (2020), hydrogen production in Finland was about 140 000 – 150 000 tons of dedicated hydrogen production and an additional 22 000 – 24 000 tons of by-product hydrogen production from sodium chloride (NaCl) electrolysis (figure 17). According to Business Finland (2020), this corresponds to an energy content of 5.4 – 8.8 TWh for the total amount of produced hydrogen in Finland.

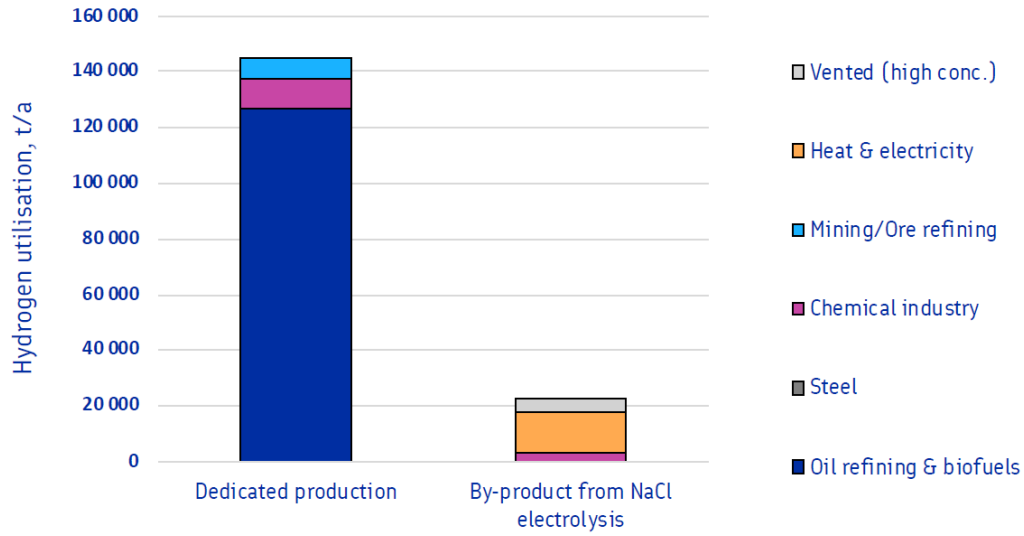


Figure 17: Hydrogen production and consumption in Finland (Business Finland, 2020).

Steam reforming or partial oxidation of fossil fuels is stated to account for 99 % of the dedicated hydrogen production, while less than 1 % is produced using water electrolysis. Business Finland states that due to data availability, these production estimates do not include the amounts of by-product hydrogen produced and consumed during the oil refining processes. However, this byproduct hydrogen is mentioned to be significant. The difference of 5.0 – 8.4 TWh between the total produced amount of hydrogen (5.4 – 8.8 TWh, Business Finland 2020) and the consumed amount of hydrogen (0.401 TWh in 2020, OSF, 2022b) is probably largely explained by non-energy use of hydrogen which is currently not included in the scope of official energy statistics (OSF, 2022c).

According to Business Finland (2020), most (88 %) of the dedicated hydrogen is consumed in oil refining and biofuel production (e.g. in hydrocracking and hydro-treating), while the chemical industry consumes about 7 % (in hydrogen peroxide production) and the mining industry about 5 % (in hydrogen sulfide production, reduction of cobalt and nickel, copper refining). Most of the by-product hydrogen is used in energy production to produce process steam, district heat and electricity at the chlor-alkali plants (Business Finland, 2020).

Figure 18 shows a map (Business Finland, 2020) presenting the current hydrogen production sites in Finland including their annual production outputs and production technology types. The biggest production site can be seen to be at an oil refinery (Neste Oyj) in Porvoo. The national hydrogen roadmap (Business Finland 2020) mentions that byproduct hydrogen production occurs also at another oil refinery in Naantali (Neste Oyj), but that the plant has been announced to be closed in a few years and due to not having dedicated hydrogen production it is not included in the map.

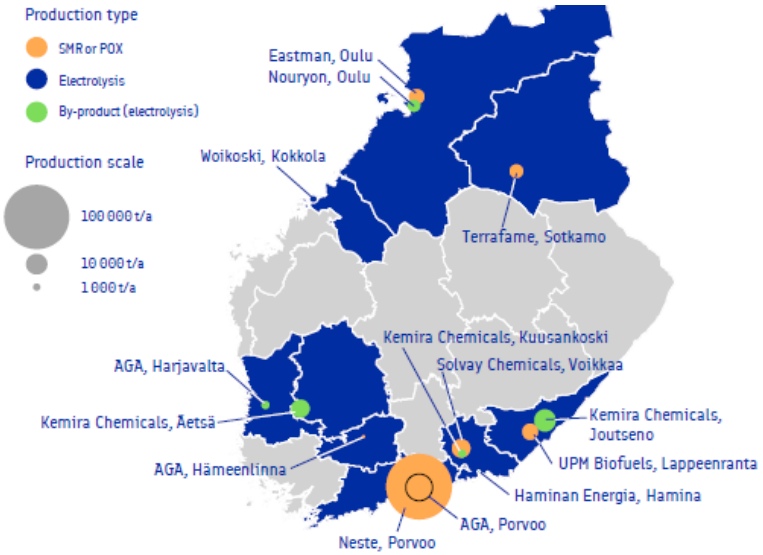


Figure 18: Map showing current hydrogen production facilities in Finland (Business Finland, 2020).

4.2 Hydrogen value chain in Finland

Both the national hydrogen roadmap (Business Finland, 2020) and system-level whitepaper vision of the Finnish hydrogen economy by Hydrogen Cluster Finland (2021) define the components of the hydrogen value chain to comprise of renewable electricity production, hydrogen production, logistics and utilisation. The possible most significant consumer fields of hydrogen in Finland are assessed to be oil refining, industrial chemicals and P2X, power generation and storage, steel production, zero emission transport and exportation (Business Finland, 2020).

Both Business Finland (2020) and Hydrogen Cluster Finland (2021) mention the availability of reliable and clean electricity, especially onshore and offshore wind power as a strength for Finland's hydrogen economy. They both also emphasise the existing strong transmission grid and energy infrastructure of Finland, as well as Finland's stable and predictable regulatory environment (Hydrogen Cluster Finland, 2021; Business Finland, 2020). High demand and existing infrastructure of district heating, and a considerable amount of energy intensive industries such as forest industry, mining, metals and chemical processing already exist in Finland and could potentially utilise hydrogen in their decarbonisation according to Hydrogen Cluster Finland (2021). Integrating hydrogen production with the production of district heat and/or industrial steam would increase the commercial viability of currently expensive hydrogen production. It is also mentioned that using power-to-hydrogen and/or power-to-heat -processes, hydrogen could be used as a balancing element of the electricity grid by transforming excess electricity into heat or hydrogen. Substantial freshwater resources of Finland are also listed as one of Finland's key advantages (Hydrogen Cluster Finland, 2021).

In addition to the strengths listed by Hydrogen Cluster Finland (2021), Business Finland (2020) mentions strong existing experience of industrial hydrogen use in Finland that could be expanded on in the future, and that existing producers of renewable transportation fuels could be significant consumers of low carbon hydrogen in the future. Similarly, relatively low electricity prices are mentioned to be favourable enough to replace and decarbonise the currently used fossil-based hydrogen with low carbon hydrogen. SSAB's plans to start producing carbon dioxide -free steel in about 2030 in Finland could be a major consumer of low carbon hydrogen (Business Finland, 2020; SSAB, 2022a; SSAB, 2022b). Producers of P2X chemicals (synthetic hydrocarbons) and producers of synthetic methane would also increase the low-carbon hydrogen demand.

The main weaknesses mentioned by Hydrogen Cluster Finland (2021) and Business Finland (2020) are the lack of geological hydrogen storage formations such as salt caverns, high price of required investments in distribution infrastructure (distant geological location) and higher electricity prices than in Sweden and Norway, the small size of Finland as a country and its

lacking funds, lack of shared vision and societal support, lack of competence in some strategic technological areas such as low-temperature electrolysis and lacking experience in hydrogen use outside of industries.

The lack of geological formations that could be used to store hydrogen at a low cost is mentioned as a weakness for Finland, although the possibility to use lined rock caverns instead is mentioned by Business Finland (2020). To transport hydrogen, the existing natural gas transmission grid allows for 1 % of hydrogen to be blended in it (IEA, 2019), and no existing dedicated hydrogen transmission pipeline network exists (Business Finland 2020). Transporting hydrogen in Finland by tube trailers or by repurposing some of the existing natural gas network pipelines are presented as plausible alternatives for Finland. The potential of chemical storage (such as LOHCs, see chapter 0) is seen as uncertain (Business Finland, 2020).

A European Hydrogen Backbone (EHB) initiative is a project that launched in 2020 with the aim to promote the development of a hydrogen market in Europe (European Hydrogen Backbone, 2022). The initiative consists of national European gas network operators and promotes construction of a European-wide hydrogen pipeline network (called the Hydrogen Backbone), which, if realised, could be a significant element affecting hydrogen economy in Finland. The map (figure 19) shows the planned Hydrogen Backbone network in Europe and in Finland. From the map it can be seen how the pipeline is planned to be situated near the west coast of Finland.

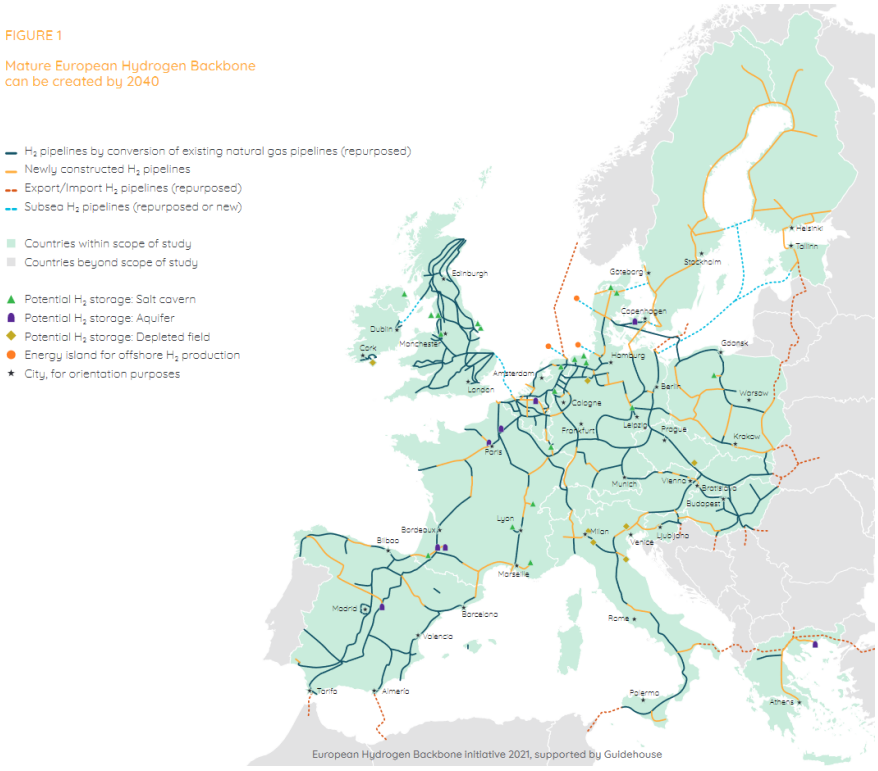


Figure 19: Map of the envisioned EHB Backbone network (European Hydrogen Backbone, 2022).

4.3 Hydrogen scenario results

Prime Minister's Office (2022) created five hydrogen scenarios (maximum A, maximum B, moderate growth, essential only A and essential only B) to assess the feasibility and effects of hydrogen economy in Finland. All their scenarios assume that Finland reaches its carbon neutrality target by 2035.

The essential only -scenarios (Prime Minister's Office, 2022) focused on national demand of hydrogen while the maximum -scenarios considered also export of hydrogen and/or e-fuels in addition to the national demand of hydrogen, so the essential only -scenarios assess the minimum (national) demand by industries and transportation. The moderate growth scenario assumes slower development of the hydrogen economy and that steel industries adopt a different solution from hydrogen to decarbonise. The essential only A scenario assumes no hydrogen use by the steel industry and no emphasis on hydrogen by the oil refining industry, while the hydrogen consumption of these two industries is considered in the essential only B scenario.

The maximum scenarios assume that export is only limited by the amount of potential available onshore wind power (estimated upper limit at 80 GW by 2050) in Finland. The other maximum scenario (A) considers only export of e-fuels, while the other maximum scenario (B) considers export of both hydrogen and e-fuels. It is mentioned that the maximum scenarios require that Finland remains cost-competitive on the international hydrogen market and that the international hydrogen demand develops at least as much as the European Commission has projected (Prime Minister's Office, 2022).

The uses of hydrogen considered in the study (Prime Minister's Office, 2022) were national industries, national and international navigation and aviation, heavy duty road transport and the export of hydrogen and e-fuels. The use of hydrogen in energy production (electricity and heat production) was assessed to become insignificant and was thus not taken into consideration. The availability of onshore wind power and an international hydrogen pipeline transmission line (EHB) was taken into consideration (offshore wind excluded). Table 6 presents the main assumptions used in each of the scenarios (Prime Minister's Office 2022).

Table 6: Assumptions of the different scenarios (adapted from Prime Minister's Office, 2022).

	Essential only A	**Essential only B**	**Moderate growth**	**Maximum A**	**Maximum B**
Hydrogen and e-fuels for domestic and international transport are produced in Finland	Yes	Yes	Yes	Yes	Yes
Direct reduction of iron using hydrogen in steel industry	No	Yes	No	Yes	Yes
Heavy emphasis on pure hydrogen in oil refining	No	Yes	Yes	Yes	No
Finland's market share of European electric fuels in 2050	Small	Small	4 %	Europe's demand does not limit export of hydrogen	10 %
Export of hydrogen	No	No	Demand limited below 25 TWh/a	No	Demand of hydrogen does not limit the dimensions of the hydrogen pipeline

Renewable hydrogen production in Finland was estimated to be 3.7 – 7.9 TWh per year by 2030 and 6.4 – 132.9 TWh per year by 2050, depending on the scenario (Prime Minister's Office, 2022). The lower end estimates present the results of the essential only scenarios and higher production estimates the results of the maximum scenarios. In the essential only scenarios (Prime Minister's Office, 2022), the required electrolysis capacity would be 0.5 – 1.3 GW by 2030 and would rise to 2.6 GW by 2050 in the essential only B scenario, while remaining the same in the essential only A scenario. The additional wind power capacity required would be 1.1 – 5.2 GW and total investment costs about 6.2 billion EUR. In the maximum scenarios, the required electolyser capacity would be about 1.3 GW by 2030 and 27 GW by 2050. This would require about 53 GW of new wind power installations. Total cumulative investment costs would be about 90 billion EUR.

The assessment (Prime Minister's Office, 2022) emphasizes that in all scenarios where export was considered, the effect of the hydrogen economy on total electricity consumption of Finland is significant; in 2050 total electricity demand would double or more than triple depending on the scenario. The export potential is highly dependent on how the international demand, market and competition for hydrogen will develop and thus it is stated that the

full maximum production potential (maximum scenarios) is difficult to achieve in reality.

In the study (Prime Minister's Office, 2022), nationally the most important user sectors for hydrogen were found to be steel industry and the oil (and bio-oil) refining industry. The results of the scenarios are presented in figure 20 and 21. Figure 20 presents the consumption of hydrogen in steel production, replacement of gas, other metal industries and other final consumption of hydrogen across the scenarios essential only A and B ("Vain välttämätön"), moderate growth ("maltillinen") and maximum A and B ("maksimi").

