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The Dutch hydrogen balance, and the current and future representation of hydrogen in the energy statistics

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Summary

Hydrogen may be an important element in the future system, because it provides a versatile carbon free connection between a variety of energy sources (solar, wind, fossil sources/biomass with CCS, nuclear) and various forms of energy demand, like transport, (high temperature) heating and feedstocks for the chemical industry.

Currently, in the Netherlands already a lot of hydrogen is produced using fossil energy, but this is not directly visible in energy statistics, because hydrogen is not considered as an energy product. We quantified total hydrogen production and consumption in the Netherlands from information on plant capacities and related this production and consumption to the current energy statistics.

Total hydrogen production was estimated from plan at 180 PJ each year. This relates to pure hydrogen and hydrogen in waste gas mixtures. If we restrict ourselves to pure hydrogen and hydrogen in waste gases that can be easily upgraded to hydrogen the estimated production is about 155 PJ. Hydrogen was mostly produced from natural gas (105 PJ) and oil (65 PJ). Main applications of pure hydrogen are N-fertiliser production (60 PJ) and hydrogenation and desulphurization by oil refineries (65 PJ). Total gross energy consumption in the Netherlands is about 3000 PJ, which implies that already to date hydrogen production has a substantial impact on our energy system and related carbon dioxide emissions.

In future new interactions of hydrogen with the energy system may arise. We described several of these possibilities, like hydrogen production from electrolysis, like various technical options for transport of hydrogen at regional and world scale and like consumption for heating or chemical products replacing naphtha.

These fundamental new ways of producing and consuming energy may affect the energy system in fundamentally new ways, implying that also the core of energy statistics may need to be adapted. This core exists of joint annual questionnaires of Eurostat and IEA and resulting energy balances very much in line with the UN manual on energy statistics. Adapting this system takes several years, because of the international coordination required and the need to thoroughly discuss the consequences, also with the relevant industry, in order to keep the system consistent, transparent and manageable. We think it is the right time to continue to already started discussions on the subject.

As first step guidelines for several items in energy statistics (indirectly) related to hydrogen production and consumption may be made more precise, for example including or excluding hydrogen as part of “other hydrocarbons” in refinery intake. Including hydrogen in energy statistics is not straight forward and we describe several issues that we think should be addressed. This issues are the definition of hydrogen (e.g. degree of purity), inclusion or exclusion of hydrogen for non-energy purposes, only traded hydrogen or also autoproduced and consumed hydrogen (captive), distinction of hydrogen by production process, considering hydrogen as primary or secondary energy product, treating international trade and broadening the discussion to other possible new products affecting the energy system, like methanol.

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1 Introduction

1.1 Drastic adjustment of the energy system is required

Many countries in the world have signed and ratified the Conference of the Parties Paris Agreement to keep global warming well below 2 degrees Celsius above pre-industrial levels, and to pursue efforts to limit the temperature increase even further to 1.5 degrees Celsius. Meeting this target requires the transition to an energy system with net zero, or even negative anthropogenic greenhouse gas emissions.

The energy transition will drastically change how we generate, distribute, store and consume energy. It will require increased energy efficiency, a radical shift towards the use of renewable energy away from fossil fuels, decarbonization of the remaining use of fossil fuels, and carbon free energy carriers as links between the primary energy sources and the end-users of energy.

1.2 Hydrogen can be important to achieve a sustainable energy system in time

Increasingly, hydrogen is regarded as an indispensable element for a sustainable energy system (IRENA 2019), (IEA 2019), (EU 2018). The potential of hydrogen as carbon-free energy carrier has also been clearly recognized in the discussions and negotiations for the purpose of the Dutch Climate Agreement (MinEZK 2019).

Hydrogen supply chains offer a way to provide end-consumers with decarbonized or renewable energy for applications where electrification and the use of batteries are not possible, not sufficient to meet end-user requirements, or not the most cost effective decarbonization option. The two most important possible supply chains include:

- Water-electrolysis, i.e. the splitting of water with electricity, preferably with electricity generated from carbon-free energy sources (including nuclear). This enables for example the capturing and storing of solar and wind energy in molecular form, which greatly enhances the possibilities to use these sources for a sustainable energy system beyond their use as electricity.
- Decarbonization of fossil energy sources in combination with carbon capture and storage (CCS). The implementation of energy saving measures, the development of new technologies and industrial processes, and the build out of renewables takes time. In the meantime large amounts of fossil energy continue to be needed. To secure the required reduction of greenhouse gas (GHG) emissions in line with the Paris Agreement, it could be necessary to decarbonate fossil hydrocarbon sources and only use the hydrogen part of these sources as fuel. In this way low-carbon fossil hydrogen could act as a stepping stone for renewable hydrogen.

Hydrogen can act as fuel, similar to natural gas, and can therefore contribute to decarbonization in all sectors that currently use natural gas, such as in industry, the built environment, and the power sector. In the transport sector hydrogen can be used as fuel for fuel cell electric vehicles, which is a truly zero-emission option if batteries are not sufficient to meet end user requirements or preferences.

In addition to being a versatile fuel, hydrogen, in particular renewable hydrogen can also be used as renewable chemical building block for the production of synthetic liquid fuels (indirect use as fuel). When combined with circular (waste) and renewable (biomass and direct air capture) forms of carbon this can even enable the phase out of oil as feedstock for plastics and other chemical industry products and materials in the longer term. Renewable hydrogen thus offers the possibility to directly use solar and wind energy as renewable feedstock for the chemical industry.

Last but not least, renewable hydrogen provides a means to transport renewables, such as sun and wind, from parts of the world where they are abundantly available to areas where they are insufficiently available (import/export of renewables other than biomass or biofuels). Another option that could arise in the course of the energy transition is to decarbonate natural gas as much as possible at their point of extraction and to import the energy in the form of hydrogen. Once hydrogen has become an established fuel this may be a more efficient and cheaper option than applying CCS domestically, especially if transport by pipeline is possible.

In view of the potential of hydrogen the Dutch government has recently published a hydrogen strategy (MinEZK 2020) which lays the foundation for a national hydrogen program to support the realization of the hydrogen ambitions from the Climate Agreement. The ambitions includes among others the installation of 3 to 4 gigawatt (GW) of water-electrolysis plants for the production of renewables-based hydrogen, and the conversion of part of the high pressure natural gas pipeline infrastructure to a basic hydrogen infrastructure. This can serve as a starting point for a central infrastructure where hydrogen can be fed in from various sources (renewable and low-carbon) and made available to the large industrial clusters in the Netherlands that consider hydrogen as an important decarbonization option. In addition, by providing a relatively inexpensive form of distribution, the infrastructure can also facilitate the development of hydrogen fuel applications in the transport sector and the built environment.

1.3 Current hydrogen production from fossil energy sources

Apart from its near future potential, hydrogen already plays a significant role in the industry today, Indications of hydrogen production and use in industry range from about 110 PJ (Trümper 2007) to 175 PJ (DNVGL 2019). Main applications are the production of ammonia and methanol, and the refining and desulphurization of oil and oil products. The use of hydrogen in the biofuels industry is a growing application. And there is a large range of smaller applications, such as in the food industry, the glass industry, the metallurgical industry, and the electronics industry.

In spite of its significant role in industry, hydrogen has no separate entry in the energy statistics because hydrogen is only used as an industrial gas in non-energy applications, and not as fuel for energy applications in end-use sectors. Currently hydrogen is produced using fossil fuels, so it is part of the energy statistics, but it is difficult to extract numbers on hydrogen from the statistics.

1.4 Possible need to integrate hydrogen in the energy statistics

Due to the versatile potential of hydrogen and the many developments in this field on national level, as well as on European and international level it is likely that the supply of hydrogen from industry or the energy sector to end users for energy applications may start to play a role within the foreseeable future. Production, international trade and consumption of hydrogen may become similar to the current flows of electricity, heat, natural gas and motor fuels, and may thus require the introduction of a separate entry in the energy statistics.

1.5 Study objectives and methodology

Given the current and potential future supply chains and applications of hydrogen, the current study has been defined with a twofold objective:

- The first goal is to establish an overall picture for hydrogen as a "baseline" for the upcoming development of hydrogen and to understand how this picture can be extracted from current energy statistics.
- The second goal is to compile a first overview of possibilities and issues to include hydrogen as a separate category in energy statistics, and what is needed for this.

The central research questions to be answered for this are:

- How much hydrogen is produced and applied in the Netherlands, subdivided by supply (production and source) and application (energy and non-energy applications)?
- What are the possible future hydrogen supply chains (source, production and application)?
- What choices are there for including hydrogen in the (inter)national energy statistics, what are the pros and cons of the different choices, and are there aspects that need further research in order to reach a decision on this?
- What procedures are in place and must be followed in order to be able to adjust statistics, and within what period of time is this possible?