Figure 21 (Prime Minister's Office, 2022) shows the consumption of hydrogen in oil refining, production of biofuels and e-fuels. Since only the moderate growth, maximum A, and maximum B scenarios considered international demand and export of hydrogen and/or e-fuels, hydrogen consumption and its variability in these sectors and in these scenarios is significantly greater than in the scenarios which only examined domestic demand (Prime Minister's Office, 2022).

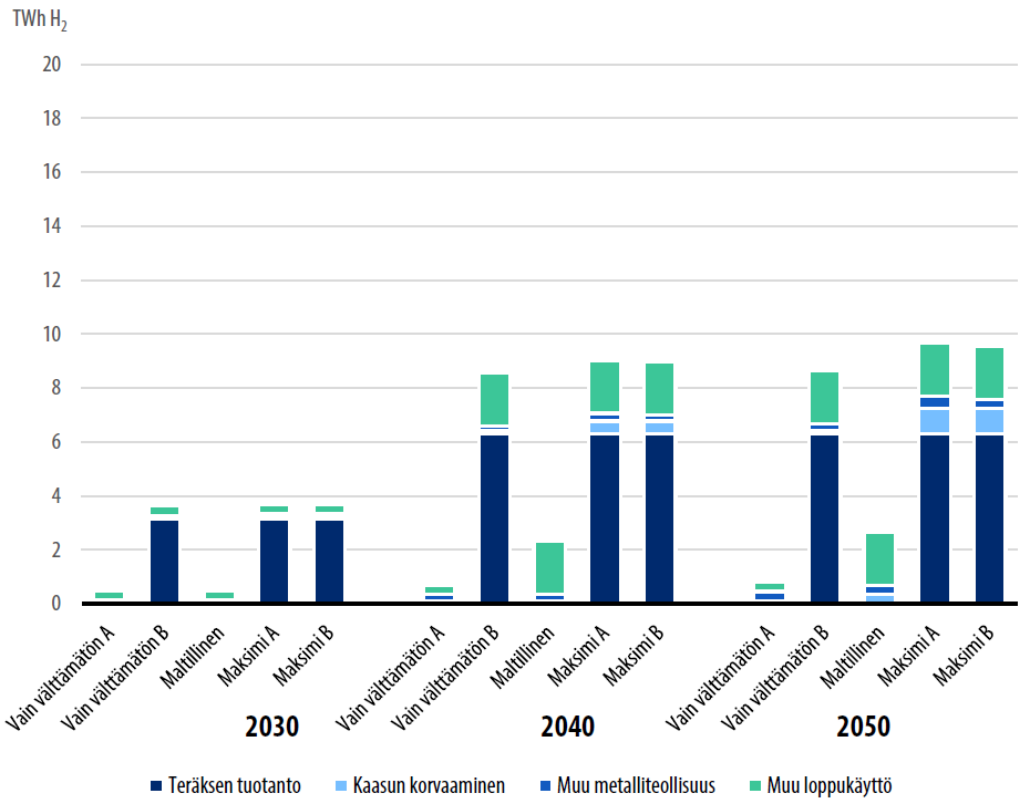


Figure 20: Hydrogen consumption in Finland by production of steel (dark blue), replacement of gas (light blue), other metal industries (blue), other final consumption (light green) (Prime Minister's Office, 2022).

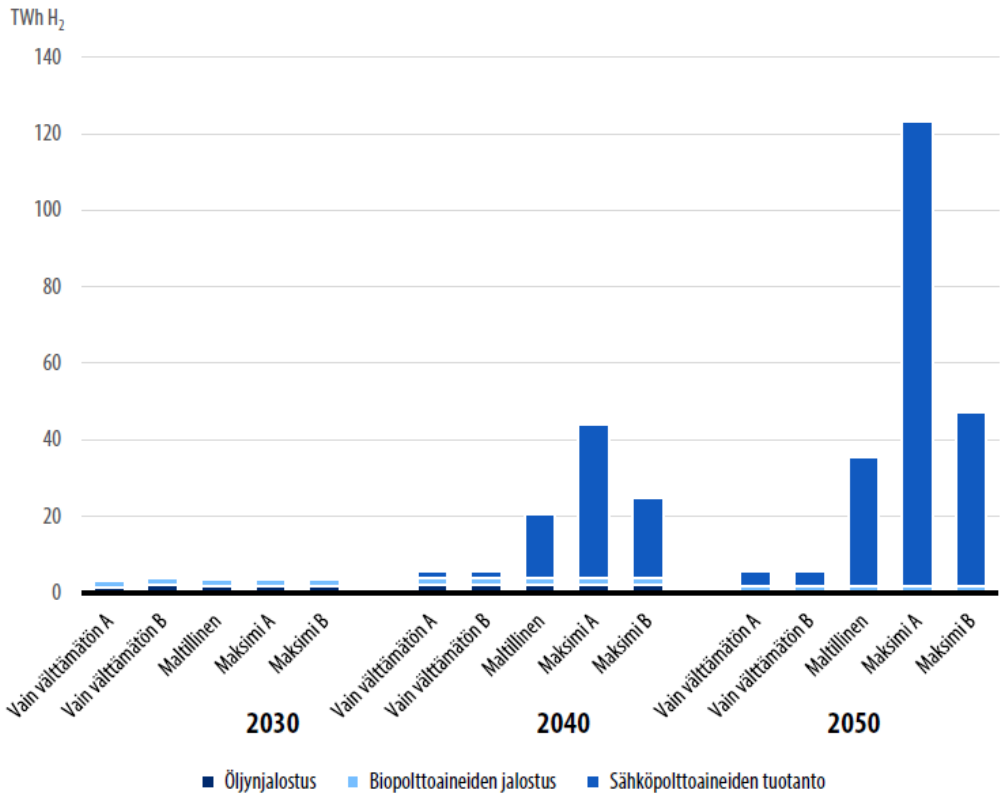


Figure 21: Hydrogen consumption by oil refining (dark blue), production of biofuels (light blue) and production of e-fuels (blue) in the different scenarios modelled (Prime Minister's Office, 2022).

A study conducted by Gasgrid Finland Oy and Guidehouse (2021) assessed hydrogen demand and export potential of Finland. According to their results, the green hydrogen production potential is about 50 TWh/a by 2030 and 150 TWh/a by 2050. Figure 22 shows the breakdown of how the excess supply of renewable wind and photovoltaic (PV) electricity could be used to produce green hydrogen (Gasgrid Finland Oy and Guidehouse, 2021).

Assessed (Gasgrid Finland Oy and Guidehouse, 2021) delivery cost of hydrogen from Finland, Bothnia region to Germany and is estimated at 2.2 EUR/kg of hydrogen, compared to 2.1 EUR/kg H_2 from Sweden (Bothnia region), 2.4 EUR/kg H_2 from Estonia, 2.2 EUR/kg H_2 from Ukraine and 1.8 EUR/kg H_2 from Spain, the price of exported hydrogen from Finland is stated to be competitive with other European countries.

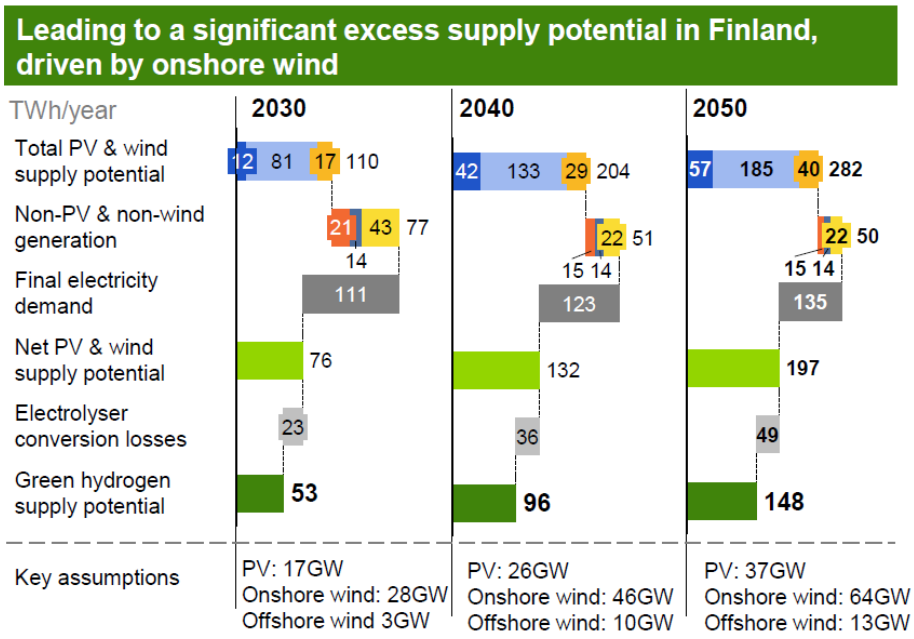


Figure 22: Supply potential of hydrogen (Gasgrid Finland Oy and Guidehouse, 2021).

The hydrogen supply potential is stated to rely on wind power production potential. Hydrogen production sites are estimated to be located in Southern Finland, while wind production sites are estimated to be mostly situated in Western Finland based on existing and planned wind power projects as shown in figure 23 (Gasgrid Finland Oy and Guidehouse, 2021).

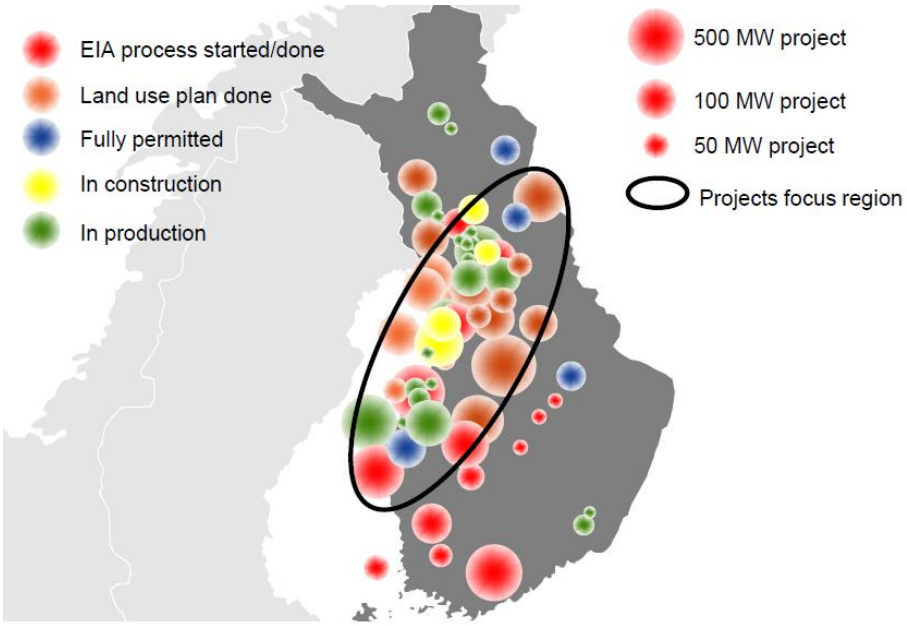


Figure 23: Planned and operational onshore wind production sites in Finland (Gasgrid Finland Oy and Guidehouse, 2021).

A third scenario assessment was conducted by LUT University, energy company St1 and manufacturing and service company Wärtsilä (LUT University et al., 2020). This study focused on the viability of producing carbon neutral P2X transportation fuels in Finland. The P2X fuels in the assessment would be produced from renewable hydrogen produced via electrolysis and carbon obtained from carbon dioxide streams from power plants and industrial units.

The study (LUT University et al., 2020) included three scenarios named: Business as Usual (BAU), BAU + P2X Bio, and BAU + P2X Bio and Fossil. The focus of the study was to assess how big of an effect large scale production of P2X fuels would affect Finland's electricity consumption and the report does not present results on how much of these synthetic transportation fuels could be produced annually in Finland. However, it is stated that the production technology for synthetic transportation fuels is in a mature stage and that about half of the carbon dioxide produced by the pulp mills in Finland would be enough to replace all transportation fuels (gasoline, kerosene and diesel) with their carbon neutral synthetic counterparts. International demand for carbon neutral transportation fuels was assumed to not be a limiting factor for exportation.

According to the results (LUT University et al., 2020), electricity consumption would increase from the current about 90 TWh to 140 – 540 TWh by 2040 depending on the scenario. Total investment costs would be 75 – 90 billion EUR, and income from exportation of fuels 10 billion EUR/a.

Total onshore wind power potential is estimated at 3 099 TWh/a, assuming that all of the windiest regions in Finland would be used one turbine per square km, with a 100 % utilisation rate. To produce enough excess electricity to cover the increase of electricity demand (462 TWh) created by the production of P2X fuels in the most electricity intensive scenario, a utilisation rate of 15 % of these wind production regions is assessed to be adequate. This would correspond to 21 400 wind turbines with a total power of 10 700 MW. For the least intensive BAU scenario, which is assessed to require 61 TWh of electricity, a utilisation rate of 2 % would be sufficient (corresponding to 2 900 turbines and 14 500 MW).

Thus, it is stated (LUT University et al., 2020) that wind power could supply enough electricity for the production of significant amounts of P2X fuels. However, the need for cross-country electricity transmission is estimated to increase, because wind power production would be concentrated in Northern Finland, while the point sources of carbon dioxide are said to be located in Southern Finland. The report brings up a question whether the transfer of electricity or hydrogen (or carbon dioxide) is less expensive, but the assessment of this was not in the scope of the study.

Comparison of the key findings of these assessments can be seen in table 7 below. The results may not be comparable because of differing scopes and assumptions used in the studies.

Table 7: Compiled results of examined hydrogen economy assessments in Finland (Prime Minister's Office, 2022; Hydrogen Cluster Finland, 2021; Gasgrid Finland Oy and Guidehouse, 2021; Business Finland, 2020; LUT University et al., 2020).

	Annual renewable hydrogen production potential	**Required renewable electricity capacity**	**Required electrolyser capacity**	**Total investment costs**
Prime Minister's Office (2022) essential only scenario A and B	about 4 TWh by 2030 and 6.4 – 14.3 TWh by 2050	1.1 GW – 5.2 GW by 2050	0.5 – 1.3 GW by 2030 and 2.6 GW by 2050	Below 6.2 billion EUR
Prime Minister's Office (2022) export-focused scenarios (moderate growth, maximum A and maximum B)	about 8 TWh by 2030 and 132.9 TWh by 2050	2.7 GW by 2030 and 53 GW by 2050	1.3 – 1.4 GW by 2030 and 27 GW by 2050	Below 90 billion EUR
Gasgrid Finland Oy and Guidehouse 2021	53 TWh by 2030 and 148 TWh by 2050	76 GW by 2030 and 197 GW by 2050	Undetermined	Undetermined
LUT University et al. 2020	Undetermined	15 – 107 GW by 2040	Undetermined	75 – 90 billion EUR

5 Hydrogen reporting, data collection and energy balance calculation

5.1 The Generic Statistical Business Process Model (GSBPM)

The Generic Statistical Business Process Model (GSBPM) is a tool developed in 2008 by a Joint Group compromising of The United Nations Economic Commission for Europe (UNECE), Eurostat and OECD (UNECE, 2022a and OSF, 2019). It is based on a business process model used by Statistics New Zealand and has been adopted as a standard framework for how to build and produce official statistics (UNECE, 2022a). The GSBPM model defines the processes needed to produce official statistics.

The GSBPM is not intended as a rigid framework with all steps needing to be considered or all of the steps followed in a specific order, instead it is advised to be used in a flexible manner (UNECE, 2022b). In practice the process steps presented in the model form iterative loops where individual steps might be revisited multiple times (figure 24).

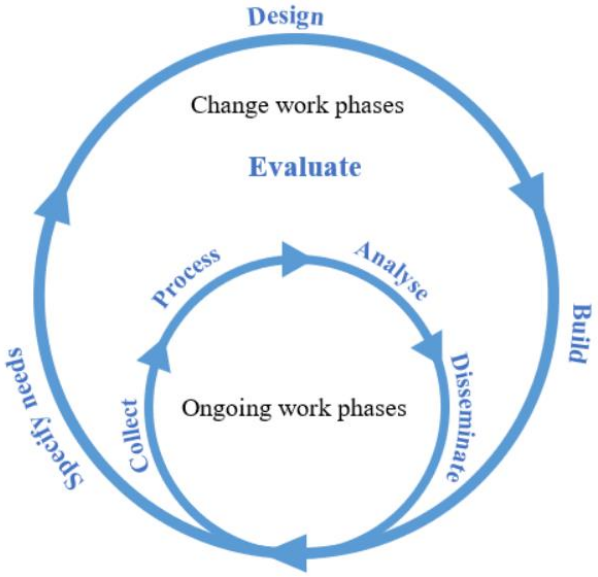


Figure 24: A diagram depicting the re-occurring iterative loops of the main process steps of the GSBPM (UNECE, 2022b).

Figure 25 presents the newest version 5.1 of the GSBPM (UNECE, 2022b). Based on UNECE (2022c), the first step “Specify needs” is concerned with identifying the most important needs, requirements, and already existing data for the statistics to be produced. The second “Design” -step is focused on the more technical design of variables to be collected, their descriptions, as well as the design of the actual data collection sample and instruments.

The process steps 3 – 6 concern data collection, processing and analysis, step 7 the publication process of the compiled statistics, and the final evaluation step 8 is concerned with analysing the whole preceding process to prepare for the continuation of the statistics in the next cycle (UNECE, 2022c).

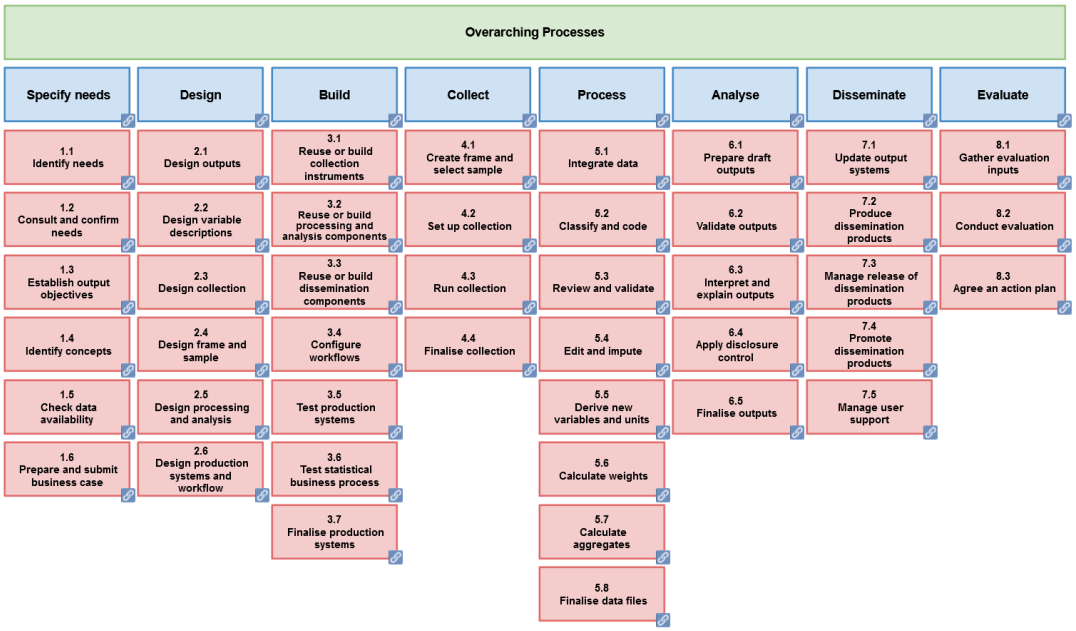


Figure 25: Process steps of the GSBPM version 5.1 (UNECE, 2022c).

In this thesis the GSBPM -model is applied loosely, focusing on the specify needs and design sub-process steps (figure 25). The design of hydrogen statistics is limited to the design of the data collection through a new hydrogen survey directed at all producers and significant users of hydrogen so, that the reporting requirements can be fulfilled. This corresponds to the GSBPM process steps 2.1 – 2.5 (figure 25). The suitability of using existing data sources in fulfilling the reporting requirements will be analysed in chapter 5.4.1 (GSBPM process step 1.5). The literature review (chapters 2 – 3) covers GSBPM step 1.4 in providing supporting background information on the important technologies used in relation to hydrogen.

The design of national statistics publications on hydrogen are outside the scope of this thesis. Data items deemed nationally important to be monitored can be included in the data collection on a voluntary basis even if they are not included in the mandatory requirements set by the new European regulation (2022/132) on energy statistics. However, consideration of this aspect is left out of the scope of this thesis (GSBPM process step 1.2).

Chapter 5.2 presents background information about international energy statistics, its terminology, reporting structure and calculation of the energy balance used in the EU. Chapter 5.3 presents the reporting requirements for the new hydrogen questionnaire and chapter 5.4 presents the results of the analysis of the existing data sources and data collection design. In the

upcoming chapters “hydrogen questionnaire” is used to refer to the new upcoming annual hydrogen questionnaire directed at statistics officials and “hydrogen survey” is used when referring to the new planned data collection on hydrogen data in Finland.

5.2 About the energy balance used in energy statistics

The energy balance is a statistical accounting tool of energy products (also referred to as energy carriers or fuels), used to track energy flows in the economy through and within the national borders (Eurostat, 2022b). As of February 2022, when the amended regulation 2022/132 came into force, the energy balance consists of about 90 different energy products. The energy balance is based on the conservation of energy (first law of thermodynamics), which states that in a closed system the total energy is constant, however it can be changed from one type to another (Eurostat, 2022b).

Eurostat (2022b) states that the energy balance is used to provide detailed and comparable information about the European Member States’ energy flows; how and where energy is produced and consumed. It is used as data to aid decision making, to construct and follow important indicators related to energy, such as import dependency, energy intensity and the sustainable development goal 7 affordable and clean energy.

The energy balance is also used to provide data for the calculation of GHG emissions from fuel combustion (Eurostat, 2022b). As about 75 % of all anthropogenic GHG emissions in the EU consist of carbon dioxide emissions from the energy use of fuels (Eurostat, 2022c), the energy balance is an essential tool to monitor the political measures set to prevent climate change as was discussed in chapter 2.

The scope of the closed system used in national energy statistics begins when an energy product is extracted from the natural environment into the economy and extends to the national borders of a state to track energy product flows through the national borders in time. For all produced or imported energy products that enter the system, some form of use (including energy losses) must be accounted for as energy cannot be destroyed (Eurostat, 2022b).

A commodity balance is first compiled individually for each of the individual energy products. Then, the complete national energy balance is formed by aggregating these individual commodity balances, while considering the transformation between fuels to avoid double counting their energy content (figure 26) (Eurostat, 2022b). EU Member States report their complete energy balances to the Eurostat annually through the use of annual questionnaires. Eurostat, as the statistical office of the EU then compiles and provides EU-wide energy statistics (Eurostat, 2022d).

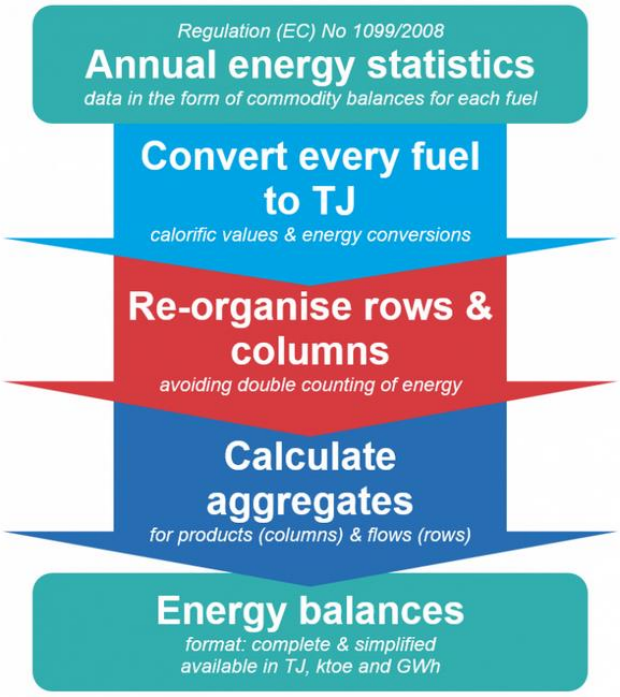


Figure 26: Steps of compiling the national energy balance (Eurostat, 2022b).

The Energy balance is categorised as physical accounting, where instead of monetary values of energy products, physical amounts (tons, cubic meters, etc.) are considered (Eurostat, 2022b). The physical units are converted into energy units (TJ, GWh, etc.) so that the amounts of different energy carriers can be aggregated and compared with one another. Also, it is important to note that the energy balance does not include only the sold quantities of energy products – the scope includes physical quantities of all produced and used energy products (Eurostat, 2022b).

In energy statistics, transformation refers to a process in which an energy product is transformed to another energy product – a transformation process always requires a transformation input and an output (Eurostat, 2022e). The energy products are divided into primary energy products and secondary (or derived) energy products, depending on if the fuel is produced as an output from a transformation process or not: Primary energy products are extracted from the natural environment, while secondary energy products are produced from primary or other secondary products through a transformation process (see figure 27) (Eurostat, 2022f). Due to thermodynamics, the energy content of transformation output is always lower than that of the input and to account for these energy losses, this difference is reported under transformation losses in the questionnaires (Eurostat, 2022e).

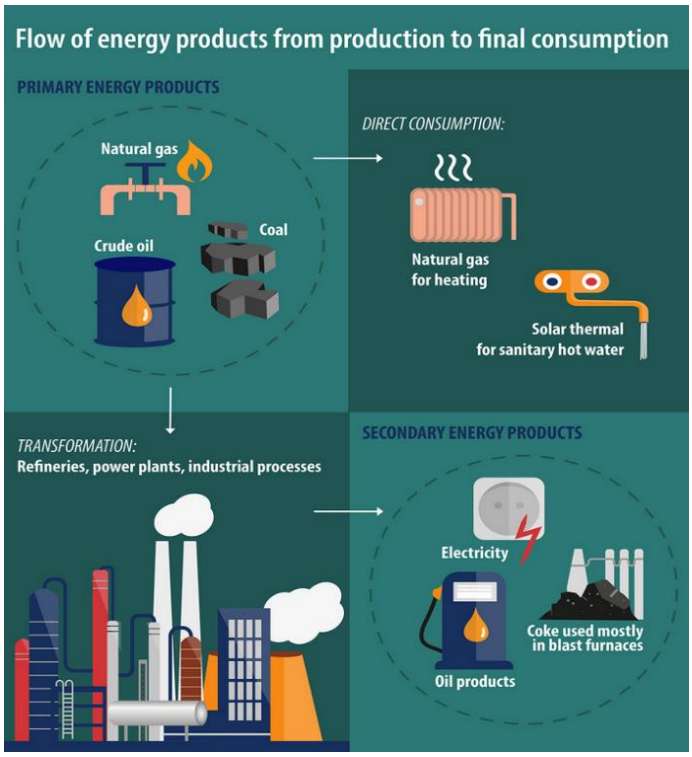


Figure 27: Flows of primary and secondary energy products in energy statistics (Eurostat, 2022f).

The individual energy commodity balances are reported in six annual questionnaires (electricity and heat, natural gas, coal, oil, renewables and wastes, nuclear). The figures 28 –30 below show sections from the 2020 renewables and wastes questionnaire (Eurostat, 2019a) presenting the commodity balance.

The basic elements of each commodity balance are the same, with some product specific details and differences. The balance consists of the so-called supply and consumption sides of the balance visible in figure 28. The supply side of the balance consists of indigenous production, imports and exports (national transboundary flows) and stock changes. Indigenous production refers to production of an energy product within the national borders (Eurostat, 2022g). The consumption side of the balance is divided into the transformation sector, energy sector and final energy consumption (figures 28 – 30).

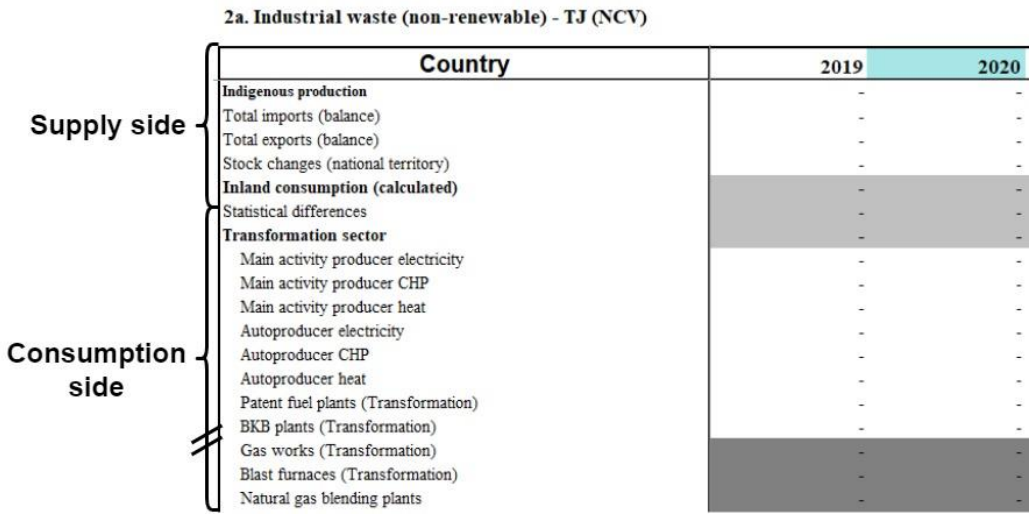


Figure 28: Section 1 showing the supply side and a part of the consumption side of the commodity balance for industrial waste (non-renewable) included in the renewables and wastes 2020 questionnaire (adapted from Eurostat, 2019a).

Between the supply side (visible in figure 28) of the balance and the consumption side of the balance (visible in figures 28 – 30) is the statistical differences -term (visible in figure 28) which can also be referred to as statistical error, as it is the difference between the calculated inland consumption and observed real consumption. The calculated inland consumption is calculated as

$$\text{Inland consumption} = \text{Indigenous production} + \text{total imports} - \text{total exports} + \text{stock changes}. \quad (15)$$

And the observed consumption is calculated as

$$\text{Observed consumption} = \text{transformation sector} + \text{energy sector} + \text{final energy consumption} + \text{distribution losses}. \quad (16)$$

The calculated inland consumption (equation 15) should equal observed consumption (equation 16), as the amount of energy within the national boundaries needs to remain constant so that energy supply equals energy use, due to the first law of thermodynamics. As multiple different sources of data are often used to compile the supply and consumption sides of the balance separately, a statistical difference of zero units might not be reached, but the objective is to minimise the statistical difference between the sides of the balance to minimise the statistical error. These instructions and equations 15 and 16 are from the official reporting instructions for the renewables

and wastes questionnaire and apply to all the questionnaires (Eurostat, 2019a).

Two different types of electricity and heat producers are distinguished in the energy balance: autoproducers and main activity producers. Main activity producers are privately or publicly owned enterprises whose primary activity is energy production to sell it to third parties (Eurostat, 2019b). In contrast, autoproducers' primary activity is not energy production – they produce electricity and/or heat to support their primary activity. Main activity producers consist of energy companies and autoproducers mainly consist of industrial enterprises (Eurostat, 2019b).