The starting point for drawing up the hydrogen balance is an overview of the hydrogen production capacity in the Netherlands that has been published as part of the EU RoadsHyCom project (Trümper 2007) that was previously checked and updated at the request of TNO (at the time ECN) by contacts in the industrial gases industry. This overview has been further supplemented and checked with information from various sources, namely:

- Published and to be published reports of the MIDDEN-project in which TNO together with PBL maps the current state of affairs in the main industrial sectors and options for decarbonization in those sectors (PBL 2020);
- Publicly available literature and data sources (e.g. internet news items, press releases, and permit requests);
- Further inquiry from industry parties;
- Background data from a recent overview by DNV·GL (DNVGL 2019).

The findings on how to include hydrogen in the (inter)national energy statistics and corresponding procedures are based on expertise of Statistics Netherlands (known in the Netherlands as Centraal Bureau voor de Statistiek, CBS).

2 Hydrogen balance for the Netherlands

2.1 Publicly available data on hydrogen production

Various numbers can be found for hydrogen production in the Netherlands. In 2007, the Roads2HyCom project reported an annual production of 10,1 billion cubic meter (bcm), equivalent to 109 PJ, of which 7,6 bcm (82 PJ) is produced from natural gas and 2,5 bcm (27 PJ) is by-product hydrogen (Trümper 2007).

Similar numbers were reported in 2016 (M. Weeda 2016). In this report, data of Dutch energy statistics on non-energy use of natural gas, both in industry and refineries are used as starting point. Data were converted to amounts of hydrogen produced by taking into account a production efficiency. The results were found to be in reasonable agreement with the data from the Roads2HyCom report, although the required capacity factor was relatively low to be able to match installed capacity with the calculated actual production based on data from the Dutch energy balance.

Much larger numbers were recently reported by DNV·GL (DNVGL 2019). In this study they have reviewed and complemented the Roads2HyCom data using publicly available data and insights from own projects to identify “new” or previously omitted production sites and sources. The study concluded that current hydrogen supply is much higher than previously assumed, and amounted to 175 PJ in 2019. This includes pure hydrogen and hydrogen in hydrogen containing gases

All findings of previous studies have been taken into account in the analysis and estimates in this report.

2.2 Current modes of hydrogen production

The term hydrogen seems to be clearly defined. However, there are many nuances. Hydrogen can be produced from hydrocarbons and water with energy from fossil (current) and renewable (future) energy sources. In production from a fossil or renewable hydrocarbon source, production can be combined with CCS so that the carbon intensity of the hydrogen produced can vary over a wide range, and can even be negative. In addition, hydrogen can be produced as a main product, or produced as part of a gas mixture, but it can also be released as a by-product. In the latter case, this can be both in pure form and as part of a mixture. The following sections provide an overview of current industrial processes in the Netherlands used to produce hydrogen, or where hydrogen is produced as a by-product.

2.2.1 Steam reforming

Most of the hydrogen in the Netherlands is produced by reforming hydrocarbon gases with steam. Natural gas is the main source. But also methane-rich residual gas from oil refining and naphtha cracking is used to produce hydrogen. And in principle also biomass derived biogas and biomethane could be used to produce hydrogen as these gases are chemically quite similar to natural gas and methane rich residual gases from the petrochemical industry.

The production of pure hydrogen by steam reforming (without CCS) is basically a two-step process. In the first step reforming of the methane takes place with steam to produce syngas, a mixture of carbon monoxide (CO) and hydrogen. In the second stage, called water-gas-shift, more hydrogen is produced by adding more steam at other process conditions at which the steam reacts with CO to produce hydrogen and carbon dioxide (CO_2). The mixture is then separated by pressure swing adsorption to produce pure hydrogen.

Different variants of the process exist. In the Steam Methane Reforming (SMR) process the heat of reaction is supplied by burning some of the natural gas or another fuel with air on the outside of the reactor, in order not to dilute the reaction mixture with nitrogen from the air. In the Autothermal reforming process (ATR) the heat is supplied by burning part of the hydrocarbon feedstock inside the reactor. If hydrogen is the desired product, this is done with pure oxygen, and thus ATR hydrogen production requires an air separation unit. For ammonia (molecular formula NH_3) production. However, also air-blown ATR is used as nitrogen is needed in the subsequent ammonia synthesis process.

In some cases only the first step is carried out. This is the case in methanol (molecular formula CH_3OH) production where both hydrogen and CO are needed for the synthesis of methanol. Hydrogen is not present in pure form in the current methanol production process that uses natural gas as feedstock. Another case is when steam reforming plants are installed with the main purpose of producing CO as feedstock for the chemical industry. Hydrogen can then be considered as a (inevitable) by-product of CO production.

2.2.2 Gasification

Basically, gasification involves the conversion of solids into gas. Coal, biomass, waste and heavy residues of oil refining can be used as feedstock. Currently, only the latter is used in gasification processes in the Netherlands, namely as part of the Flexicoker process of ExxonMobil and in the Shell Gasification Hydrogen Plant. There are many process configurations for gasifiers, but a rough distinction can be made between gasifiers operating at relatively low temperatures (typically 600 - 800 degrees Celsius) and high temperature gasifiers (>1000 degrees Celsius). The gasifier that is part of the Flexicoker process falls into the former category, whereas the Shell gasifier falls into the latter category. Low temperature gasification processes produce a methane- and hydrogen-rich gas mixture, which is mainly used as fuel gas. To produce hydrogen, gasification should be followed by steam reforming of the product gas. In high temperature gasification processes the thermodynamic equilibrium shift from methane to carbon monoxide and hydrogen. This produces a syngas which can be converted to hydrogen and CO_2 by further processing in a water-gas-shift unit.

2.2.3 Catalytic reforming

Catalytic reforming is an important process in oil refining. In catalytic reforming, naphtha fractions are treated to increase their octane rating for use in fuel mixtures. This is mainly done by converting unsaturated or saturated hydrocarbons into aromatics such as benzene, toluene and xylenes. Catalytic reforming is also important for the production of a variety of aromatics for the chemical industry (e.g. styrene production). A number of reactions take place during catalytic reforming, including dehydrogenation. This produces significant amounts of fairly pure hydrogen streams within refineries and the chemical industry that are used for hydrocracking and hydrogenation reactions in other processes.

2.2.4 *The chlor-alkali process*

The chlor-alkali process is an industrial electrolysis process for the production of chlorine. In the Netherlands the process is conducted by Nouryon (formerly part of AkzoNobel) on an aqueous solution of NaCl. In this case chlorine and sodium hydroxide (NaOH, also known as caustic soda) result as main products, which are commodity chemicals required by industry. When using calcium chloride or potassium chloride, the products contain calcium or potassium instead of sodium. The process yields two moles of sodium hydroxide per mole of chlorine, but for every mole of chlorine produced, also one mole of by-product hydrogen is produced. Much of this hydrogen is delivered directly or via the industrial gases industry to the chemical industry, or is combusted for power and/or steam production.

2.2.5 *Steam cracking or naphtha cracking*

Steam cracking is a petrochemical process in which saturated hydrocarbons are broken down into smaller, often unsaturated, hydrocarbons. It is the principal industrial method for producing the lighter alkenes (or commonly olefins), including ethene (or ethylene) and propene (or propylene). Dow Chemical (Terneuzen), Sabic (Geleen) and Shell Chemicals (Moerdijk) operate large steam cracking plants in the Netherlands. Steam cracker units are facilities in which a feedstock such as naphtha, liquefied petroleum gas (LPG) and natural gas liquids (NGL) is thermally cracked through the use of steam in a sequence of pyrolysis furnaces (i.e. in the absence of oxygen) to produce lighter hydrocarbons. At the end of the process a residual gas stream rich in hydrogen and methane results. In Zeeland, an amount of residual gas from Dow, in total containing 4.5 kton of hydrogen, is delivered annually through a section of natural gas transmission pipeline to Yara (hydrogen for ammonia production) and ICL (production of hydrogen bromide and bromine based specialty products). Most residual gas, however, is used as fuel in furnaces, and for power and steam production.

2.2.6 *Cokes production*

Cokes is a hard and porous fuel with high carbon content which is produced on a large-scale at TATA Steel in IJmuiden. It is used as a fuel and as a reducing agent in smelting iron ore in a blast furnace. The product is derived from low-ash and low-sulphur bituminous coal by heating the coal at temperatures of around 1000–1100 degrees Celsius in the absence of air (oxygen). This process decomposes and vaporizes organic substances in the coal, releasing volatile products in the form of coal-gas (or coke oven gas) and coal-tar. The coke oven gas contains about 55% to 60 vol.% of hydrogen, and is used as fuel for the coke oven, the blast furnace, heating purposes in downstream steelmaking processes, and for power production.