The reporting of energy products under transformation differs slightly for autoproducers and main activity producers (table 8): All production of electricity and all fuels used to generate electricity are always reported under the transformation sector (no matter if the producer is an autoproducer or a main activity producer). For heat, all heat and fuels used to produce heat are reported under transformation if the producer of heat is a main activity producer (Eurostat, 2019b). In case of autoproducers, only the quantity of heat sold, and the corresponding fuel consumption is reported under the transformation sector. So, for autoproducers fuels consumed to produce heat for their own consumption is reported under final energy use (Eurostat, 2019b).

Table 8: Reporting instructions for electricity, CHP and heat for main activity producers and autoproducers (Eurostat, 2019b).

	Electricity	**CHP**	**Heat**
Main activity producer	Report all production and all fuel used	Report all electricity and heat produced and all fuel used	Report all heat produced and all fuel used
Autoproducer		Report all electricity produced and only heat sold and corresponding fuel used	Report only heat sold and corresponding fuel used

If an energy product is consumed as an input to a transformation process, this is reported under the transformation sector. It is further divided into more detailed sectors based on where the transformation occurs as shown in figures 28 and 29. For example, in the case of non-renewable industrial waste, if it is used to produce electricity this consumption would be reported under the transformation sector in the correct data point based on where the consumption occurs. The electricity produced from this non-renewable waste is then reported in the electricity and heat questionnaire under the correct fuel.

NACE is an abbreviation from French "Nomenclature statistique des activités économiques dans la Communauté européenne" (Eurostat, 2016). It is the statistical classification of economic activities used in the European

Community. Fuels consumed by enterprises belonging to specific NACE sectors in supporting activities of mining, oil and gas production, and plant operation of transformation activities are reported under the energy sector (figure 29) (Eurostat 2019a).

Consumption of a fuel used to support pipeline operations (such as oil or gas pipelines) is reported elsewhere under the transformation sector (Eurostat, 2019b). For example, consumption of a fuel used in the operation of equipment such as coke ovens or blast furnaces would be reported under the energy sector. The input fuel which enters the actual conversion (transformation) process in the coke oven or blast furnace is reported under transformation (Eurostat, 2019c).

2a. Industrial waste (non-renewable) - TJ (NCV)

Country	2019	2020	2021
Blast furnaces (Transformation)	-	-	-
Natural gas blending plants	-	-	-
For blending with Motor gasoline/Diesel/Kerosene	-	-	-
Charcoal production plants (Transformation)	-	-	-
Not elsewhere specified (Transformation)	-	-	-
Energy sector	-	-	-
Gasification plants for biogas	-	-	-
Own use in electricity, CHP and heat	-	-	-
Coal mines	-	-	-
Patent fuel plants (Energy)	-	-	-
Coke ovens (Energy)	-	-	-
Oil refineries	-	-	-
BKB plants (Energy)	-	-	-
Gas works (Energy)	-	-	-
Blast furnaces (Energy)	-	-	-
Charcoal production plants (Energy)	-	-	-
Not elsewhere specified (Energy)	-	-	-
Distribution losses	-	-	-
Total final consumption	-	-	-
Final energy consumption	-	-	-
Industry sector	-	-	-

Figure 29: Section 2 (Energy sector) of the commodity balance for industrial waste (non-renewable) included in the renewables and wastes 2020 questionnaire (adapted from Eurostat, 2019a).

Distribution losses (visible in figure 29) include all energy losses which occur during the transport and distribution of the fuel in question. Final energy consumption (figure 30) consists of fuel consumption in other than energy sectors. It is further divided into industry, transport, and other sectors. The consumption of fuels under this category is mainly determined by the NACE code of the entity consuming the fuel (Eurostat, 2019b).

2a. Industrial waste (non-renewable) - TJ (NCV)

Country	2019	2020	2021
Total final consumption	-	-	-
Final energy consumption	-	-	-
Industry sector	-	-	-
Iron and steel	-	-	-
Chemical and petrochemical	-	-	-
Non-ferrous metals	-	-	-
Non-metallic minerals	-	-	-
Transport equipment	-	-	-
Machinery	-	-	-
Mining and quarrying	-	-	-
Food, beverages and tobacco	-	-	-
Paper, pulp and printing	-	-	-
Wood and wood products	-	-	-
Construction	-	-	-
Textiles and leather	-	-	-
Not elsewhere specified (Industry)	-	-	-
Transport sector	-	-	-
Rail	-	-	-
Road	-	-	-
Domestic navigation	-	-	-
Not elsewhere specified (Transport)	-	-	-
Other sectors	-	-	-
Commercial and public services	-	-	-
Residential	-	-	-
Agriculture/Forestry	-	-	-
Fishing	-	-	-
Not elsewhere specified (Other)	-	-	-

Figure 30: Section 3 of the commodity balance for industrial waste (non-renewable) showing the final energy consumption elements (adapted from Eurostat, 2019a).

5.3 Hydrogen reporting requirements

The new European regulation on energy statistics (regulation 2022/132) entered into force on 20 February 2022. As discussed in chapter 2, the official international reporting framework is periodically updated to reflect technological progress and new needs for data. The newest amendment (Regulation (EC) No 1099/2008) defined hydrogen to be included into the energy balance framework as a new energy product.

In the amended regulation (regulation 2022/132), hydrogen to be reported is defined as:

> Hydrogen used as a feedstock, a fuel or an energy carrier/storage must be reported. All hydrogen must be reported, regardless whether it is sold or not sold. When in a mixture, hydrogen should be reported only when it is the main component with a high degree of purity.

The regulation (2022/132) sets the following provisions to apply to all data collections:

a) Reporting period: The reported period of declared data will be a calendar year (1 January to 31 December), starting at reference year 2024.
b) Frequency: Data should be declared on an annual basis.
c) Deadline for transmission of data: Data should be submitted by 31 October of the year following the reported year unless otherwise specified.
d) Transmission format: The transmission format should conform to the relevant interchange standard specified by Eurostat.
e) Transmission method: Data should be sent in or uploaded by electronic means to Eurostat's single-entry point for data.

The annex B of the regulation (2022/132) lists the individual data items to be reported for all energy products. For hydrogen, mandatory data reporting will begin from the reporting year 2024 and data concerning 2022 and 2023 will be voluntary (attachment A). The detailed transmission format will be defined and published by Eurostat as stated by European Commission (2022/132).

Background documents from Eurostat include these initial definitions regarding hydrogen reporting (attachment A):

1) The reporting unit for hydrogen will be terajoules (TJ) and hydrogen is to be considered a secondary energy product.
2) Only high purity hydrogen (> 98 % hydrogen content) is reported. If hydrogen is present naturally in a gas (e.g. biogas, natural gas), this hydrogen will not be reported.
3) Non-energy and energy use will be reported.
4) Sold and not sold hydrogen are both included in the reporting.
5) Auto-produced and auto-consumed hydrogen needs to be reported.
6) Blended or injected hydrogen will be reported as for other blended fuels.

The draft hydrogen questionnaire provided by Eurostat (attachment A) is divided to six data sheets: production (chapter 5.3.1), transformation and energy sectors consumption (chapter 5.3.2), final consumption (chapter 5.3.3), stocks (chapter 5.3.4), trade (chapter 5.3.4) and capacities (chapter 5.3.5). In addition to hydrogen, the new questionnaire most likely will include a voluntary reporting column for ammonia and possibly other e-fuels, such as methanol (attachment A). However, ammonia or other e-fuels are not included in the energy statistics regulation (2022/132) and thus, not within the mandatory energy product framework.

5.3.1 Hydrogen production data sheet

As was discussed in chapter 3.1 no significant natural deposits of pure hydrogen gas are found on Earth, and thus hydrogen has been defined a secondary energy product and no data point for indigenous production of hydrogen is included in the production data sheet. Instead, produced amounts of hydrogen will be reported by the source energy product used (attachment A).

For natural gas, oil and petroleum products, solid fuels (coal), renewables and wastes, information about the use of CCS will be required (production without CCS, with "LOW" CCS where below 90 % of carbon dioxide is captured and "HIGH" CCS where above 90 % of carbon dioxide is captured). The exact definition for high and low CCS is pending. It is not yet decided if this refers to only CCS or if the utilisation of captured carbon (CCUS) will also be included. So far it is not certain if all Member States will be able to set the levels for what is considered low or high levels of CCS individually or if common thresholds will be defined. Also, how the share of captured carbon will be calculated has not yet been defined. The data points regarding CCS used in the production of hydrogen may also be moved to the shares tool instead of the hydrogen questionnaire, which is a tool used to monitor official policy targets regarding sustainability and shares of energy from renewable sources (Eurostat, 2022h). Regardless of what the exact definition for CCS will be, or in which questionnaire it will be reported in – data about the use of CCS and its CC-effectiveness in relation to hydrogen production will need to be collected.

Hydrogen produced with electrolysis will be reported under "from electricity (electrolysis)" (see figure 31 or attachment A). To be able to monitor the sustainability of hydrogen produced with electricity, the source of electricity needs to be reported. This section is thus further divided into hydrogen production using either a DTL or grid electricity.

DTL refers to an electrolysis facility directly connected to an electricity generation facility, for example an on-shore wind farm directly connected to an electrolysis plant (DTL: ELE from sustainable renewables) or a DTL connected to a nuclear power plant (DTL: ELE from nuclear). Under grid electricity the share of used grid electricity covered using green certificates is reported.

from electricity (electrolysis)	0.0	0.0
DTL: ELE from sustainable renewables		
DTL: ELE from nuclear		
DTL: ELE from fossil fuels		
grid electricity		
of which: green certificates		
other (by-product)	0.0	0.0

Figure 31: A section from the draft hydrogen questionnaire production sheet concerning electrolysis (attachment A).

Byproduct hydrogen is reported under “from electricity (electrolysis)” data point “other (by-product)” if hydrogen is produced as a byproduct in electrolysis (other than water electrolysis). Hydrogen produced as a byproduct in other processes than electrolysis is reported under the “other processes” element in “chemical reactions” (attachment A).

The data about hydrogen production must be collected in a way that distinguishes the source fuel used in its production. The amounts of fuels used for hydrogen production will need to be reported in the corresponding commodity balances of the source fuels as a transformation input, so both the consumption of the source fuel as well as how much hydrogen is produced need to be collected.

5.3.2 Transformation and energy sectors sheet

The draft transformation and energy sectors -sheet (attachment A) includes the supply and consumption sides of the balance. Here, on the supply side of the balance “indigenous production” refers to the total amount of produced hydrogen reported on the production sheet. Imports, exports and stock changes are also reported on their corresponding sheets and linked from there to this sheet.

Some identically named data points exist under transformation and energy sector, for example blended in gas grid, blended with fossil liquid fuels, and gas works. The difference being is the fuel (hydrogen) consumed as a transformation process input (reported under transformation sector), or as a fuel to support a transformation process (energy sector consumption). So, what is essential regarding these data points is that the data must be collected so that transformation use needs to be able to be separated from energy and final energy uses of hydrogen.

5.3.3 Final consumption sheet

The sheet for final consumption data (attachment A) includes final consumption of hydrogen and it is divided into industry, transport and other sectors. On this sheet both energy and non-energy use of hydrogen needs to be reported separately by sector; the data collection must be designed in such a way that this dissemination for reporting can be made.

The energy use on this sheet means consumption of hydrogen as a fuel, excluding the uses of hydrogen reported under transformation use. If hydrogen is used in supporting activities in energy production, it should be reported under the energy sector. If hydrogen is consumed in support of industrial operations, it should be reported on this sheet under the correct industrial sector.

Non-energy use refers to the use of a fuel as a raw material. For example, the use of hydrogen as a feedstock in the chemical industry to produce

ammonia, other fertilizers or chemicals would be reported under non-energy use of the chemical and petrochemical industry.

If hydrogen is used as a fuel in transport this consumption should be reported on this sheet under the correct transport sector (domestic aviation, road, rail, domestic navigation). International aviation and international navigation (maritime transport) are reported on the supply side of the balance on the transformation and energy sectors -sheet (chapter 5.3.2). International marine navigation is labeled “international marine bunkers” in the annual questionnaires.

Pipeline transport refers to fuel used to support the operation of pipelines that transport gases, liquids, slurries and other commodities. This includes the energy used for pump stations and pipeline maintenance work. This definition is taken from the instructions for the natural gas questionnaire (Eurostat, 2019c), however definitions between the questionnaires need to be commensurate for the data to be comparable.

5.3.4 Stocks and trade data sheets

The stocks sheet for hydrogen (figure 32) includes the annual opening and closing stock levels for hydrogen. Hydrogen stock levels need to be categorised based on how hydrogen is stored, either as a physical storage (pressurised or liquefied storage of pure hydrogen), or chemical storage where hydrogen is transformed into ammonia or other chemicals (see chapter 3.4).

Storage of hydrogen for both energy and non-energy purposes needs to be included, but not specified separately on this sheet. It is so far unclear how or if hydrogen losses occurring during chemical storage phase will be reported (see chapter 3.4).

2022	Hydrogen						e-Fuels
	Physical storage (Pure)		Chemical storage				
TJ NCV	Pressurized	Liquefied	As Ammonia	Other chemicals	Others	TOTAL	
Stock (national territory) _Opening							
Stock (national territory) _Closing							

Figure 32: Stocks and storage sheet of the draft questionnaire for hydrogen (attachment A).

On the trade information sheet imports and exports of hydrogen (mandatory) and e-fuels (voluntary) data is reported by country of ultimate origin (figure 33). If the ultimate origin of imports or exports is not known, the data is reported based on the country of previous consignment as is done for all other energy products.

2022 TJ NCV	Hydrogen		e-Fuels	
	imports	exports	imports	exports
Albania				
Algeria				
Andorra				
Angola				
Argentina				

Figure 33: A portion of the trade sheet of the draft questionnaire for hydrogen (attachment A).

5.3.5 Capacities sheet

The energy statistics regulation (2022/132) requires the capacities sheet to mirror that of the production data sheet. For this reason, the capacities sheet is divided based on the source fuels used in hydrogen production (including information about the use of CCS), rather than the different technology types used (SMR, electrolysis, etc.) (attachment A). It is not yet clear which capacity is to be reported, the draft questionnaire (attachment A) proposes installed capacity, hydrogen production capacity, or electricity production capacity to be reported in terajoules. It is not yet clear if the terajoules refer to the energy content of produced hydrogen or the source fuel used, or what the exact definition for the production capacity will be (e.g. the designed maximum production capacity or the observed annual production capacity). The detailed definition for the capacity of CCS is also uncertain as of now.

In its current form, the capacities need to be reported by the used source fuels instead of technology types used. Since some of the production technologies can use multiple different types of fuels that can vary annually, the reported production capacities might then vary year-by-year based on the consumption of different fuels. In this case, the reported annual capacities would not really reflect the actual built technical production capacity of hydrogen. It may be necessary to produce these capacities computationally.

5.4 Data collection design

This chapter focuses on the GSBPM step “1.5 check data availability”. The goal is to examine if existing data sources can meet the requirements and conditions for the statistics to be produced. The existing data sources may be for example administrative data sets (UNECE, 2022d).

This step is also required by the Finnish Statistics Act (280/2004), which stipulates:

> When compiling data for the compilation of statistics, priority shall be given to data collected in the performance of public administration tasks and generated as a result of the normal activities of traders, associations and foundations.

Thus, the options to use alternative existing data sources will next be examined, after which the new hydrogen survey form will be designed considering what data might already be available and need not be collected.

5.4.1 Existing data sources

The relevant existing data sources at Statistics Finland were identified and are presented below. Each of the data sets' boundaries and scope in relation to the requirements of the hydrogen questionnaire were analysed to examine if any of them could be used. The chosen data sets were included in this analysis based on them including some data about hydrogen.

The information compiled here about the possibilities and limitations of each of the datasets and registries has been collected by examining the contents of each of the datasets, the available documentation regarding each dataset and by consulting statisticians at Statistics Finland who are familiar with the contents and definitions of the data sets.

- industrial output -statistics data (OSF, 2022d)
- emissions trading registry data (Energy authority, 2022b)
- energy use in manufacturing -statistics data (OSF, 2022e)
- environmental protection reporting service data (Centre for Economic Development, Transport and the Environment, 2022)
- data on raw material hydrogen production (OSF, 2022f)
- international trade -statistics data (Finnish Customs, 2022)
- production of electricity and heat -statistics data (OSF, 2022g)

Table 9 presents the findings related to each existing data source listed above and their suitability to be used as they are for the hydrogen questionnaire.

Table 9: Table presenting the results of analysing the suitability of existing data sources for the hydrogen questionnaire.

Existing data source	Data administrator	Suitability for hydrogen questionnaire	Main data deficiencies
Industrial output statistics data (OSF, 2022d)	Statistics Finland	Not sufficient for filling the questionnaire. Can be used to identify relevant companies.	No data on hydrogen production, all hydrogen producers not within scope (by-product hydrogen), no data on hydrogen consumption, storage, capacities or international trade
Emissions trading registry data (Energy authority, 2022b)	Energy Authority	Can be used to validate data on individual companies, can be used to identify relevant companies.	No data on hydrogen production, no data on non-energy use, not all consumers of hydrogen within scope, no data on hydrogen storage, capacities or international trade
Energy use in manufacturing data (OSF, 2022e)	Statistics Finland	Can be used to compile data about transformation and some energy uses of hydrogen in enterprises working in industrial sectors. Can be used to identify relevant companies and verify individual data points.	No data on hydrogen production, no data on non-energy use, not all consumers of hydrogen within scope, no data on hydrogen storage, capacities or international trade
Environmental protection reporting service data (Centre for Economic Development, Transport and the Environment, 2022)	Centre for Economic Development, Transport and the Environment	Not suitable for filling the questionnaire. Can be used to identify relevant companies and verify individual data points.	Includes mandatory monitoring data required by environmental permits – data varies from operator to operator and is not in a form that is technically easy to collect from the system for statistical purposes.
Data on raw material hydrogen (OSF, 2022f)	Statistics Finland	Not suitable for filling the questionnaire. Can be used to identify relevant companies and verify individual data points.	Does not include all production of hydrogen or data about the use of CCS in hydrogen production. No other hydrogen data included.
International trade statistics data (Finnish Customs, 2022)	Finnish Customs	Suitable for the reporting of hydrogen international trade data.	None.
Production of electricity and heat statistics data (OSF, 2022g)	Statistics Finland	Can be used to compile data about transformation and some energy uses of hydrogen in enterprises working in energy and industrial sectors.	No data on hydrogen production no data on non-energy use, not all consumers of hydrogen within scope, no data on hydrogen storage, capacities or international trade

All the recognised existing data sources have significant deficiencies in their data content in relation to the new hydrogen questionnaire's requirements, apart from international trade statistics data provided by Finnish Customs (table 9). Only this dataset can be used as it is to cover the international trade data reporting requirements set for hydrogen (presented in chapter 5.3.4).

The monthly dataset received by Statistics Finland from the Finnish Customs (Finnish Customs, 2022) includes data about international trade of commodities. The classification of products is based on the Combined Nomenclature (CN) classification of goods, which is used in all Member States of the EU (Finnish Customs 2021a) and includes a code for hydrogen (2804 10 00) (Finnish Customs, 2021b). This dataset is used in international trade data reporting of other energy products as well and is suitable to fill the upcoming reporting requirements set for the hydrogen questionnaire as well. The annual data can be compiled from this dataset by summing up the monthly import and export data.

Data about energy use of hydrogen is already included in energy statistics produced by Statistics Finland as was discussed in chapter 4.1, but especially comprehensive hydrogen production data and non-energy consumption data are lacking in the existing datasets. Hydrogen storage and production capacities data also does not exist. The data on hydrogen that is available in these datasets is fragmented and does not directly meet the needs of the questionnaire, because of the differing scope of each dataset.

Some of the existing datasets can be used to identify new enterprises that more detailed data may need to be collected from, such as industrial output statistics (OSF, 2022d), which contains value and quantity data on domestically produced products, including hydrogen, by industrial companies. Its scope is not comprehensive enough as it only includes enterprises classified in the NACE industrial sectors B, C and E and excludes producers of hydrogen whose branch might differ from these. It also does not include data detailing the production technologies or input fuels used in the production of hydrogen.

The same applies for the energy use in manufacturing (OSF, 2022e) statistics, which includes information about the use of energy products in manufacturing. This statistic is compiled using its own sample-based data collection and data provided by other datasets and registries, such as the emissions trading registry data (Energy authority, 2022b and OSF, 2022h). It includes all energy use of those enterprises whose NACE is defined as belonging into mining and quarrying (B) or manufacturing (C) but excludes all non-energy use. Some enterprises overlap in this statistic and in the production of electricity and heat statistic (OSF, 2022h).

In the data collection for energy use in manufacturing statistic, hydrogen is classified as a rare energy product, which means that all the known consumers of hydrogen need to provide their hydrogen consumption data

annually, thus the acquisition of hydrogen consumption data is not dependable on hitting the random sample otherwise used. This dataset can be used in identifying companies consuming hydrogen for energy use within industries, but since the data does not include detailed information about in which processes hydrogen has been used (only the total amount), this data cannot really be used in filling the hydrogen questionnaire.

A benefit to a new dedicated data collection on hydrogen is that the collected data can be used to supplement the existing statistics on energy and GHGs. Since hydrogen is currently undergoing unprecedented political and media interest, it is possible that additional hydrogen-related information needs arise later. Responding to these user needs is easier if a focused data collection on hydrogen is already implemented. The existing data sources analysed can be used to compare and verify the data acquired through this data collection, this would be part of the later data analysis stage.

5.4.2 Design of the new hydrogen data collection survey form

The new data collection on hydrogen was implemented as an excel survey form (attachment B). Later, the excel survey form will be implemented as an online form using the existing surveying services used by Statistics Finland, such as XCola or Webropol (outside of thesis scope).

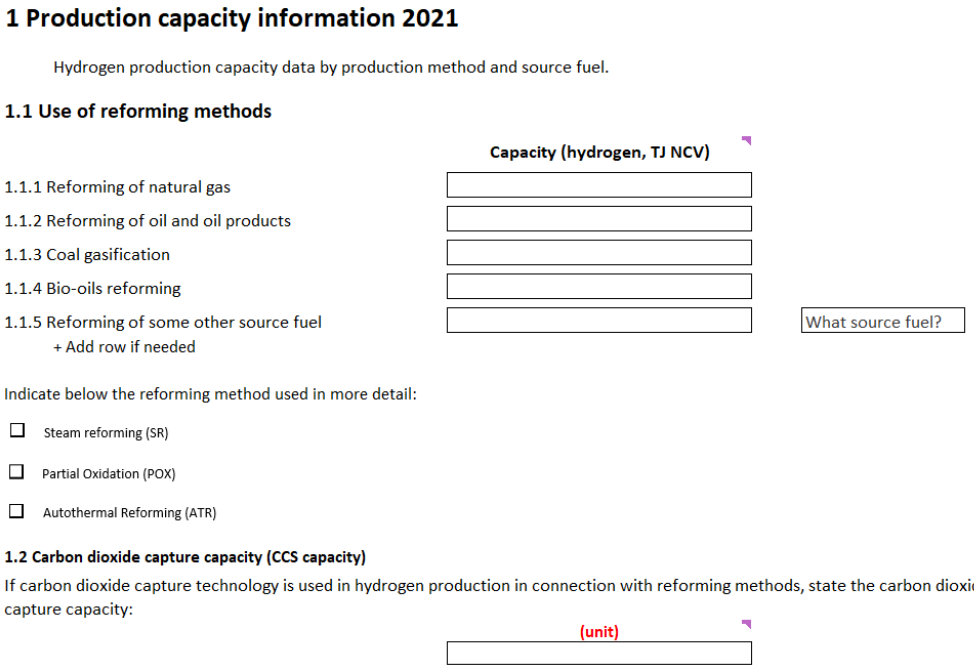
The data collection is planned as a census survey, where all targets of the population (all significant producers and consumers of hydrogen) are included. The hydrogen data is collected on a facility or enterprise scale so that the full hydrogen balance of the collection unit is considered; all produced or acquired hydrogen needs to be reported to some form of consumption, because due to the first law of thermodynamics no energy (hydrogen as an energy carrier) can be lost in a closed system. Here, consumption includes all flows of used hydrogen, including hydrogen leaks, storage, and distribution of hydrogen to other operators/enterprises. Therefore, the survey form contains detailed information on hydrogen consumption.

The decision to collect data either on an enterprise scale or on a facility scale should be consulted from the relevant companies to ensure minimal response burden. If the data is collected on a facility scale, it will require the respondents to fill the survey form multiple times in case they own multiple facilities.

The hydrogen survey form (attachment B) consists of five data sheets: contact, production capacity, production, and consumption information sheets. On the contact information sheet basic contact details for the survey will be collected, divided into contact person information and facility location information. The status of operations and starting year of operations (as well as cessation of operations) is collected. A comment field where the respondent can give additional information regarding the operations of the facility is presented on this page – here the informant is asked to report for example major

disruptions or changes in their operations. This information is collected, because it is helpful in the later stages of data analysis when the collected data is reviewed and scanned for possible errors (GSBPM stages 5.3 and 5.4, see figure 25). In this stage anomalous data or outlier data points need to be reviewed and possibly confirmed from the informant if no additional information has not already been provided during the data collection stage.

The production capacity information sheet (figure 34) mirrors that of production data but was designed so that both technical information about production technologies, and capacities divided by source fuels can be collected. As the reporting requirements demand the capacities to be reported by the source fuels used (see chapter 5.3.5). To achieve this, the source fuel is connected directly to the production technology, for example by asking the respondent to inform the production capacity for "reforming of natural gas" and "pyrolysis of natural gas" separately.



1 Production capacity information 2021

Hydrogen production capacity data by production method and source fuel.

1.1 Use of reforming methods

	Capacity (hydrogen, TJ NCV)	
1.1.1 Reforming of natural gas		
1.1.2 Reforming of oil and oil products		
1.1.3 Coal gasification		
1.1.4 Bio-oils reforming		
1.1.5 Reforming of some other source fuel		What source fuel?

+ Add row if needed

Indicate below the reforming method used in more detail:

☐ Steam reforming (SR)

☐ Partial Oxidation (POX)

☐ Autothermal Reforming (ATR)

1.2 Carbon dioxide capture capacity (CCS capacity)

If carbon dioxide capture technology is used in hydrogen production in connection with reforming methods, state the carbon dioxide capture capacity:

(unit)

Figure 34: A section of the production capacity information sheet on the designed hydrogen survey form (attachment B).

However, this way of collecting capacity information should be tested and consulted with a respondent from the industry, to ensure the viability of collecting capacity data this way. As mentioned in chapter 5.3.5, it is possible that the capacity data will be derived computationally from the reported consumption of source fuels instead. Since the details of how CCS capacities will be reported are so far unclear, the unit for CCS capacity has so far been left unspecified (figure 34). This portion of the survey form will need to be further developed as the official reporting instructions for hydrogen are released.

The hydrogen production information sheet (attachment B) is used to collect information of how much of each source fuel was consumed to produce hydrogen. The amounts of consumed fuels correspond to transformation inputs and the produced hydrogen as transformation outputs, as hydrogen has been defined a secondary energy product. The respondent is given an option to report the data either in tons or terajoules. For electrolysis, the origin of electricity is collected.

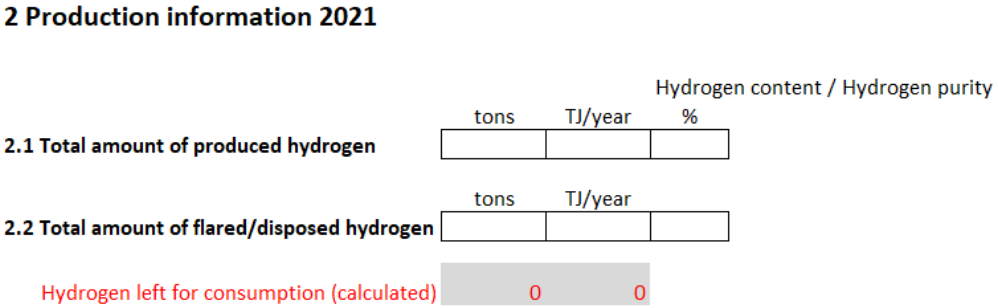


Figure 35: Section of the hydrogen production information sheet on the hydrogen survey form (attachment B).

At the top of the production information sheet, the total amount of produced and disposed (flared) hydrogen during the reporting year is collected (figure 35), the difference of which is used to automatically check that the reported amount of production will match that of consumption to ensure no hydrogen is left unreported. Below 2.1 and 2.2 (figure 35), hydrogen production information is requested in more detail divided by each source fuel used.

So, the total amount of hydrogen left for all forms of consumption is calculated automatically as

hydrogen left for consumption = total amount of produced hydrogen – total amount of flared/disposed hydrogen. (17)

The storage information sheet collects the opening and closing stock levels for hydrogen. In addition, the storage method (pressurised gas, liquefied, chemical storage) is asked to be specified. Stock change on this sheet is calculated as

stock change = amount of stored hydrogen at the end of the year – amount of stored hydrogen at the beginning of the year. (18)

On the consumption sheet of the survey form all consumption flows of hydrogen need to be reported so that the total amount equals that of the reported produced amount of hydrogen (considering stock change). The total

amount of hydrogen to be declared for consumption in total on this sheet is calculated automatically as

$$\text{hydrogen to be declared for consumption} = \text{total amount of produced hydrogen} - \text{total amount of flared/disposed hydrogen} - \text{stock change}. \quad (19)$$

Where stock change refers to equation 18. This is presented at the top of the sheet for the respondent, after which detailed forms of hydrogen consumption are listed. As was mentioned in chapter 5.3.2, the consumption data needs to be collected so that transformation use can be separated from energy use, where hydrogen is used for energy as a support fuel instead of it being input to a transformation process. To ensure this, for relevant items, sub-items “a. Hydrogen use as feedstock” (depicted orange in figure 36) and “b. Hydrogen use as support fuel” (depicted yellow in figure 36) have been included. Instructions for how to report data is given at the beginning for the informant. Sub-items “a. Hydrogen use as feedstock” correspond to transformation processes of hydrogen, and sub-items “b. Hydrogen use as support fuel” correspond to energy use of hydrogen. The respondent is also asked to fill the corresponding transformation output products and their amounts for each item.

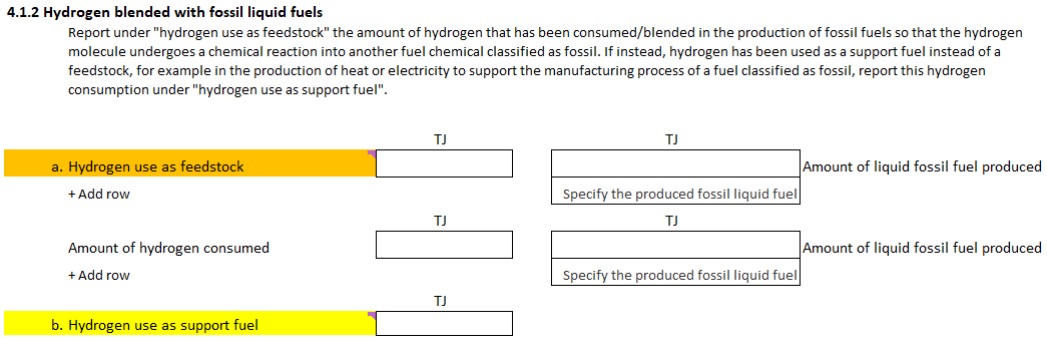


Figure 36: Section of the hydrogen consumption information sheet on the hydrogen survey form (attachment B).