2.3 Transport and distribution of hydrogen

Most of the hydrogen production is production for own use (captive), where hydrogen is produced and used on site. In some cases where hydrogen or hydrogen-rich residual gas is released as by-product, it is delivered to neighbouring or close by located external parties through a pipeline. Examples are Nouryon that delivers part of the pure by-product hydrogen to Teijin (Delfzijl), Dow that delivers hydrogen-rich residual gas to Yara and ICL (Zeeuws-Vlaanderen) and TATA Steel that delivers coke oven gas (about 10%) to Vattenfall (Velsen power plants).

Industrial gas producers Air Products and Air Liquide produce pure hydrogen for external customers (merchant hydrogen). Both operate their own hydrogen pipeline network to supply their major customers. Air Products operates a pipeline system of approximately 140 km length in the Rotterdam harbour region, stretching from the Botlek to Moerdijk and Zwijndrecht. Air Liquide operates the largest European network with a length of approximately 1000 km, stretching from Northern France to Rotterdam, connecting several production sites and customers in Northern France, Belgium and the south-west of the Netherlands. Because the pipeline is cross-border, imports and exports of hydrogen can take place. Situations of import and export can arise when production locations are taken offline for major overhaul, and supply has to come from elsewhere because local customers cannot sufficiently reduce their demand for hydrogen. At the moment, however, the balance is on average about zero (M. Weeda 2020).

In addition to pipeline supply, merchant hydrogen is delivered by truck. The most common way to transport hydrogen by truck is as compressed gas in cylinders. This type of transport takes place in small quantities, over limited distances, and mainly concerns domestic distribution. Hydrogen is also distributed by truck as a liquid. In this case some cross-border delivery does take place due to the fact that Air Products operates one of only few European liquid hydrogen plant in Rotterdam. Total quantities, however are still small. The capacity of the plant is 5 ton/day. If the plant would operate at full capacity and all hydrogen were to be exported this would be equivalent to 0.2 PJ of hydrogen energy.

2.4 Production and formation of hydrogen in industry in the Netherlands

Based on all available information, we estimate that currently (in 2019) the production capacity of all processes in which hydrogen plays a role, adds up to a possible annual amount of hydrogen in industry of total 18.3 bcm. This is equivalent to 1646 kton/y of hydrogen, or 198 PJ/y based on lower heating value (LHV). These figures apply when processes are in operation 24 hours a day, 365 days a year, and include all hydrogen, whether available as pure hydrogen, in syngas or in residual gases (only hydrogen shares included).

These figures decrease if plant capacity factors are taken into account as plants are never in full operation for 8760 hours per year. Typical capacity factors for large-scale industry processes are in the range of 85% to 95% under normal conditions. This leads to an estimate of 16.5 bcm or 1481 kton of hydrogen produced annually equivalent to roughly 178 PJ (LHV).

One might argue that hydrogen in a gas mixture, which is used as mixture should not count as hydrogen. If we then consider only production processes for pure hydrogen, the amount reduces to 117 PJ/y (see Table 1) or 142 PJ/y depending on whether hydrogen from catalytic reforming of naphtha within refineries is included or not.

Often only hydrogen produced from natural gas is considered in discussions about hydrogen. In that case the estimate would reduce to 104 PJ. This all, is not yet about the new interest in hydrogen which mainly concerns the use of renewable hydrogen from water-electrolysis. If the focus would be on hydrogen in the industry which could easily be replaced by hydrogen from water-electrolysis then only about 50 PJ would remain of the initial 198 PJ. Finally, for use of pure hydrogen as new fuel a non-significant amount would remain, although we estimate that about 24 PJ of hydrogen is used as fuel as part of residual gas mixtures. So clearly, the relevant amount of hydrogen strongly depends on definition and context of discussion.

Due to the many dimensions of the subject, the results can be categorized in different ways. In the following sections, the results are presented by hydrogen quality, hydrogen source, hydrogen application and geographic production location. The results that are presented are estimates of hydrogen production based on an assumed capacity factor of 90% (7884 hours per year).

2.4.1 Hydrogen production by quality

In the industrial gases industry, the quality of hydrogen is represented by the degree of purity in the number of 'nines'. The indication 3.0, for example, means 99.9% pure hydrogen. Usual industrial hydrogen grades are 3.0 or 4.0. The use of hydrogen for fuel cells requires 5.0, especially keeping contaminants of CO and sulphur compounds to an absolute minimum, because these poison the fuel cell catalyst causing degradation of fuel cell performance.

In this section, however, we use a much coarser grading of quality ranging from 'pure' to 'other residual gases'. ‘Pure’ covers all common industrial grades of hydrogen. 'Syngas' refers to situations where reforming takes place but hydrogen is not separated from CO, which mainly includes methanol production in the Netherlands. 'Rich residual gases' refers to residual gases with a high share of hydrogen where the remainder is mainly methane. These gases can easily be upgraded to pure hydrogen or directly be used for ‘pure’ hydrogen applications. This is done, for example with hydrogen from catalytic reforming of naphtha in refineries. 'Other residual gases' can still contain a considerable share of hydrogen, but also contain a range of other components. These gases would require significant further processing to obtain pure hydrogen, and are therefore mainly used as fuel gas. Table 1 presents an overview of estimated annual hydrogen production based on this subdivision in type of hydrogen quality.

Table 1 Overview of estimated annual hydrogen production by quality type

Quality type	Estimated hydrogen production		
	bcm/y	kton/y	PJ/y (LHV)
Pure [a]	10.9	972	117
Syngas [b]	1.1	102	12
Rich residual gas [c]	3.5	314	38
Other residual gas [d]	1.0	93	11
Total (hydrogen only)	**16.5**	**1,481**	**178**

[a] SMR/ATR-natural gas and refinery gas; Shell Gasifier; by-product Chlor-alkali; water-electrolysis

[b] SMR-natural gas for methanol

[c] Naphtha and other catalytic reforming processes; naphtha steam cracking

[d] Coke oven gas and Flexicoker fuel gas.

Clearly, the majority of hydrogen in industry is available as 'pure' hydrogen. About 90% of this comes from reforming natural gas and refinery gas, the rest mainly from gasification, and a small part from electrolysis processes. This pure hydrogen is mainly used for the production of ammonia, and for desulphurization and hydrocracking of oil products in refineries.

2.4.2 Hydrogen by energy source

Table 2 provides an overview of hydrogen production divided by source type. The majority of hydrogen appears derived from natural gas. But actually, this requires some nuance, which becomes clear from the overall reaction equation of the SMR/ATR process:

$$CH_4 + H_2O \rightarrow 4\,H_2 + CO_2$$

The reaction equations shows that half of the hydrogen actually originates from water. So the source of the hydrogen is both from natural gas and water. But all the energy used to produce the hydrogen comes from natural gas. In that sense natural gas is the only source.

Table 2 Overview of estimated annual hydrogen production by source of the hydrogen

Source type	Estimated hydrogen production		
	bcm/y	kton/y	PJ/y (LHV)
Natural gas [a)]	9.7	867	104
Oil [b)]	6.1	550	66
Coal [c)]	0.5	45	5
Electricity/water [d)]	0.2	19	2
Total	**16.5**	**1,481**	**178**

[a)] Hydrogen from SMR/ATR; main product; by-product CO/Syngas; part of syngas

[b)] SMR-refinery gas; naphtha and other catalytic reforming; naphtha steam cracking; heavy residue processing

[c)] Hydrogen in coke oven gas

[d)] By-product Chlor-alkali; water-electrolysis.

In the case of natural gas, approximately 7.2 bcm hydrogen is produced in processes where hydrogen is the main product. In the other cases CO is the main product, in which case hydrogen is an inevitable by-product, or syngas is produced. This is important in discussions about replacing fossil hydrogen by carbon-free hydrogen from water-electrolysis using electricity from renewables. Replacement is difficult if hydrogen is not the main product. But even if hydrogen is the main product, there may be restrictions on replacement. This is the case with ammonia production for fertilizers or chemicals where CO_2 is required for the production of urea in a subsequent process. If no CO_2 source is available other than the CO_2 that is released during the production of hydrogen with natural gas, then only part of the fossil hydrogen can be replaced by hydrogen from electrolysis.

The hydrogen that comes from oil is closely linked to the processing of oil and oil products into fuels and base chemicals for the chemical industry. About two-thirds of the hydrogen is an inevitable by-product of catalytic reforming processes and steam cracking of naphtha. The hydrogen produced from steam reforming of refinery residual gas, and gasification of refinery heavy residues can in principle be replaced by renewable hydrogen from water-electrolysis, but a different application must then be sought for these by-products. As hydrogen production generates a concentrated CO_2 tail gas, CCS could be an attractive and more cost-effective alternative to reduce CO_2 compared to replacement by renewable hydrogen.