Non-energy use of hydrogen is included as item “4.2.0 Hydrogen as a raw material / non-energy use of hydrogen”, where the informant is asked to the amount of raw material hydrogen used, and to specify the process in which this use occurred. For example, hydrogen used in fertilizer production or in the production of hydrogenated oils in the food industry is to be reported here.

At the end of the consumption information sheet, the forms of distributing hydrogen out of the facility’s scope are listed: injection of hydrogen to the national natural gas grid, sale or distribution of hydrogen as transport fuel, and sale or delivery of hydrogen to another enterprise (figure 37). In the case

of delivering hydrogen to another enterprise, the name of the enterprise is asked as voluntary information. This information is requested to ensure the quality of hydrogen data, so that the hydrogen consumption sector can be specified correctly for the sold hydrogen.

For the automated energy balance check for hydrogen, sum of all reported consumption is calculated (figure 37) and the final balance check is completed by checking if equation 20 is true or not.

$$\text{total amount of produced hydrogen} = \text{total amount of hydrogen consumed} \qquad (20)$$

If equation 20 is not true, an error message will be shown to the informant, asking them to check that all reported numbers are correct.

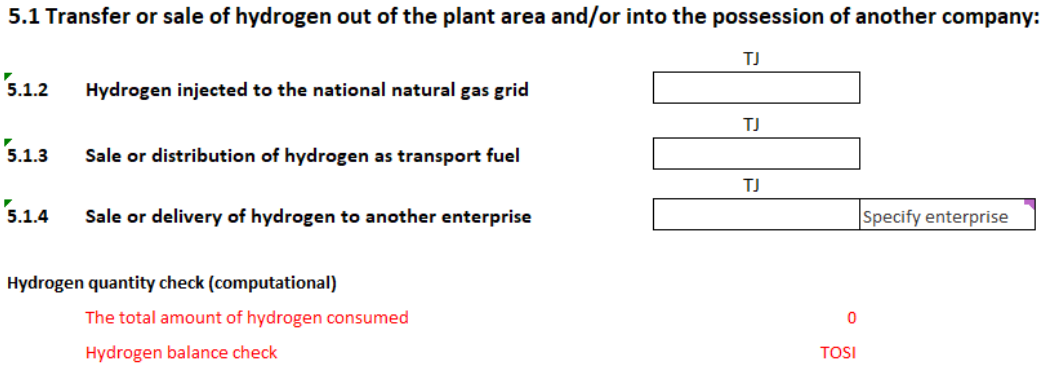


Figure 37: Bottom section of the hydrogen consumption information sheet on the hydrogen survey form (attachment B).

Attachments C – F present the reporting instructions for how each of the data points of the survey form are connected to the reporting requirements of the draft questionnaire that will be filled and reported to Eurostat. The numbers filled into the draft questionnaire's data sheets in attachments C – F refer to the question numbers in attachment B.

5.4.3 Coverage of the new hydrogen survey

The figure 38 shows which components of the hydrogen's commodity balance can be obtained from the new hydrogen survey (attachment B) or the existing data sources analysed in chapter 5.4.1. As it can be seen, all elements of the consumption side of the balance can be covered with data collected with the new hydrogen survey and supported by some of the existing data sources. On the supply side of the balance imports and exports can be covered with the data provided by Finnish Customs Office. The new hydrogen survey covers the rest of the elements on the supply side except for two elements: international aviation and international marine bunkers.

The companies that will have hydrogen consumption in international aviation or maritime transport are very likely to be different parties than the actual hydrogen producers, storage operators and industrial consumers who will be targeted with the designed survey form. Because of its detailed scope, the designed hydrogen survey form is most likely not ideal for these operators, even though in theory it does contain the collection of hydrogen distribution as a transport fuel and thus could be used. If hydrogen will become a fuel used in aviation or marine vessels, these data elements would be better to be collected separately, most likely via a small, targeted survey.

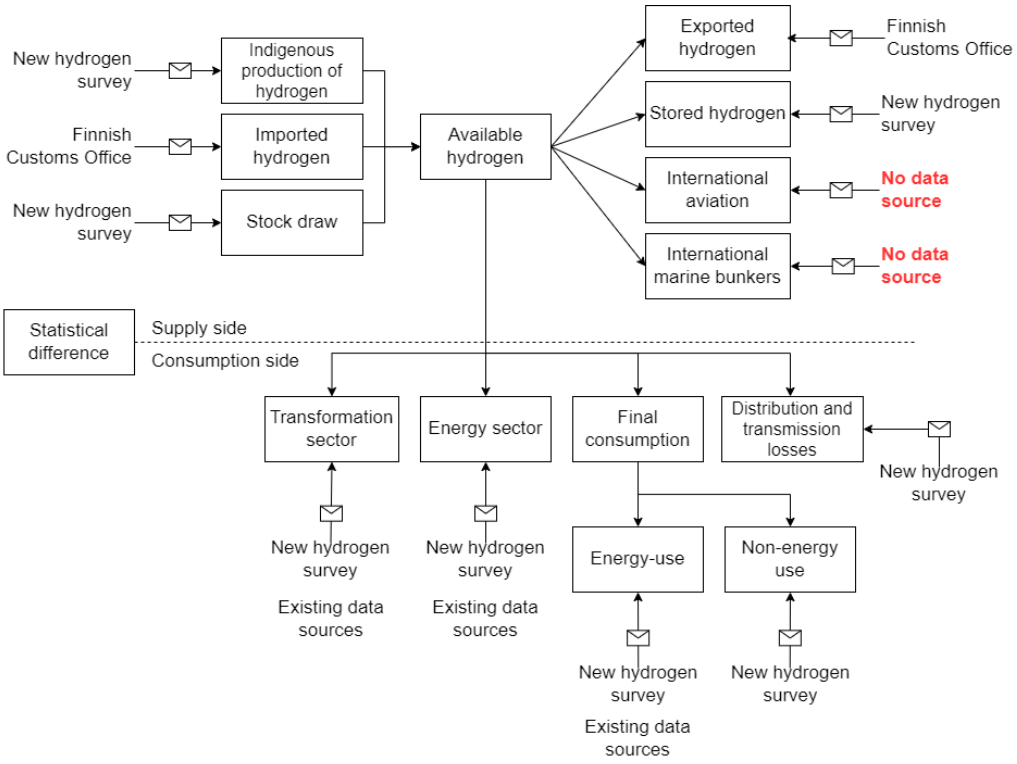


Figure 38: Data sources for each of the elements of the commodity balance for hydrogen used in the international energy balance framework.

6 Key results and discussion

According to IPCC (2018a), hydrogen is needed to achieve the carbon neutrality targets to stop global warming at 2 or preferably 1.5 degrees Celsius. According to IEA's net zero emissions scenario global hydrogen demand should double by 2030 for net zero to be reached (IEA, 2021c). Since hydrogen can be combusted directly in burners, boilers, ICEs, gas turbines or converted into electricity and used via a FC (Azzaro-Pantel, 2018), in theory hydrogen could be used very widely in society in a multitude of different applications. However, hydrogen faces many major challenges: lacking storage and distribution infrastructure, safety risks and lacking regulations and common standards (IEA, 2019).

It is not yet clear to what extent a hydrogen economy will develop globally or in Finland, and especially from Finland's point of view, the realisation of an EU-wide hydrogen pipeline (EHB) network is likely to be a factor that significantly affects the development of the Finnish hydrogen sector. In addition, the yet lacking public funding, incomplete legislation (Prime Minister's Office, 2022) and "lack of shared vision" (Hydrogen Cluster Finland, 2021) may be significant factors which slow down the deployment of hydrogen technologies in Finland. Nevertheless, as Prime Minister's Office (2022), Gasgrid Finland Oy and Guidehouse (2021), and LUT University et al. (2020) found out in their assessments, Finland has many advantageous qualities and possibilities to produce even significant amounts of hydrogen and/or e-fuels, even for export. The so far published new Finnish hydrogen investments exceeding one billion euros (Talouselämä, 2022) also signal interest by Finnish actors in joining the developing hydrogen market.

The most significant consumers of hydrogen in Finland were assessed to be oil refining, industrial chemicals and P2X, power generation and storage, steel production, zero emission transport and exportation (Business Finland, 2020; Prime Minister's Office, 2022). The results of the hydrogen economy scenarios (Prime Minister's Office, 2022; Gasgrid Finland Oy and Guidehouse, 2021; LUT University et al., 2020) vary considerably in their results, though it should be noted that the differing scopes and assumptions used in the assessments hinders their comparability. However, they do give somewhat similar estimates that the maximum hydrogen production potential in Finland by 2050 could be around 130 – 150 TWh. This should be considered a rough estimate, as it is based on only two studies, that of Prime Minister's Office (2022) and Gasgrid Finland Oy and Guidehouse (2021).

Since the total energy consumption in Finland in 2020 was 355 TWh (OSF, 2022b) – the maximum amount (150 TWh) of hydrogen production would correspond to 42 % of Finland's current total energy consumption. As is emphasised in the assessments as well, the effect of this on the total electricity consumption would be significant, even doubling or tripling the total consumption of electricity due to electrolysis alone (Prime Minister's Office,

2022; LUT University et al., 2020). In addition, the true export potential is highly dependent on how the international demand, market and competition for hydrogen will develop and Prime Minister's Office (2022) does state that the full maximum production potential is difficult to achieve in reality. The short-term estimates for Finnish hydrogen production for 2030 vary more, ranging from 4 TWh by Prime Minister's Office (2022) to 53 TWh by Gasgrid Finland Oy and Guidehouse (2021).

The results of the scenarios assessed in chapter 4.1 should be viewed critically due to the limitations, assumptions, uncertainties, and possible conflicts of interest contained in them. The scenario assessments discussed in this thesis are not peer-reviewed publications and at least some of them are in part published by industrial companies operating in the relevant fields of work.

According to Statistics Finland (OSF, 2022b), hydrogen use of total energy consumption in Finland currently corresponds to about 0.1 %, totalling at 0.401 TWh in 2020. According to Business Finland (2020) dedicated annual hydrogen production in Finland is currently at 140 000 – 150 000 tons (4.7 – 5.0 TWh), with additional 22 000 – 24 000 tons (730 – 800 TWh) of byproduct hydrogen production and an unknown but significant amount of hydrogen produced and consumed in the oil refining industry.

The hydrogen production estimates provided by Business Finland (2020) vary considerably from the amounts of hydrogen consumed for energy in Finland (OSF, 2022b) – the difference being about 4.0 – 8.4 TWh of consumed hydrogen missing from the data provided by Statistics Finland (OSF 2022b). This signals that most of hydrogen produced in Finland is consumed for non-energy purposes, since the Statistics Finland data does not include raw material use of hydrogen (OSF, 2022c). The hydrogen balance difference may also in part be explained by international trade of hydrogen (exports), assessment of which was not conducted in this thesis.

The national hydrogen roadmap (Business Finland, 2020) does not provide detailed information on how the hydrogen production estimate has been formed. It is unclear if it is based on collected or modelled data, and some of the balance difference might be due to statistical errors. However, these estimates are from two different sources with differing methodologies and scopes and thus cannot really be deeply analysed or compared with one another.

So, a clear need for more comprehensive national hydrogen statistics was identified. So far, Statistics Finland has not had a dedicated data collection for hydrogen, but the new EU-level statutory reporting requirements further increase a need for one, especially because this work revealed that the currently existing data sources are not sufficient in meeting the detailed reporting requirements.

The hydrogen survey form was designed so that it includes the full hydrogen balance, including all produced and consumed amounts of hydrogen

(including storages and losses). This way the collected data can be integrated into the national energy balance. Although the form is designed for the collection of hydrogen data, it is possible to copy and modify it to suit possibly other new e-fuels, which may be added into the same reporting framework in the future.

The designed new hydrogen survey form (chapter 5.4.2, attachment B) should be tested to confirm its usability and ease of use with test users from a relevant industry before its full implementation in statistics data collection, so that feedback can be collected for example on the terminology used and so that proper user instructions can be created. The designed survey form turned out to be very detailed, especially in regard to the consumption data. By user-testing the survey, feedback could also be obtained on what could be simplified so that the response burden could be minimised.

A challenge in the creation of the survey form was that the final reporting questionnaire and its instructions have not yet been released, but only a draft version was available. Thus, some unclarities remain and need to be finished later. In practise, the data collection form will be subject to continuous development. It was also noted that the designed survey form does not cover data from international aviation or maritime transport – a separate data collection for these elements of the energy commodity balance for hydrogen needs to be implemented if these sectors become statistically significant consumers of hydrogen in Finland.

With the help of a new dedicated data collection for hydrogen, in addition to fulfilling the mandatory data requirements for international reporting, the collection of additional hydrogen data deemed nationally important is also possible by modifying the survey. It would be beneficial to conduct a need assessment study from relevant users of the new hydrogen statistics to map out these national needs so that they can be considered.

7 Conclusions

This thesis conducted a literature review on hydrogen production, storage, and distribution technologies and reviewed literature on hydrogen applications to collect background information for the production of new national hydrogen statistics on the developing hydrogen economy. To form a picture of the role of hydrogen and P2X fuels in Finland, results of three hydrogen economy scenarios and publicly available information about hydrogen production and consumption in Finland was compiled. In addition, a new hydrogen data collection form was designed taking into consideration the upcoming statutory reporting requirements and the energy balance framework used in energy statistics in the EU.

Based on the reviewed literature, renewable hydrogen has great potential to decarbonize many different sectors, as it is technically possible to utilise hydrogen by combusting it directly or by using fuel cells in electricity-powered applications. It is possible to produce hydrogen from several different sources using different technologies. Low-carbon, carbon-neutral or carbon-negative hydrogen can be produced either using CCS, DAC, renewable electricity and electrolysis, or biogenic sources. However, hydrogen being highly flammable, its safety aspects must be carefully considered. Anyhow hydrogen has been used safely in industries for decades. The biggest global user of hydrogen currently is the fertilizer (ammonia) industry.

Hydrogen can be stored and transported using physical or material storages. In physical storage solutions, hydrogen does not chemically react with other substances, but is stored in cryogenic conditions as a liquid or pressurized gas. Hydrogen can be transported by pipelines or tanks by land, water, or railways. It would be technically possible to feed approximately 15 % of hydrogen into existing natural gas networks.

Based on assessments made in Finland so far about the potential of hydrogen economy, Finland could produce enough hydrogen and/or e-fuels to cover domestic demand and in addition produce enough for export, due to renewable wind power potential and abundant freshwater resources. The construction of a hydrogen pipeline network (EHB) and the development of international demand are especially important factors affecting Finland's hydrogen economy potential.

Through the new data collection form designed in this thesis, detailed information on hydrogen production, storage and consumption can be collected. The new data collection makes it possible to respond to the statutory reporting requirements and to produce and publish new statistics on hydrogen.

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A. Background document on hydrogen reporting methodology and annual questionnaire (draft hydrogen questionnaire)

EUROPEAN COMMISSION
EUROSTAT

Directorate E: Sectoral and regional statistics
Unit E.5: Energy

TASK FORCE METHODOLOGY AND FUTURE REPORTING

BACKGROUND DOCUMENT

HYDROGEN METHODOLOGY AND ANNUAL QUESTIONNAIRE

1. BACKGROUND

The European Green Deal, the Hydrogen Strategy for a climate-neutral Europe, the Commission Communication "A clean planet for all - A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy", the Fit for 55 package, and the European Clean hydrogen alliance among others, highlight the increasingly important role of hydrogen. Hydrogen and e-fuels are expected to play a relevant part in a fully decarbonised energy system.