The hydrogen from coal is an inevitable by-product of coke production which is linked with blast furnace based steelmaking. Production of this hydrogen can only be avoided by switching to a coke-free steelmaking process, such as the Hisarna process of TATA Steel (IJmuiden), or the Direct Reduced Iron process.

Finally, the overview shows that hydrogen produced by electrolysis currently only represents about 1% of the total amount of hydrogen in industry. And it is not even hydrogen from water-electrolysis that is at the heart of the large and growing interest in hydrogen. At this moment, virtually all electrolytic hydrogen is a by-product of the chlor-alkali process for the production of chlorine.

2.4.3 Hydrogen by application

Table 3 shows an overview of estimated annual hydrogen production per type of application. The majority of the hydrogen in industry, about 37%, is used in oil refinery. This only includes the use of pure or relatively pure hydrogen for desulphurization and hydrocracking, and not hydrogen that may be present in residual gas and is used as fuel. Ammonia is the other large application with about one-third of the total amount of hydrogen. If only the production of pure hydrogen is considered (see Table 1), then ammonia consumes almost 50% of the hydrogen. The category “other pure hydrogen use” consumes approximately 15% of the pure hydrogen, and almost 10% of the total amount of hydrogen. This category includes a wide variety of smaller applications in the chemical industry (e.g. in production of hydrogen peroxide, resins and fibers), the biofuels industry, the food industry, the glass industry, the metallurgical industry, and the electronics industry. A large part of this hydrogen, together with a part of the hydrogen for refineries, is so-called merchant hydrogen, which is produced by the producers of industrial gases.

Table 3 Overview of estimated annual hydrogen production by application type

Application type	**Estimated hydrogen production**		
	bcm/y	kton/y	PJ/y (LHV)
Ammonia [a)]	5.3	480	58
Refinery [b)]	6.1	548	66
Other pure hydrogen use [c)]	1.6	148	18
Methanol [d)]	1.1	102	12
Fuel gas [e)]	2.3	214	24
Total	**16.5**	**1,481**	**178**

[a)] SMR-natural gas

[b)] SMR-natural gas and refinery gas; Shell Gasifier; Naphtha catalytic reforming

[c)] SMR/ATR-natural gas; by-product chlor-alkali; water-electrolysis

[d)] SMR-natural gas

[e)] Various catalytic reforming; naphtha steam cracking; by-product chlor-alkali; Flexicoker fuel gas (but excluding small fractions of hydrogen that may be present in other residual refinery gas) and coke oven gas.

The applications ‘fuel gas’ includes energy applications like fuel for steam production and combined heat and power generation. This result indicates that about 13% of the total amount of hydrogen within the industry, roughly equivalent to 24 PJ, is used as fuel.

2.4.4 *Hydrogen production by industrial cluster*

In Table 4 the results are subdivided by geographical location or industrial cluster. Because of their relative proximity and interconnectedness, the Rotterdam harbour area (Europoort, Botlek and Pernis) and Moerdijk have been merged, but basically they are two separate clusters. In Zeeland, too, it is not a contiguous location, but a few cores that are some distance apart. Part of the industry is located near Vlissingen (Zeeland Refinery), while another part is located at the other site of the Westerschelde in Terneuzen (Dow) and Sluiskil (Yara). In addition, the plant of Air Liquide in Bergen op Zoom is included in Zeeland.

Rotterdam / Moerdijk is the cluster with the most hydrogen, with Rotterdam accounting for the vast majority by far (95%). Table 5 further subdivides the amount of hydrogen per cluster by application. These results show that currently in most clusters hydrogen use is dominated by a single application, such as methanol in Delfzijl, ammonia in Zuid-Limburg and Zeeland, and oil refining in Rotterdam.

Table 4 Overview of estimated annual hydrogen production by geographical location

Location	Estimated hydrogen production		
	bcm/y	kton/y	PJ/y (LHV)
Delfzijl [a)]	1.2	105	13
IJmond [b)]	0.5	45	5
Rotterdam / Moerdijk [c)]	7.2	644	77
Zeeland [d)]	5.3	478	57
Zuid-Limburg (Chemelot) [e)]	2.3	209	25
Total	**16.5**	**1,481**	**178**

[a)] SMR natural gas; by-product chlor-alkali; water-electrolysis

[b)] Coke oven gas

[c)] SMR/ATR-natural gas and refinery gas; Shell gasifier; naphtha and other catalytic reforming; naphtha steam cracking; by-product chlor-alkali; Flexicoker fuel gas

[d)] SMR natural gas; naphtha catalytic reforming and steam cracking

[e)] SMR-natural gas; naphtha steam cracking.

Table 5 Indicative distribution of hydrogen use per industry cluster

	Delfzijl	IJmond	Rotterdam/ Moerdijk	Zeeland	Zuid-Limburg
Refinery	-	-	64%	25%	-
Ammonia	-	-	-	60%	91%
Methanol	97%	-	-	-	-
Other [a)]	1%	-	22%	6%	-
Fuel	2%	100%	14%	9%	9%

[a)] Use of hydrogen as industrial gas for a wide range of applications

2.5 Comparison with data from energy statistics and evaluation

2.5.1 Comparison of results with previous findings

The results of the analysis indicate that the amount of hydrogen present in industry is significantly more than previously estimated based on data from literature (Trümper 2007) and the energy balance of the Netherlands (M. Weeda 2016). This finding is consistent with DNV·GL's conclusion in their recent review (DNVGL 2019).

The main factors contributing to the increase in this study are also consistent with factors identified by DNV·GL, namely:

- Two large SMR plants by Air Liquide and Air Products that have been installed in the last decade. These two plants were already included in the previous ECN study, but not explicitly mentioned. In that study, data on non-energy use of natural gas from the Dutch energy balance were basically leading in estimating hydrogen production. The total amount of hydrogen based on data of production facilities, including the two plants, was merely used to compare orders of magnitude;
- Update of the ammonia production capacity of the main fertilizer producers, and the associated hydrogen production capacity as a derivative thereof;
- Taking into account a number of previously omitted sources of hydrogen, such as hydrogen from catalytic reforming and gasification within refineries, and hydrogen as part of coke oven gas.

As a result, the figures in this study are also fairly comparable to those in the DNV·GL study, although there are some differences. This study leads to slightly higher values for the Rotterdam / Moerdijk region and for Zeeland due to different estimates for the internal hydrogen production within refineries. On the other hand, the amount of hydrogen for methanol production (Delfzijl) and the amount of hydrogen in coke oven gas (IJmond) is estimated to be lower.

Finally, the question remains which processes or process flows to include, or not, to determine the amount of hydrogen. That depends on the definition, or the criteria that must be met before you can call something hydrogen. For example, should there be a minimal share of hydrogen in a process stream, or should it be possible to simply upgrade a process stream to industrial-grade hydrogen so that it can in principle be used for pure hydrogen applications? If we add up all the process streams that contain hydrogen, we will have an amount of 198 PJ if all processes run at full load all year round. Taking into account a capacity factor of 90%, this figures drops to an estimated annual amount of hydrogen produced in industry of 178 PJ. Reasoning further that hydrogen is only hydrogen if it is available in pure form, then the figure further drops to 117 PJ, or 142 PJ if the hydrogen-rich residual gas from naphtha catalytic reforming within refineries is included (part of hydrogen-rich residual gas in Table 1).

2.5.2 Comparison of results with data from the Dutch energy balance

Currently, hydrogen is not considered as a tradeable energy product in international energy statistics (Eurostat, IEA and UN) and the closely related national energy statistics. However, production of hydrogen, pure or as part of residual gas mixture, is almost always related to consumption or conversion processes of energy that are covered by energy statistics. So hydrogen is present in the energy balance, but not explicitly. Table 6 presents an overview of energy flows in the Dutch energy balance with a relation to the production and presence of hydrogen in industry processes as described above (CBS 2020). Sections 2.5.2.1 to 2.5.2.3 describe how the results as presented in Table 2 relate to the figures in Table 6.

Table 6 Energy flows in the Dutch energy balance strongly or loosely related to the production and presence of hydrogen in industry processes (PJ LHV)

	Average 2000-2005	Average 2006-2010	Average 2011-2015	2016	2017	2018
Natural gas						
Non-energy use of natural gas in chemical industry	92	86	97	96	107	101
of which fertilizer industry	n.a.	n.a.	66	68	70	66
of which industrial gases industry	n.a.	n.a.	20	20	24	28
Input for transformations other than electricity production in refineries	12	15	20	13	14	16
Oil waste gases						
Production of oil residual (waste) gases by refineries [a), b)]	81	89	92	101	95	88
Production of oil residual (waste) gases of chemical industry [a), c)]	126	124	119	129	125	131
Coal gases						
Production of coke oven gas	17	16	16	16	16	16

[a)] Excluding residual gases that are re-used in refinery or chemical processes

[b)] Including all gases that are sold

[c)] Including residual gases that are sold for energy purposes

2.5.2.1 *Natural gas*

The most straightforward connection to hydrogen production is the non-energy consumption of hydrogen in the chemical industry. This is about 100 PJ each year. In principle this refers to natural gas that is not combusted but converted to chemical products. This means that natural gas that is used to produce steam for the SMR process is not included. Nevertheless, the figures cannot simply be read as energy content of hydrogen because not all energy ends up in hydrogen as intermediate product. In some cases non-energy use of natural gas serves to produce carbon monoxide as feedstock for the chemical industry simultaneously with the production of hydrogen,

The majority of the non-energy use of the natural gas occurs in the two fertilizer plants and in the hydrogen/carbon monoxide production plants of the industrial gases industry. A smaller amount is used for methanol production and other applications.

Oil refineries also use natural gas to produce hydrogen. However, non-energy use of energy products by refineries is by definition excluded in energy statistics. Therefore, in international energy statistics Statistics Netherlands reports all natural gas consumption by refineries used as input for processes (like production of hydrogen) as ‘own use’ in the energy sector. In the national energy balance, however, we report natural gas input for processes in refineries as input for ‘other transformations’. The input of natural gas for these other transformations in refineries was about 15 PJ (Table 6). Most likely this input for other transformation is to a large extent used for hydrogen production.

So, from energy statistics it follows that the order of magnitude of the total amount of natural gas converted to hydrogen is typically 100-120 PJ, which is more or less the same as the amount estimated from the capacities of the installations (see Table 2). These amounts relate to the purposely produced pure hydrogen, usable for many applications. To put this 100-120 PJ in perspective: total natural gas consumption in the Netherlands is about 1300 PJ.

2.5.2.2 Residual gases from the processing of oil and oil products

Current processes by refineries and the petrochemical industry lead to production of substantial amounts of residual gases, called refinery gas in international energy statistics. In these statistics there is no separate category for oil related residual gases (oil waste gases) from petrochemical industry. These are included in refinery gases by Statistics Netherlands. The residual gases are mostly combusted to produce heat that drives processes. The composition of the residual gases differ, depending on the process from which they originate. The composition of the residual gases is not covered by energy statistics. Statistics Netherlands records these gases in ton equivalents, representing 45,2 MJ/kg.

Part of the hydrogen in residual gases is not combusted for heat but used as hydrogen for several processes in refineries, often after separation or gasification. This hydrogen is not part of residual gases production from oil or oil products as recorded in energy statistics, because input and output of transformations in refineries and petrochemical industry (other than transformations for electricity and heat) is netted. This type of hydrogen production and consumption is considered being part of the black box of refinery and petrochemical industry processes.

The amount of hydrogen of oil related residual gases is estimated at 66 PJ (see Table 2) Most of this hydrogen (more than 60% to possibly over 80%) is hydrogen which is produced and consumed in the ‘refinery and petrochemical industry black box’ (e.g. hydrogen from naphtha catalytic reforming and residues gasification). But it also includes hydrogen that is part of oil related residual gases production in energy statistics, which amounts about 220 PJ (Table 6). The latter mainly concerns residual gas used as fuel (may include some of the hydrogen reported as ‘fuel gas’ in Table 3), but also, for example, hydrogen rich residual gas delivered by Dow to Yara, and refinery gas delivered by ExxonMobil to Air Products for hydrogen production.

2.5.2.3 Cokes oven gas

Cokes oven gas is a by-product in the coke factory, with an annual production of about 15 PJ. This includes the energy content of the entire coke oven gas mixture. The value relates well to the energy content of the hydrogen in the mixture as given in Table 2 (5 PJ), taking into account the heating value of coke oven gas (19 MJ/m^3) and hydrogen (10,8 MJ/m^3), and a 55-60 vol% hydrogen in the gas mixture.

3 Near term and future hydrogen value chains

3.1 New roles for hydrogen

Currently hydrogen is mainly produced domestically, in-house for industry's own use, almost exclusively from fossil fuels, and is mainly used as chemical building block or industrial gas for non-energy applications. Although mapping the flows from hydrogen plants to refineries would certainly provide more insight into the energy and CO_2 balance of the system, there has so far been insufficient reason to explicitly include hydrogen in national and international energy balances.

The vision for the future is that hydrogen will be produced almost exclusively from renewable sources and will be also used as carbon-free energy carrier for a multitude of energy applications (Annex A). This will be in addition to its current industrial uses, and potentially also a much wider use in the fuels and chemical industry as a renewable building block for synthetic liquid fuels, and sustainable chemical products and materials. On top of that, it is envisioned that international supply chains will develop to distribute renewable energy, especially solar and wind energy, through hydrogen between areas with an abundant availability of these sources and areas with limited availability. In the transition to such an energy system, the production of low-carbon hydrogen, i.e. the production of hydrogen from natural gas with CCS, may appear a cost-effective temporary intermediate step that can lead relatively quickly to significant reduction in CO_2 emissions, and may facilitate the development of the use of hydrogen for energy applications. By aiming for converting fossil fuels to hydrogen as close as possible to the point of exploitation, and to store the produced CO_2 as much as possible, this may also facilitate the development of international trade of hydrogen as a commodity.

If the production and distribution of hydrogen for energy applications in end-use sectors materializes, and/or the import of hydrogen, hydrogen will have to be included in energy balances as a separate category, similar to for example natural gas, oil and oil products and biomass. The next chapter explores the choices that can and need to be made, and provide an outline of the process to be followed and an indication of the associated time frame. As a further introduction to this, the next section first examines some insights from current forecasts for the demand of hydrogen. This is followed by an overview of possible options for domestic production and distribution of hydrogen and potential routes for the import of hydrogen.

3.2 Projections for future hydrogen demand in the Netherlands

The majority of scenario studies indicate a significant future use of hydrogen.
Last year, two meta-studies have been published which provide an overview of hydrogen demand projections for the Netherlands (Knoors 2019), (Detz 2019). To this, the results of two other scenario studies can be added (den Ouden 2020), (M. Scheepers 2020). The estimates in the studies show a large bandwidth in potential or projected hydrogen demand. This is due to differences between the studies in scope, modelling approach, and most likely also in underlying assumptions. Especially whether or not to include hydrogen for the production of synthetic bunker

fuels and products in the chemical industry based on hydrogen and CO_2 has a major impact. Without these categories, the demand for hydrogen in 2050 generally ranges from the current industrial level of natural gas based pure hydrogen, which is roughly 10 billion cubic meter (bcm) (110 PJ) to about 50 bcm (540 PJ). This easily rises to more than 100 bcm (> 1080 PJ) when these categories are included. The studies also diverge with regard to the sectors and applications in which hydrogen plays a role, but on average show a relatively even distribution across end-use sector, including power generation. To put these numbers in perspective, current total primary energy consumption in the Netherlands is about 3000 PJ.

No clear conclusions can yet be drawn from this about the future demand level, except that it could be significant and easily amount to tens of bcm of hydrogen, or hundreds of petajoules (PJ) of hydrogen energy. This may not seem a lot, but one should realize that the production of 10 PJ of hydrogen roughly requires 1 gigawatt (GW) of offshore wind. The production of hundreds of PJ hydrogen would thus already require tens of GW offshore wind. So far, the installation of 11.5 GW offshore wind is planned in the Netherlands in 2030, while it is generally assumed that there is a total potential of about 60 GW

3.3 New perspectives for production and distribution of hydrogen

3.3.1 Electrolysis of water

As already mentioned in the introduction, the potential of hydrogen is basically about being able to produce it by splitting water using energy from renewable energy sources, in particular sun and wind. In this way, the energy from these sources can be captured in a carbon-free fuel that can be transported over long distances, stored at large-scale, and be used as a chemical building block. Water-electrolysis, i.e. splitting of water using electricity, is a key technology. There are other technologies, such as photo-electrochemical cells (direct electrochemical splitting of water by sunlight), and catalysed thermal splitting of water using concentrated solar power. But these technologies are still in an early stage of development, and of no or limited use for domestic production because of the limited power of the sun in the Netherlands.