"Clean" hydrogen will contribute to decarbonise various sectors: first, as storage in the power sector to accommodate for variable energy sources; second, as an energy carrier option used in heating, transport and industry and, finally, as a feedstock for industry such as steel, chemicals and e-fuels in those sectors that are most difficult to decarbonise.

Eurostat is working to address the data needs stemming from the recent and foreseen developments in the energy market and the new monitoring needs.

2. SUMMARY OF RECENT DEVELOPMENTS

- Eurostat proposed the collection of data for hydrogen (H2)
- Constructive discussions in the ESWG (including exchange of views) and task force meetings followed.
- The reporting of hydrogen data was introduced with the Commission Regulation (EU) 2022/132 of 28 January 2022 amending Regulation (EC) No 1099/2008 of the European Parliament and of the Council on energy statistics, as regards the implementation of updates for the annual, monthly and short-term monthly energy statistics
- Voluntary data for the reporting years 2022 and 2023. Mandatory data from reporting year 2024.
- Agreed contests: different ways of production, transformation and consumption, as well as production capacity. A similar approach could be adopted gradually for different e-fuels (e.g. production pathways for synthetic molecules of methane), depending on their expected penetration in the market in the near future.
- In order to avoid methodology discrepancies, some modifications of other annual questionnaires will be introduced in the next amendment to the Energy Statistics Regulation (ESR) and will apply to the reporting year 2024.
- Ongoing tasks (from 2021 to mid-2022): To clarification of definitions, to identify statistically relevant flows, to discuss methodological issues, to develop the new hydrogen questionnaire.
- Future tasks (mid-2022 to mid-2023): To finalize hydrogen questionnaire and to document the methodology.

3. PREVIOUS DISCUSSIONS IN THE ESWG (INCLUDING EXCHANGE OF VIEWS) AND TASK FORCE MEETINGS

Several methodological issues were raised during internal Eurostat meetings, in discussion with the IEA, during the Exchange of views, in recent ESWG events, and in meetings of the Task Force. These exchanges provided a solid ground of understanding and inspired some further methodological discussion points. Some definitions were agreed and some methodological issues were debated and clarified. The main ones are summarized below.

PREVIOUSLY DISCUSSED:

- Reporting in energy units: TJ
- Hydrogen will be considered as derived (secondary) product or energy vector.
- Hydrogen presence in other gasses will not be reported
- Both sold and not sold hydrogen would be reported
- Non-energy use of hydrogen will be included
- Auto-consumed hydrogen in principle should be reported
- Blended or injected hydrogen will be reported as for other blended fuels
- E-fuels were not included in the amendment to the Energy Statistics Regulation (ESR). The obligation to report them might be added in the future depending on their penetration in the market.
- Transformation into hydrogen from other energy carriers (e.g. natural gas) will be reported in the respective questionnaires (so that these quantities can be properly linked to the hydrogen questionnaire). For the reporting years 2022-2023: Report as currently done in the annual questionnaires, but also in the voluntary hydrogen questionnaire.

4. PROPOSED FOR DISCUSSIONS IN THE NEXT TASK FORCE MEETING

Eurostat, in cooperation with the IEA, proposes some points for further discussion regarding unclarified topics, new flows, or ambiguous concepts. It is important to know from reporting countries if they will be able to report the new flows (also by estimation) and/or if they have methodological concerns or suggestions regarding any of these points. Also it would be highly appreciated if the Task Force participants could offer any additional feedback or information on possible methodological issues not yet considered.

Some of the content below has been debated and therefore some points are presented in a summarized manner to help the continuation of the discussion. Others points offer new questions to be discussed and eventually answered.

The sections of the commodity balance are also presented to aid the discussion and to illustrate the current state of the work in progress which will lead to the final structure and content of the annual hydrogen questionnaire.

TABLE 1: DRAFT HYDROGEN QUESTIONNAIRE - PRODUCTION

2022	Hydrogen	e-Fuels
TJ NCV		
Total	**0.0**	**0.0**
from natural gas	0.0	
without CCS		
with CCS <90% (LOW)		
with CCS 90%+ (HIGH)		
from oil and petroleum products	0.0	
without CCS		
with CCS <90%		
with CCS 90%+		
from solid fuels (coal)	0.0	
without CCS		
with CCS <90%		
with CCS 90%+		
from renewables	0.0	0.0
without CCS		
with CCS <90%		
with CCS 90%+		
from wastes	0.0	0.0
without CCS		
with CCS <90%		
with CCS 90%+		
from electricity (electrolysis)	0.0	0.0
DTL: ELE from sustainable renewables		
DTL: ELE from nuclear		
DTL: ELE from fossil fuels		
grid electricity		
of which: green certificates		
other (by-product)	0.0	0.0
Other processes	0.0	0.0
chemical reactions		
(dark) fermentation		
non-specified		
unknown		
from hydrogen		

POINTS FOR DISCUSSION – PRODUCTION

- Hydrogen purity to be reported for energy statistics must be defined. It could be at 98%. In fuel cells must be 99.99%, 98% purity is reasonable for hydrogen for space heating equipment. A 98% purity seems to be also the minimum requirement recommended by the industries. Task force should discuss and decide a purity % for reporting purposes. In extremes this could this lead to having two or more different columns in the commodity balance with different purities (not advisable).

- Carbon Capturing and Storing (CCS) standards for low-carbon fossil based hydrogen is currently proposed at a maximum of 90% in EU policy documents. However, the percentage in the questionnaire could be changed with non-absolute limits such as "HIGH" and "LOW". The metadata data could define the limit for each macro-region in the world. Alternatively there could be the possibility of an automatic label with different percentages (%) based on country name selection in the Menu tab.

- From Electricity: DTL (direct transmission line) from fossil fuels. This flow was added to the previous draft of the questionnaire as this is also a technological possibility nowadays.

- By-product production for H2 as currently in total about 20% of H2 is produced as a by product in other processes. For example during the production of Chlorine.

- “From natural gas”, “from oil and petroleum products” …to “from wastes” should be used for H2 production as exclusive (as intentional) and as a by-product. If the H2 as by-product is produced via electrolysers it should be reported under “from electricity – other”

- “Other processes” includes all other production processes for H2 which use primary products that are not in other energy commodities (questionnaires). This might be considered as primary production in the Energy Balances (to be discussed later).

- Reporting of electricity consumption for the production of hydrogen (and e-fuels) will be discussed for its inclusion in the electricity questionnaire to avoid double-accounting once hydrogen data are reported. This would happen as there is currently not possibility to report the use of electricity in the transformation sector.

- Hydrogen can used to produced ammonia (or electricity) but also vice versa. How shall the repetition of these flows during the year be considered and reported? The loop might be negligible in reality. It is mostly a methodological clarification.

TABLE 2: DRAFT HYDROGEN QUESTIONNAIRE - TRANSFORMATION AND ENERGY SECTORS

2022 TJ NCV	Hydrogen	e-Fuels
Indigenous production	link	link
Imports	link	link
Exports	link	link
Stock changes (national territory)	link	link
International aviation		
International marine bunkers		
Inland consumption (calculated)	0.0	0.0
Statistical differences	0.0	0.0
Transformation sector	0.0	0.0
Main activity producer electricity		
Autoproducer electricity		
Main activity producer CHP		
Autoproducer CHP		
Main activity producer heat		
Autoproducer heat		
Blended in gas grid		
Blended with fossil liquid fuels		
Blended with renewables		
For production of e-Fuels		
*		
Gas works (and conversion to other gases)		
Refineries		
Petrochemical industry		
Not elsewhere specified (Transformation)		
Energy sector	0.0	0.0
Own use in electricity, CHP and heat		
Coal mines		
Petrochemical industry and oil refineries		
Oil and gas extraction		
Main activity producer heat		
Autoproducer heat		
Blended in gas grid		
Blended with liquid fuels		
*		
Coke ovens		
Blast furnaces		
Gas works		
Not elsewhere specified (Energy)		
Transmission and distribution losses	0.0	

POINTS FOR DISCUSSION - TRANSFORMATION AND ENERGY SECTORS

- Blended in gas grid, Blended with fossil liquid fuels, Blended with renewables will be also reported (transferred to) the Natural Gas, Oil and Renewables questionnaires respectively (or reported according to the same principles for all annual energy questionnaires, in case different reporting structure are agreed).

- Hydrogen used in refineries could be reported under transformation. The general reporting principle is that if the hydrogen molecules end up in the energy product the flow should be reported as transformation. In practice it could be reported in the Transformation sector in refineries if the hydrogen used, in cracking for example, for the largest part or above a set percentage makes it into the final products. In theory for example desulphurisation eliminates the sulphur when reacting with hydrogen and produces H2S which would be eliminated. In this case it will not be part of the final product and not reported under transformation. We should identify which processes lead to having hydrogen in the output.

- Reporting H2 input to blast furnaces could be reported under energy sector or transformation sector. This is methodologically the same issue as for transformation in the refinery processes described above

- Production of ammonia, methanol as a form of storage of hydrogen will be a possibility, at industrial scale, in a few years. This could be reported under Transformation sector – Petrochemical industry. Projects are also developing the possibility of storing hydrogen as other organic liquids and metal hydrides and the feasibility at a significant scale should be assessed. The use of hydrogen to produce these could be reported in a similar way.

- Hydrogen should be reported under Energy sector when used in support of the operation (for example - Petrochemical industry and oil refineries). In the production of transport fuels (if consumed and does not go in the final product).

TABLE 3: DRAFT HYDROGEN QUESTIONNAIRE - STOCKS – STORAGE

2022	Hydrogen						e-Fuels
	Physical storage (Pure)		Chemical storage				
TJ NCV	Pressurized	Liquefied	As Ammonia	Other chemicals	Others	TOTAL	
Stock (national territory) Opening							
Stock (national territory)_Closing							

POINTS FOR DISCUSSION - STOCKS AND STORAGE

- Report storage for both energy and non-energy purposes.

- Pressurized: These are reported similarly to the stocks as for other fuels: in industries for example. Smaller tanks. It is the most widely used method for storage of small amounts of gas. It is pure. There is a physical compression (Pressure and temperature are related in the pressuring process). But less density and more bulky.

- Liquefied: Bigger tanks: in industries. It is pure. For aviation in the future for example. It has higher density than the when pressurized. Is usually stored in deposits of up to 300 m3.

- As ammonia: Special storage method for hydrogen (Hydrogen density due to the molecular structure is higher and therefore less space is needed)

- As (or in) other chemicals: Special storage method for hydrogen. With organic liquids (LOHC) or with metal hydrides (highest density - less bulk - most efficient). Both are under development. LOHC are organic compounds that can absorb and release hydrogen through chemical reactions (hydrogenation, de-hydrogenation). Metal hydrides uses the properties of hydrogen when combined with other metallic elements, producing compounds in solid or liquid state.

- Others: For example the cryo-compressed hydrogen (combination of low temperature and high pressure) which is under development. Also possibly other forms of non-pressurized gas.

TABLE 4: DRAFT HYDROGEN QUESTIONNAIRE - TRADE

2022 TJ NCV	Hydrogen		e-Fuels	
	imports	exports	imports	exports
Albania				
Algeria				
Andorra				
Angola				
Argentina				

POINTS FOR DISCUSSION - TRADE

- Report as for other fuels/commodities – ultimate origin of available, otherwise country of previous consignment.

- Does trade of H2 raise different practical or methodological issues than other fuels?

TABLE 5: DRAFT HYDROGEN QUESTIONNAIRE - FINAL CONSUMPTION

2022 TJ NCV	Hydrogen		e-Fuels	
	energy	non-energy	energy	non-energy
Final consumption	0.0	0.0	0.0	0.0
Industry sector	0.0	0.0	0.0	0.0
Iron and steel				
Chemical and petrochemical				
Non-ferrous metals				
Non-metallic minerals				
Transport equipment				
Machinery				
Mining and quarrying				
Food, beverages and tobacco				
Paper, pulp and printing				
Wood and wood products				
Construction				
Textiles and leather				
Not elsewhere specified (Industry)				
Unknown (Industry)				
Transport sector	0.0	0.0	0.0	0.0
Domestic aviation				
Road				
Rail				
Domestic navigation				
Pipeline transport				
Not elsewhere specified (Transport)				
Unknown (Transport)				
Other sectors	0.0	0.0	0.0	0.0
Commercial and public services				
Residential				
Agriculture				
Forestry				
Fishing				
Not elsewhere specified (Other)				
Unknown (Other)				

POINTS FOR DISCUSSION - FINAL CONSUMPTION

- Report the consumption of hydrogen for the production of hydrogenated oil under Industry sector – Food, beverages and tobacco.

- H2 use in treating metals -> report as non-energy use in FC Industry – Iron and steel

- Report under Transport sector - Road the hydrogen used to fuel hydrogen powered vehicles. This apply to:

    - Hydrogen used in the internal combustion engines cells. Here the chemical energy of hydrogen is converted to mechanical energy through a reduction/oxidation reaction between hydrogen and oxygen within a specially developed fuel cell.

    - Hydrogen used to charge the fuel-cell vehicles. FCEVs produce electricity for the car using a fuel cell powered by hydrogen. The propulsion system is similar to that of electric cars and energy stored as hydrogen is converted into electricity by the fuel cell.

- Hydrogen used to produce ammonia and other fertilizers -> report as non-energy use in FC Industry. Yet, ammonia could be used as fuel in the near future. Task force should consider how this could be reported, for example it could be added as fuel when e-fuels are introduced.

- Hydrogen used in support of the operations in producing energy-> if consumed must be reported under the Energy Sector

- Hydrogen used in support of the industrial operations -> if consumed report under the Industry Sector

TABLE 6: DRAFT HYDROGEN QUESTIONNAIRE - CAPACITIES

2022	Hydrogen	e-Fuels
TJ NCV	INSTALLED CAPACITY H2 PRODUCTION CAPACITY ELECTRICITY PRODUCTION CAPACITY	Capacity
Total		
from natural gas	0.0	
without CCS		
with CCS <90%		
with CCS 90%+		
from oil and petroleum products	0.0	
without CCS		
with CCS <90%		
with CCS 90%+		
from solid fuels (coal)	0.0	
without CCS		
with CCS <90%		
with CCS 90%+		
from renewables	0.0	0.0
without CCS		
with CCS <90%		
with CCS 90%+		
from wastes	0.0	0.0
without CCS		
with CCS <90%		
with CCS 90%+		
from electricity (electrolysis)	0.0	0.0
DTL: ELE from sustainable renewables		
DTL: ELE from nuclear		
DTL: ELE from fossil fuels		
grid electricity		
of which: green certificates		
other (by-product, ie Chlorine)	0.0	0.0
other	0.0	0.0
chemical reactions		
(dark) fermentation		
non-specified		
unknown		
from hydrogen		

POINTS FOR DISCUSSION - CAPACITY

- The structure will reflect the production section.

- Which capacity to report? The possibilities are: installed capacity, hydrogen production capacity, electricity production capacity from hydrogen. These are all mentioned in policy documents.

B. New hydrogen survey form

Hydrogen survey 2021

Contact information for the survey

Company	
Contact person	
Email	
Phone number	
Mailing address	
Postal code	
Postal district	
Municipality	
Municipality number	

Facility information

Name of facility	
Visiting adress	
Postal code	
Postal district	
Municipality	
Municipality number	

Status	(X)		Year
In operation		Start of operations	
Not currently in operation		Cessation of operations	
Facility closed permanently			

Additional information

Report major changes in operations here. Indicate here if the information to be reported only applies to a part of the year.