3.3.1.1 Central conversion and production onshore

Electrolysis of water can take place centrally near places where electricity from offshore wind comes ashore. Then there are a number of options:

- The conversion can be carried out by a utility in the energy sector. The electrolysis plant acts as a kind of reverse power plant that converts electrical energy into gaseous energy which subsequently is supplied to a central infrastructure for the transport and distribution of hydrogen to end-users. This will probably be a pipeline infrastructure, but can also partly be transport of compressed gaseous or liquid hydrogen by truck.
- The conversion can also take place in industry that needs hydrogen. In this case electricity is supplied to the end-use sector industry, which uses the electricity for production of hydrogen. If the industry consumes all hydrogen for own use, then the situation is no different than today, although today natural gas is supplied to produce hydrogen instead of electricity. In addition, hydrogen could not only be used as industrial gas or chemical building block, but also as fuel. In the opposite case all produced hydrogen

is fed back into a central infrastructure. It is possible, but it is not clear why this would then be an industry activity. A more likely case may be that industry consumes part of the hydrogen for own use and feeds the other part back into a central infrastructure for supply of hydrogen to other end-users, similar to combined heat and power (CHP) production in industry.

3.3.1.2 *Central production offshore*

As the energy transition progresses, the extraction of offshore wind will take place further and further from the coast. At some point, it may then become more cost-effective to carry out the conversion to hydrogen offshore, and to transport the energy in the form of hydrogen to the coast via a pipeline instead of as electricity via electricity cables. Sufficient electrolysis capacity can perhaps be installed on platforms, but one or more artificial islands will probably be required if many (tens of) GW's of wind and electrolysis are involved. In these cases, there can be full conversion to hydrogen without connection to a central electricity infrastructure, i.e. offshore wind farms dedicated to renewable hydrogen. But there may also be a combined electricity and hydrogen infrastructure to the coast, in which part of the wind energy is converted into hydrogen and part of it is transported as electricity depending on the ratio of supply and demand.

A third option, next to an island or a platform, might be to perform conversion to hydrogen at the wind turbine. Each wind turbine (with a capacity of 10-15 MW) then has its own electrolysis unit, and in principle only has a hydrogen outlet with a connection (directly or via an offshore hydrogen substation) to a central hydrogen pipeline to the coast.

3.3.1.3 *Decentral production onshore*

Electrolysis can also take place decentralized, regionally or even locally, in conjunction with the further expansion of the exploitation of solar and wind energy on land. Placing it in strategic locations can facilitate the incorporation of variable solar and wind power supply and help optimize investments that would otherwise be required to strengthen and expand the electricity infrastructure. To be able to exploit the full benefit of this option it should be combined with local use of hydrogen in industry and/or it should be possible to directly feed the hydrogen into a pipeline infrastructure for delivery to other end-users either. This can be as pure hydrogen but could also be in a mixture with natural gas or another renewable gas. Other modes of transport are relatively expensive and may even outweigh savings achieved in the electricity system.

3.3.2 *Reforming of natural gas with CCS*

Transport and distribution of natural gas to small-scale end-users will inevitably lead to emissions of CO_2. The scale of use does not favour CCS. To be able to timely achieve required GHG emission reductions upfront decarbonization of natural gas and use of hydrogen as a fuel could be an attractive robust option. It is typically an option that should be carried out as centrally as possible.

In addition to natural gas, it is also possible to decarbonize refinery gas or other residual gases from industry. This is basically what is already happening with ExxonMobil refinery gas used by Air Products in their Steam Methane Reformer for hydrogen production. However, no CCS is taking place yet. The concept of natural gas and refinery gas conversion into hydrogen with CCS is subject of study in the H-Vision project (Deltalinqs 2019).

Steam reforming of green gas from upgraded biogas is also possible. Combined with CCS this even leads to negative emissions. But biogas is typically produced decentral at relatively small scale. Also the regional upgrading of biogas to natural gas quality green gas, and feeding of the green gas into the gas network does not take place at very large scale, nor at sites close to expected infrastructure for removal and underground storage of CO_2 offshore. The negative emissions will thus have to be realized through administrative coupling of centrally processes methane with the green gas.

3.3.3 *Gasification of biomass and waste*

Low-carbon hydrogen can also be produced by coal gasification, but this is unlikely in the Netherlands due to the required large amount of CO_2 storage. Gasification of biomass is an alternative. Also combining this option with CCS leads to negative emissions. However, the use of the limited amount of truly sustainable biomass will probably be of higher value as carbon source for the chemical industry or for biofuels than for the production of hydrogen for which there are more alternatives. The same applies to waste which in circular economy will also be needed as a sustainable carbon source for the chemical industry. This requires gasification to syngas and not full conversion to hydrogen and CO_2.

A new type of gasification currently under development is supercritical water gasification. The ultimate size of the process is not yet clear, but is not likely to be very large-scale. The process operates at temperatures above 375 degrees Celsius and pressures of at least 220 bar, and is suited to convert wet biomass waste streams, such as manure and sewage sludge, into a methane rich or more hydrogen rich product gas depending on the process conditions. The option is therefore a competitor for decentral biomass digesters and not so much an alternative for large-scale central gasifiers of woody biomass.

3.3.4 *International trade of hydrogen*

Currently vast amounts of fossil energy are transported and distributed across the world from areas with an abundance of resources to areas with insufficient or only expensive local resources. Undoubtedly these patterns will change in the course of the energy transition. Supply chains for bio-based energy products already exist and are expanding. These bio-based energy products can basically be considered as import of solar energy. Hydrogen adds possibilities by enabling the development of new international supply chains for solar energy and for wind energy, but also for decarbonized fossil fuels.

Various options for transport are being considered. The main options are:

- Pipeline transport for continental scale trade, similar to current pipeline transport of natural gas from, for example, Norway, Russia or North Africa. This may require new pipelines, but it may also be possible to use parts of the existing infrastructure if the need for natural gas transmission capacity decreases during the energy transition. One could think of transport of solar and wind energy in the form of hydrogen from the Mediterranean area to northern European demand centres, but also transport of decarbonized natural gas (hydrogen from natural gas with CCS) from Norway and Russia.

- Transport of liquid hydrogen (LH2). This is comparable to the transport of Liquified Natural Gas (LNG), the difference being that natural gas becomes liquid at about -162 degrees Celsius, while for liquid hydrogen temperatures are required as low as -253 degrees Celsius. Currently, Japan is building a first liquid hydrogen tanker in a demonstration project to import hydrogen from Australia. The advantage for liquid hydrogen is that it is very pure. After arrival at a port it can be transported further as a liquid to the hinterland, e.g. by barges, or can be gasified and transported by pipelines.
- Liquid Organic Hydrogen Carriers (LOHC) appear an attractive alternative to liquid hydrogen for long distance transport, primarily thanks to ease of handling and storage. Typical examples are organic molecules containing aromatic rings, such as toluene, naphthalene, or dibenzyl-toluene. When hydrogenated, these molecules contain nearly as much hydrogen per cubic meter as liquid hydrogen, without requiring the use of special materials and storage under cryogenic conditions. At the receiving end of the supply chain, a dehydrogenation plant is needed to release the hydrogen from the carrier, which is then send back for the next cycle.
- A fourth option is to combine hydrogen with nitrogen and to transport the hydrogen as ammonia. Ammonia is already traded internationally as a commodity and shipped by tankers also to the Netherlands, So the supply chain already exists. However, currently ammonia is used as ammonia and not reconverted to hydrogen. The combined annual production capacity of Yara and OCI amounts to almost 3 Mton of ammonia for which more than 530 kton, or almost 65 PJ of hydrogen is needed. Until domestic production of ammonia has been replaced by imports, it makes no sense to import and decompose ammonia to hydrogen, which can then be used again further downstream to produce ammonia.
- Instead of combining hydrogen with nitrogen it can also be combined with carbon or CO_2. In this context, methanol is also considered as an option for hydrogen imports. As with ammonia, the question is whether we will decompose methanol to hydrogen (and CO_2) when it is imported. Methanol is commonly used as both solvent and reactant in chemical industry. It can also be used as motor fuel or blended with gasoline. So it can be used as such which can replace domestic production. In addition, methanol can also be used to produce olefins (e.g. ethylene and propylene) through the methanol-to-olefins process. This would enable replacing naphtha, and thereby crude oil, as a source of olefins.

4 Hydrogen in energy statistics

4.1 Hydrogen in the current energy statistics

In current national and international energy statistics hydrogen is not considered as an energy product, but it may be related to non-energy use of energy products like natural gas (section 2.5.2).

Oil refineries use hydrogen for desulphurization and hydrogenation. Often they produce their own hydrogen, but they also buy hydrogen. This hydrogen may be reported as part of ‘other hydrocarbons’ and in the reporting instructions hydrogen is listed as an example of a product that is part of ‘other hydrocarbons’. However, thus far in communication with Eurostat and IEA there is little attention for reporting hydrogen this way. Also, in the data published by Eurostat only few countries report data for ‘other hydrocarbons’ and data that are reported are mostly connected to gas-to-liquid conversions (Eurostat 2020). Thus far Statistics Netherlands does not report hydrogen as part of ‘other hydrocarbons’.