1 Production capacity information 2021

Hydrogen production capacity data by production method and source fuel.

1.1 Use of reforming methods

	Capacity (hydrogen, TJ NCV)	
1.1.1 Reforming of natural gas		
1.1.2 Reforming of oil and oil products		
1.1.3 Coal gasification		
1.1.4 Bio-oils reforming		
1.1.5 Reforming of some other source fuel		Specify source fuel

+ Add row if needed

Indicate below the reforming method used in more detail:

- ☐ Höyryreformointi / Steam Reforming (SR) -menetelmä
- ☐ Osittainen hapettaminen / Partial Oxidation (POX) -menetelmä
- ☐ Autoterminen reformointi / Autothermal reforming (ATR) -menetelmä

1.2 Carbon dioxide capture capacity (CCS capacity)

If carbon dioxide capture technology is used in hydrogen production in connection with reforming methods, state the carbon dioxide capture capacity:

(unit)

1.3 Use of thermochemical methods

	Capacity (hydrogen, TJ NCV)	
1.3.1 Gasification of wood		
1.3.2 Gasification of other biomass		
1.3.3 Gasification of some other source fuel		Specify source fuel
1.3.4 Pyrolysis of natural gas		
1.3.5 Pyrolysis of ammonia		
1.3.6 Pyrolysis of wood		
1.3.7 Pyrolysis of other biomass		
1.3.8 Pyrolysis of other source fuel?		Specify source fuel

+ Add row if needed

1.4 Carbon dioxide capture capacity (CCS capacity)

If carbon dioxide capture technology is used in hydrogen production in connection with thermochemical methods, state the carbon dioxide capture capacity:

(unit)

1.5 Use of electrolysis

Origin of used electricity	Capacity (hydrogen, TJ NCV)
1.5.1 Grid electricity	
1.5.2 Of which green certificates	
1.5.3 DTL: Renewable electricity production plant	
1.5.4 DTL: Nuclear electricity	
1.5.5 DTL: Fossil electricity production plant	
1.5.6 Hydrogen formed as a byproduct	

Indicate below in more detail the electrolysis method(s) in use:

- ☐ Elektrolyysi / Electrolysis
- ☐ Fotolyysi / Photolysis
- ☐ Termolyysi / Thermolysis

1.6 Other production methods

State the other hydrogen production method in use:

- ☐ Biofotolyysi / Biophotolysis
- ☐ Pimeä fermentointi / Dark fermentation
- ☐ Valofermentointi / Photo fermentation
- ☐ Muu, mikä? / Other, what?

Specify here, if "Other, what?" is selecte

	Capacity (hydrogen, TJ NCV)
1.6 Hydrogen production capacity using other methods:	

2 Production information 2021

	tons	TJ/year	Hydrogen content / Hydrogen purity %
2.1 Total amount of produced hydrogen			

	tons	TJ/year	
2.2 Total amount of flared/disposed hydrogen			
Hydrogen left for consumption (calculated)	0	0	

2.3 Hydrogen production by source fuel

Report here in detail how much of source materials were used in the production of hydrogen during the year.

	Consumption of source fuel		Amount of hydrogen produced	
	tons	TJ/year	tons	TJ/year
2.3.1 Natural gas				

2.3.2 Oil and oil products	tons	TJ/year	tons	TJ/year

+ Add row

2.3.3 Coal and coal products	tons	TJ/year	tons	TJ/year

+ Add row

2.3.4 Renewable sources	tons	TJ/year	tons	TJ/year

+ Add row

2.3.5 Wastes	tons	TJ/year	tons	TJ/year

+ Add row

2.3.6 Electrolysis (electricity)

	Consumed electricity	Amount of hydrogen produced	
	TJ/year	tons	TJ/year
Grid electricity			
Of which nuclear certificates			
Of which renewable certificates			
	TJ/year	tons	TJ/year
DTL: Renewable electricity			
DTL: Nuclear electricity			
DTL: Fossil electricity production plant			
	TJ/year	tons	TJ/year
Other electricity (byproduct)			

2.3.7 Other source fuel or process

		Amount of hydrogen produced	
	(X)	tons	TJ/year
Chemical reaction (byproduct hydrogen)			
Dark fermentation			
Other, what?			

2.3.8 Carbon dioxide Capture and Storage (CCS) information

	(X)
In use	
Not in use	

	%
Carbon dioxide recovery rate	

	tons	TJ/year
Amount of captured carbon in total		
	tons	TJ/year
Of which placed in long term storage		
Of which other consumption or short-term storage		

3 Storage information 2021

3.1 Amount of stored hydrogen

	TJ
3.1.1 Amount of stored hydrogen at the beginning of the year:	
3.1.2 Amount of stored hydrogen at the end of the year:	

Inventory change (computational): 0 TJ

3.2 Hydrogen storage method

		(x)	
3.2.1			Pressurised gaseous hydrogen
3.2.2			Liquefied hydrogen
3.2.3			Hydrogen stored as ammonia
3.2.4			Hydrogen stored as methane
3.2.5			Hydrogen stored as some other chemical compound
3.2.6			Other storage method, specify

Specify chemical
Specify storage method

4 Consumption of hydrogen 2021

Total amount of hydrogen to declare for consumption in total — TJ: 0 (computational)

4.1 Consumption of hydrogen at facility

4.1.1 Hydrogen consumed for energy production

Report the amount of hydrogen that has been consumed in the production of electricity or heat.

	TJ	TJ	TJ
a. Electricity production		Amount of produced electricity	
b. Separate heat production		Amount of produced heat	
c. CHP-production		Amount of produced electricity	Amount of produced heat

4.1.2 Hydrogen blended with fossil liquid fuels

Report under "hydrogen use as feedstock" the amount of hydrogen that has been consumed/blended in the production of fossil fuels so that the hydrogen molecule undergoes a chemical reaction into another fuel chemical classified as fossil. If instead, hydrogen has been used as a support fuel instead of a feedstock, for example in the production of heat or electricity to support the manufacturing process of a fuel classified as fossil, report this hydrogen consumption under "hydrogen use as support fuel".

	TJ	TJ	
a. Hydrogen use as feedstock			Amount of liquid fossil fuel produced
+ Add row		Specify the produced fossil liquid fuel	
Amount of hydrogen consumed	TJ	TJ	Amount of liquid fossil fuel produced
+ Add row		Specify the produced fossil liquid fuel	
b. Hydrogen use as support fuel	TJ		

4.1.3 Hydrogen blended with renewables

Report under "hydrogen use as feedstock" the amount of hydrogen that has been consumed (or blended with) in the production of renewable fuels so that the hydrogen undergoes a chemical change into another fuel classified as renewable. If hydrogen has been used as a support fuel instead of a feedstock, for example in the production of heat or electricity to support the manufacturing process of a renewable fuel, report this hydrogen consumption under "Hydrogen as a support fuel".

	TJ	TJ	
a. Hydrogen use as feedstock			Amount of renewable fuel produced
+ Add row		Specify the produced renewable fuel	
b. Hydrogen use as support fuel	TJ		

4.1.4 Hydrogen used in the production of e-fuels

Electric fuels (e-fuels) refer to compounds classified as a non-fossil (carbon neutral) fuel produced with the help of electricity, carbon dioxide and hydrogen, for example synthetic methane. Enter here the amount of hydrogen consumed for the production of electric fuels, as well as the quantity and quality of the produced electric fuel.

	TJ	TJ	
Amount of consumed hydrogen			Amount of produced e-fuel
+ Add row		Specify produced e-fuel	

4.1.5 Hydrogen consumed for gas works (including hydrogen conversion to other gases)

Indicate under "hydrogen as feedstock" the amount of hydrogen that has been fed into the gas works process or hydrogen that has been converted to another gas. If hydrogen has been used as a support fuel for a gas works process instead of used as a feedstock, for example in the production of heat or electricity to support an industrial process, report this hydrogen consumption under "Hydrogen use as support fuel".

	TJ	TJ	
a. Hydrogen use as feedstock			Amount of produced gas
+ Add row		Specify produced gas	
b. Hydrogen use as support fuel	TJ		

4.1.6 Hydrogen use in refineries

Report under "hydrogen use as feedstock" the amount of hydrogen that has been fed into the oil refinery process as a transformative or reactive substance so that the hydrogen molecule undergoes a chemical transformation into some other compound classified as an oil product. If hydrogen has been used as a support fuel for the oil refinery process instead of as input to the oil refinery process, for example in the production of heat or electricity to support the process, report this hydrogen consumption under "hydrogen use as support fuel".

	TJ	TJ	
a. Hydrogen use as feedstock			Amount of produced oil product
+ Add row		Specify produced oil product	
b. Hydrogen use as support fuel	TJ		

4.1.7 Hydrogen use in the petrochemical industry

Report under "hydrogen use as feedstock" the amount of hydrogen that has been fed into a petrochemical process as a transforming or reacting substance so that the hydrogen molecule undergoes a chemical transformation into another compound. If hydrogen has been used as an auxiliary fuel in the petrochemical industry instead of as a feedstock for a petrochemical process, for example in the production of heat or electricity to support the process, report this hydrogen consumption under "hydrogen use as support fuel".

	TJ	TJ	
a. Hydrogen use as feedstock			Amount of product
+ Add row		Specify product	
b. Hydrogen use as support fuel	TJ		

4.1.8 Hydrogen use in coke ovens

Report here the amount of hydrogen combusted in coke ovens.

	TJ
Amount of consumed hydrogen	

4.1.9 Hydrogen use in blast furnaces

Report here the amount of hydrogen combusted in blast furnaces.

	TJ
Amount of consumed hydrogen	

4.2.0 Hydrogen as a raw material / non-energy use of hydrogen

Report here raw material hydrogen consumption. Raw material consumption of hydrogen is consumption of hydrogen that is not related to energy production. Consumption of hydrogen as a feedstock for a chemical process in which hydrogen is converted into a compound other than a fuel (for example production of pharmaceuticals, cosmetics ingredients, etc.) is regarded raw material use of hydrogen. Other examples of the use of hydrogen as a raw material: hydrogen used for processing metals, hydrogen used for the production of ammonia or other fertilizers, hydrogen used for the production of hydrogenated oil in the food industry. If hydrogen has been consumed as a support fuel for an industrial process in operations that generate electricity or heat - the consumption of hydrogen should be reported in the above sections of the survey form under "hydrogen as support fuel".

	TJ	
Consumption of hydrogen as a raw material		Specify how hydrogen is used as a raw material

+ Add row

4.2.1 Other use of hydrogen, specify

Report the consumption of hydrogen either as a feedstock in a process where hydrogen is converted into some other compound (a), or the consumption of hydrogen as a support fuel in a process that is not mentioned above (b).

	TJ	TJ	
a. Hydrogen use as feedstock			Amount of product
+ Add row		Specify product	
	TJ		
b. Hydrogen use as support fuel		Specify the process in which hydrogen has been used as a support fuel	

4.2.2 Known or estimated hydrogen losses and leaks

Report here all known or estimated conversion and distribution losses and leaks of hydrogen.

	TJ
Total hydrogen losses	

5.1 Transfer or sale of hydrogen out of the plant area and/or into the possession of another company:

		TJ	
5.1.2	**Hydrogen injected to the national natural gas grid**		
5.1.3	**Sale or distribution of hydrogen as transport fuel**		
5.1.4	**Sale or delivery of hydrogen to another enterprise**		Specify enterprise

Hydrogen quantity check (computational)

The total amount of hydrogen consumed	0

C. Reporting instructions for hydrogen capacity data collected via the new hydrogen survey

2022	Hydrogen
TJ NCV	INSTALLED CAPACITY H2 PRODUCTION CAPACITY ELECTRICITY PRODUCTION CAPACITY
Total	
from natural gas	1.1.1 and 1.3.4
without CCS	
with CCS <90%	
with CCS 90%+	
from oil and petroleum products	1.1.2
without CCS	
with CCS <90%	
with CCS 90%+	
from solid fuels (coal)	1.1.3
without CCS	
with CCS <90%	
with CCS 90%+	
from renewables	1.1.4, 1.3.1, 1.3.2, 1.3.6, 1.3.7
without CCS	
with CCS <90%	
with CCS 90%+	
from wastes	1.1.5, 1.3.8
without CCS	
with CCS <90%	
with CCS 90%+	
from electricity (electrolysis)	1.5
DTL: ELE from sustainable renewables	1.5.3
DTL: ELE from fossil fuels	1.5.5
grid electricity	1.5.1
of which: green certificates	1.5.2
other (by-product, ie Chlorine)	1.5.6
other	4.1
chemical reactions	
(dark) fermentation	
non-specified	
unknown	

D. Reporting instructions for hydrogen production data hydrogen production data collected via the new hydrogen survey

2022		Hydrogen
TJ NCV		
Total		
from natural gas		2.3.1
	without CCS	
	with CCS <90% (LOW)	
	with CCS 90%+ (HIGH)	
from oil and petroleum products		2.3.2
	without CCS	
	with CCS <90%	
	with CCS 90%+	
from solid fuels (coal)		2.3.3
	without CCS	
	with CCS <90%	
	with CCS 90%+	
from renewables		2.3.4
	without CCS	
	with CCS <90%	
	with CCS 90%+	
from wastes		2.3.5
	without CCS	
	with CCS <90%	
	with CCS 90%+	
from electricity (electrolysis)		2.3.6
	DTL: ELE from sustainable renewables	
	DTL: ELE from fossil fuels	
	grid electricity	
	of which: green certificates	
other (by-product)		
Other processes		2.3.7
	chemical reactions	
	(dark) fermentation	
	non-specified	
unknown		
from hydrogen		

E. Reporting instructions for hydrogen storage data collected via the new hydrogen survey

2022	Hydrogen					
	Physical storage (Pure)		Chemical storage			
TJ NCV	Pressu-rized	Liquefied	As Ammo-nia	Other che-micals	Others	TOTAL
Stock (national territory) _Opening	3.2.1	3.2.2	3.2.3	3.2.4 and 3.2.5	3.2.6	
Stock (national terri-tory)_Closing						

F. Reporting instructions for hydrogen consumption data collected via the new hydrogen survey

2022 TJ NCV	Hydrogen
Indigenous production	link
Imports	link
Exports	link
Stock changes (national territory)	link
International aviation	-
International marine bunkers	-
Inland consumption (calculated)	0.0
Statistical differences	0.0
Transformation sector	0.0
Main activity producer electricity	4.1.1 a.
Autoproducer electricity	4.1.1 a.
Main activity producer CHP	4.1.1 c.
Autoproducer CHP	4.1.1 c.
Main activity producer heat	4.1.1 b.
Autoproducer heat	4.1.1 b.
Blended in gas grid	5.1.1
Blended with fossil liquid fuels	4.1.2 a.
Blended with renewables	4.1.3 a.
For production of e-Fuels	4.1.4
*	-
Gas works (and conversion to other gases)	4.1.5 a.
Refineries	4.1.6 a.
Petrochemical industry	4.1.7 a.
Not elsewhere specified (Transformation)	4.2.1
Energy sector	0.0
Own use in electricity, CHP and heat	4.1 a., b., & c.
Coal mines	-
Petrochemical industry and oil refineries	4.6 b. & 4.7b.
Oil and gas extraction	-
Main activity producer heat	4.1 b.
Autoproducer heat	4.1 b.
Blended in gas grid	5.1.1
Blended with liquid fuels	4.2 b.
*	-
Coke ovens	4.1.8
Blast furnaces	4.1.9
Gas works	4.5 b.
Not elsewhere specified (Energy)	4.2.1
Transmission & distribution losses	4.2.2