4.2 Need for hydrogen as separate category in energy statistics

As described in chapter three, hydrogen is potentially an important commodity in the future energy system that may be produced, traded and consumed in several ways. At national and international level several modelling studies are carried out to investigate this future system. Often, the energy balance forms the basic framework for these models, and as a result researchers working with these types of models, both at EU level and at national level, start to ask questions to the statistical community on how to cope with hydrogen.

As shown in chapter 2 there is already substantial production and consumption of hydrogen for non-energy purposes (like nitrogen fertilizer production) and for refinery processes (where it is a bit unclear whether this should be considered as an energy purpose). Also there is already a pipeline network for transport and international trade of hydrogen. In the future new ways of production and consumption of hydrogen may develop (Chapter 3). It is quite possible that the system for these modes of production, transport and consumption will be connected to, and perhaps even integrated with, the current system. Therefore, in developing ideas to cover hydrogen in the future energy systems it is also relevant to what extent the current ways of producing and consuming hydrogen should be integrated.

Hydrogen is an important product increasingly used by refineries. Projected trends of CO_2 emissions by refineries are influenced by changes in demand for desulphurization (PBL 2019), a process which needs hydrogen. To follow the development of (CO_2-)efficiency of refineries it is relevant to be able to quantify the intake of hydrogen by refineries which is not possible now.

4.3 Methodological choices

Inclusion of hydrogen in energy statistics is not straight forward. There are several methodological choices to be made, strongly affecting the outcome of the statistics and the data need. Developing meaningful and comparable international statistics needs a common understanding for solving issues. In this section we list seven issues, without having in mind yet the optimal solution.

4.3.1 Discrimination between hydrogen for energy and for other purposes?

Currently, ‘pure’ hydrogen and hydrogen as part of specific synthesis gases (e.g. for production of ammonia and methanol) are mainly used for applications that are considered as non-energy use. Furthermore, there is quite some combustion of hydrogen in residual gases, but in these cases the hydrogen is not considered as hydrogen but as residual gas.

The distinction ‘energy’ and ‘non-energy’ is however a bit unclear for use of ‘pure’ hydrogen in refineries. Hydrogen for desulphurization is clearly non-energy, but hydrogen for hydrocracking where (part of) the hydrogen can end up in fuel is a more doubtful case. In practice it may be difficult to distinguish between both types of application if both receive hydrogen from the same local network which is fed by various internal sources (sources within the ‘refinery black box’) and possibly external suppliers.

In future, new energy applications of hydrogen may develop like blending in natural gas network, dedicated hydrogen distribution networks for heating of buildings, direct use for transport or conversion to electricity in times of short renewable supply. Also new non-energy applications may develop, like feedstock for the petrochemical industry replacing fossil feedstocks like naphtha.

The question is whether energy statistics should be restricted to energy-applications only or cover non-energy applications for hydrogen as well, like for natural gas or oil.

An advantage of including the non-energy applications as well is that this would provide a complete overview of the hydrogen market and system. It also may be more easy in practice as hydrogen producers and importers/exporters would not need to know the destination of their hydrogen (if possible) to decide whether they should include this in surveys for energy statistics. Another advantage is that including all hydrogen avoids the issue of discriminating between energy and non-energy application of hydrogen, which may be complex (e.g. in refineries). A disadvantage of including non-energy application is that more users may need to report hydrogen consumption.

4.3.2 Only sold hydrogen or also hydrogen as intermediate product?

Usually energy statistics is about bought and sold energy products, as these quantities are relatively easily available in administrations. An exception is electricity for which always total production and consumption is recorded. For waste gases (like refinery gas) production of all gases that are finally combusted is included.

For hydrogen one could ask whether energy statistics should be restricted to bought and sold quantities (merchant hydrogen) or one should record hydrogen as an intermediate product as well. Examples for current hydrogen production as intermediate product are hydrogen production by refineries for their own processes and hydrogen by the nitrogen fertilizer industry. An example of future hydrogen production as intermediate is hydrogen produced by electrolysis and directly blended into the natural gas grid. For the time being, this could be seen as conversion of electricity into hydrogen and conversion of hydrogen into natural gas, or as conversion of electricity directly into natural gas.

An advantage of covering also hydrogen as intermediate product is that this would provide a more complete picture and helps to reveals the potential for new ways of hydrogen supply. A disadvantage is that surveys will be complicated and perhaps also quite difficult to answer, especially in refineries or petrochemical plants which may have several ways to produce hydrogen as intermediate product in several grades of purity.

A compromise may be to cover all sold hydrogen and captive production of hydrogen from a limited number of clearly defined processes, like reforming (SMR and ATR) of natural gas and electrolysis.

4.3.3 Demarcation between residual gas and hydrogen

Refinery gas and cokes oven gas are mixtures of several gases of which hydrogen may be an important one. However, if the hydrogen is part of a gas mixture the flexibility of its usage is much less. This raises the question how we should discriminate residual gas from hydrogen. Three type of criteria may play a role. Ideally a definition arises which fits to all criteria:

- Physical properties like degree of purity
- Suitability for use for specific meaningful applications
- Existing technical and market standards

The degree of purity already plays a role in defining other energy products. Aromatics with a low degree of purity are included in the energy product naphtha and often blended into motor fuels. High-purity aromatics on the other hand are used as basic chemical product, and are considered as non-energy products. The high-purity aromatics are excluded from energy statistics (input for production is considered as non-energy use).

4.3.4 Distinction between hydrogen by production process?

In many discussions the way of producing hydrogen plays an important role, speaking about renewable and conventional hydrogen. Of course it will be important to distinguish the various energy sources for hydrogen production. The questions is whether the energy source should ‘travel’ with the hydrogen to the consumption, introducing separate balances for e.g. renewable and fossil hydrogen.

For this discussion it is important to realize that the system of energy balances is a pure physical system. Administrative allocation of properties (like Guarantees of Origin for electricity) do not play a role. This means that if separate balances of renewable and conventional hydrogen are compiled there should also be separate physical systems. In several circumstances this may be the case. However, one may also envisage a hydrogen transport system in which renewable and conventional hydrogen are mixed.

The most simple solution for energy statistics may be to distinguish hydrogen by energy source only when produced. For administrative purposes, like target accounting or energy disclosure, it may be desirable to allocate the way of production to the users. For these type of purposes separate systems may be developed alongside energy statistics, like the system of Guarantees of Origin for electricity or SHARES for allocating biomethane injected into the grid to transport.

4.3.5 Hydrogen production as primary or secondary production?

In energy statistics there is a fundamental difference between primary production (the moment when energy enters the system) and secondary production (transformation of one energy commodity into another energy commodity). It would be most logical to consider hydrogen production as secondary production for which another energy input (e.g. electricity or natural gas) is needed. The position of hydrogen in an energy balance would be comparable with electricity.

If electricity from wind turbines is directly converted to hydrogen (before feeding into the grid), than this could be seen as primary production and transformation input of wind energy (value equal to electricity production) with transformation output of hydrogen. Alternatively, one could choose to map the complete electricity production as well, in which case this situation would be primary production and transformation input of wind energy, transformation output and transformation input of electricity and transformation output of hydrogen.

By considering hydrogen as secondary production double counting of the same energy as primary production (and gross consumption) is avoided.

4.3.6 International trade of hydrogen

Energy statistics contains items covering imports and exports of energy products. These flows are physically defined with geographical borders of countries as demarcation. This definition would be also applicable for hydrogen.

The physical character of the system implies that imports of hydrogen produced from e.g. wind energy (e.g. in case of a direct connection) would be recorded as imports of hydrogen and not of wind energy. If the hydrogen is converted to e.g. ammonia or methanol and subsequently traded than this would be import of ammonia or methanol if these commodities are actually used or considered as energy product. If they are used or otherwise as non-energy product they would fall outside the scope of energy statistics.

4.3.7 Introducing other new energy products with similar role as hydrogen

As discussed before other products may obtain a role in the energy system comparable to the role foreseen for hydrogen. One could think of methanol or ammonia that can be produced from various energy sources, transported and stored, and used for various energy applications and non-energy applications replacing fossil products. Therefore, it would be logical to raise the question whether these other potentially new energy products should not be included as well in energy statistics.

4.4 Process for possible introduction of hydrogen in energy statistics

The core of international energy statistics for EU countries exists of the five joint annual questionnaires (oil, coal, gas, electricity & heat and renewables & waste) which are sent to Eurostat and IEA. Every five years these questionnaires are adapted to changing needs of users.

Discussion on necessary and possible changes take place in meetings of the Eurostat Energy Statistics Working Group (EWSG) and the ESDG (Energy Statistics Development Group) of IEA. Participants in these meetings are Eurostat, IEA, representatives of statistical departments in member states and sometimes also DG Energy or the EU Joint Research Centre. Sometimes there are task forces with a limited number of experts. Formal decisions for the EU are taken at higher levels, but the general way of work is to achieve consensus at the working group level, in particular because harmonization with IEA is desirable.

The current joint annual questionnaires are fixed until the reference year 2021. So reference year 2022 will be the first possible year for new products. Eurostat indicated that this year (2020) will be the main year for discussions and next year the decision making is planned.

Introducing hydrogen as separate commodity in the joint annual questionnaires already for the next 5-year cycle may be a bit too early, because there is not yet a common idea on how to cope with all the dilemma’s when introducing hydrogen as listed in the sections above. We hope that this report will contribute in developing these common ideas.

As a first step the current reporting guidelines for the existing joint annual questionnaires may be made more clear on how to deal with hydrogen which is hidden in certain products and flows of the energy balance. Possibly, voluntary memo-items regarding hydrogen may be introduced.

So far, the discussion on hydrogen in energy statistics is mainly performed by people from governments and research institutes. The hydrogen producing and using industry is still missing. In order to develop something that is practical and useful for everyone input from the industry, both at national and EU level, it is recommended to include the industry as well.

Hydrogen may influence the future energy systems in fundamentally new ways and thus may also effect the core of international energy statistics. Changing the core of international energy statistics is a process that takes time, because these statistics use concepts that are harmonized at a world scale and because the set of concepts is already quite complex. Based on the current views on the importance of hydrogen as energy carrier, integrating hydrogen in the energy statistics as a separate category seems needed, but preferably it should not further complicate matters.

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A Potential applications of low-carbon and renewable hydrogen

Looking into more detail a large number of potential applications or markets can be identified for renewable hydrogen. This includes both energy and non-energy applications. The following sections provide an overview of the possibilities.

High-grade heat for industry
Use as fuel for replacement of natural gas for the production of steam and high-grade heat in industrial processes where electrification is not possible or not the most cost effective option. For industrial processes that operate at high temperatures and require high heat output, electrification may not be possible from a process point of view (investment in new process needed) or from an infrastructure point of view (major reinforcement of electricity infrastructure needed). Continuing to use a gaseous fuel could be a necessity or the best solution, in which case the fuel should preferably be carbon-free.

Electricity production
Use as a fuel for replacement of natural gas for electricity production in dispatchable power plants to supplement variable renewable energy-based power generation when needed. Zero-emission electricity production in flexible controllable power plants may be required more or less continuously as part of the range of flexibility measures to achieve a stable electricity system, or especially as a backup option for production in periods when there is insufficient supply of wind and sun. Production can take place in large central gas-fired power stations, but also in smaller decentralized units that can be used for combined heat and power (CHP) generation, including fuel cell-based power and CHP units in the near future at regional, district or even building level.

Heat for the built environment
Use as fuel for the replacement of natural gas for the production of low-grade heat in hydrogen boilers and hybrid heat pumps for space and tap water heating in the built environment. This may be an option for situations where insulation up to a level required for electric heat pumps is not possible or too expensive, and where buildings are insufficiently concentrated for district heating systems. Old city centers and existing buildings in rural areas are typical examples. But in areas with many owner-occupied homes, it can also be a robust and flexible option for rapid decarbonization of the heat supply, giving owners time to gradually upgrade the insulation level of their home.

Heat for district heating systems
In addition to direct use hydrogen for heat in the built environment, it can also be used indirectly. This is about the use as a fuel for replacement of natural gas to produce heat for district heating systems at times of peak demand and as backup. Significant amounts of natural gas are currently used to support heat supply through district heating systems. This is not expected to be any different if the networks are to be expanded considerably and if there is a shift towards more supply of residual heat from industry and geothermal energy.

Fuel for transport
Use as fuel to produce electricity onboard of fuel cell electric vehicles (FCEV). The advantage of hydrogen is that a relatively large amount of energy can be stored in tanks, with the weight and volume not scaling proportionally to the amount of energy, as is the case for batteries. In addition, the tanks can be filled up quickly, also in case of larger amounts. The option is therefore well suited to electrification of the more energy-intensive transport applications, especially if long-term and flexible use of vehicles is required. Hydrogen fuel cells, together with batteries provide the options to fully electrify a wide range of vehicles, mobile equipment and possibly also ships, and to deliver ‘zero emissions’ transport.

At the moment use as fuel for FCEVs is the only energy application of pure hydrogen. This application is also still in its infancy but type of vehicles and numbers are increasing. Cars and buses are already commercially available, and there is a growing number of demonstration projects with trucks. Worldwide more than 15,000 cars are on the road, and hundreds of buses (IPHE sd). Two fuel cell trains are currently being successfully demonstrated in Germany, which are seen as an economically beneficial alternative to direct electrification of all regional diesel trains with overhead lines.

Currently, there are about 250 cars and 8 buses in operation in the Netherlands (RVO 2020). In the short term, at least 50 buses will be added as part of a European project. These developments fit in well with the government's aim for zero-emission public bus transport and the sale of only zero-emission cars from 2030. In addition, many demonstration projects are ongoing or under development, including projects with fuel cell (garbage) trucks and even barges (TKI Nieuw Gas 2020).

Feedstock for synthetic fuel for transport
In addition to the direct use of hydrogen as a fuel for transport applications, hydrogen can also be used indirectly through pathways known as Power-to-Liquids, Electrofuels or Solar Fuels. Liquid fuels are likely to remain necessary for aviation and maritime shipping for the time being. In this case hydrogen can be used as feedstock for production of synthetic fuels (synfuels) to replace oil-based kerosene and fuel oil. Climate-neutral synfuels also require renewable carbon sources. This can be carbon from sustainable biomass, circular carbon from waste processing, and carbon from direct air capture (DAC). Re-use of fossil carbon from industrial processes and power plants is seen as a necessary transition step, but because the climate potential of this route is very limited, lock-in must be avoided.

Replacement of today’s natural gas based industrial hydrogen
Today, hydrogen is used non-energetically on a large scale in the industry as a feedstock and an industrial gas. In a pure form hydrogen is used mainly for the production of ammonia (mainly for fertilizer), and in refineries for the desulphurization of oil products and hydrocracking of heavy oil fractions into higher value lighter fractions. In addition to these high-volume application and other applications in the chemical industry, there are many smaller applications in a wide range of industry sectors, such as the biofuels, food, metallurgical, glass and electronics industry. In the Netherlands, hydrogen is largely produced by steam reforming of natural gas. Renewable hydrogen can act as direct replacement for

this hydrogen in all cases where there is no need for the carbon component in natural gas. The fertilizer industry requires CO_2 to convert part of the ammonia into urea. So in that case not all fossil hydrogen can be replaced unless there is another external source of CO_2. And in some cases steam reforming of natural gas is used to produce carbon monoxide. Hydrogen is then an inevitable by-product.

Feedstock for climate-neutral products from the chemical industry

Renewable hydrogen can be used as feedstock for the production of plastics and other hydrocarbon products from the chemical industry via a pathway also known as Power-to-Chemical. In the long run it can contribute to the replacement of oil as basis for chemical products. The pathway is quite similar to the pathway of synfuels. Besides hydrogen also a carbon source is needed to produce hydrocarbons. If CO_2 is the starting product, this first needs to be reduced to CO. Currently this requires reverse-WGS with hydrogen. A better option might be to reduce CO_2 electrochemically if possible, as this would avoid the need to first produce hydrogen. Then the CO is mixed with hydrogen to syngas, which can be used to produce basically any plastic or hydrocarbon product through the methanol and methanol-to-olefins pathway, or the Fisher-Tropsch route. Just as with synfuels, this application requires renewable carbon sources to exploit the full GHG mitigation potential. But if products are produced in which carbon is virtually stored permanently, also reuse of fossil CO_2 can make a significant contribution to reducing GHG emissions through this pathway.

Decarbonization of steelmaking

The combination of blast furnace and basic oxygen furnace (BF/BOF) is the main process for the production of steel from iron ore. But worldwide there is also a significant part produced through the Direct Reduced Iron process combined with an Electric Arc Furnace (DRI/EAF). In the latter case iron ore is reduced by syngas which is produced by steam reforming of natural gas. Therefore, this process can typically be found at places where gas prices are low or stranded gas assets are available. Although syngas is used the process can in principle also be operated only using only hydrogen as reducing agent, which offers a route to carbon-free steelmaking. And perhaps also other alternative processes are suitable for switching to hydrogen as single reducing agent for iron ore.