Noordelijke InnovationBoard

Green Hydrogen Economy in the Northern Netherlands

Executive Summary

1. Green Hydrogen (H_2) will play an important future role in a sustainable energy system:
    a. For worldwide transport and storage of large scale low-cost renewable energy.
    b. To supply a green feedstock to the chemical industry.
    c. To supply a green fuel to the transportation sector.
    d. To balance the electricity system, seasonally and weekly, from local to national level.

2. The Northern Netherlands is uniquely positioned to develop the green hydrogen economy:
    a. In view of the Paris Agreement, the change towards a fully sustainable energy system is inevitable. In the Northern Netherlands, this change is even more pronounced, because of the earthquake issues due to the production of natural gas.
    b. Because of the Slochteren gas field, the gas industry is situated in the Northern Netherlands. This industry could relatively easy switch to hydrogen as the required knowledge, infrastructure and industrial activities for both gasses is to a certain extent comparable.
    c. There is a large future supply of electricity from Norwegian hydropower, Danish wind and Dutch + German offshore wind, while the electricity transport grid has limited inland capacity.
    d. Chemical and agricultural companies are present in the Northern Netherlands that could profit from a green hydrogen supply in combination with a green syngas and green carbon-dioxide supply.
    e. Rapid development of electric transport, with batteries and with hydrogen fuel cells in Europe, which creates extra demand for green hydrogen, especially in neighboring Germany.

3. A green hydrogen economy can only be realized when green hydrogen production, markets, infrastructure and societal aspects are developed in interdependence with one another. As a first phase, in the Northern Netherlands, up to 2025-2030 the following projects, activities and systems must be realized.

Production

- 4,000 MW Wind Offshore
- 1,000 MW Electrolysis Hydrogen Production
- 1,000 MW Biomass Gasification
- 100 Solar-Hydrogen Smart City Areas

Infrastructure

- H_2 Pipeline to Rotterdam + Germany
- Hydrogen Trading platform
- Hydrogen Harbor Facilities Eemshaven
- 5 Hydrogen Distribution Centers

Green Hydrogen Economy Northern Netherlands

Markets

- 300,000 ton Green Methanol + 300,000 ton Green Ammonia
- 100 H_2 Fueling station in Northern NL
- 5 Hydrogen Fuel cell balanced Data-Centers
- 3 Hydrogen Innovation/start-up Centers

Society

- Zero Emission Public Transport
- Hydrogen Trade Fair and Exhibition
- Hydrogen Regulatory Framework
- Green Hydrogen Certificates

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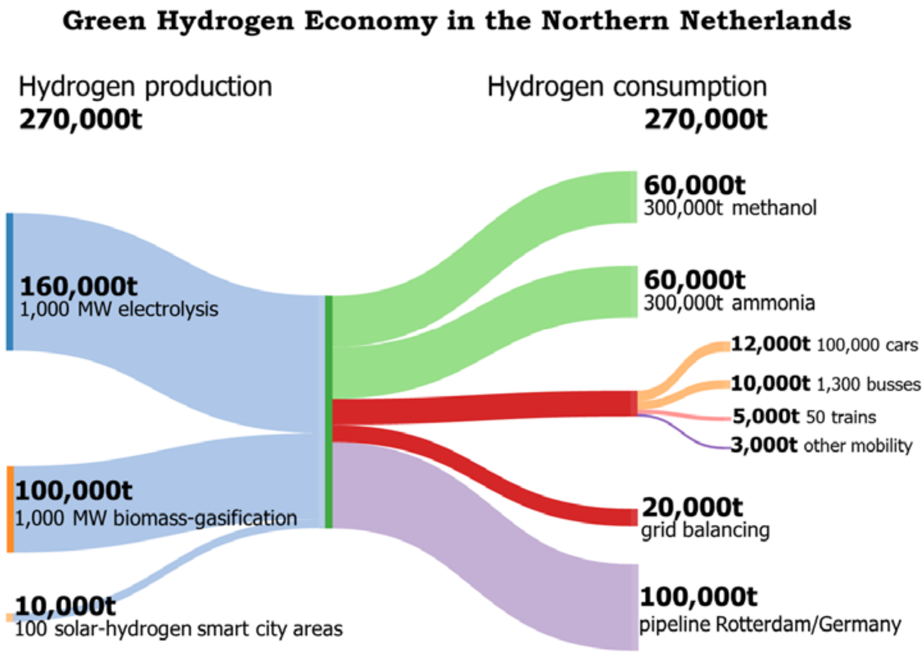
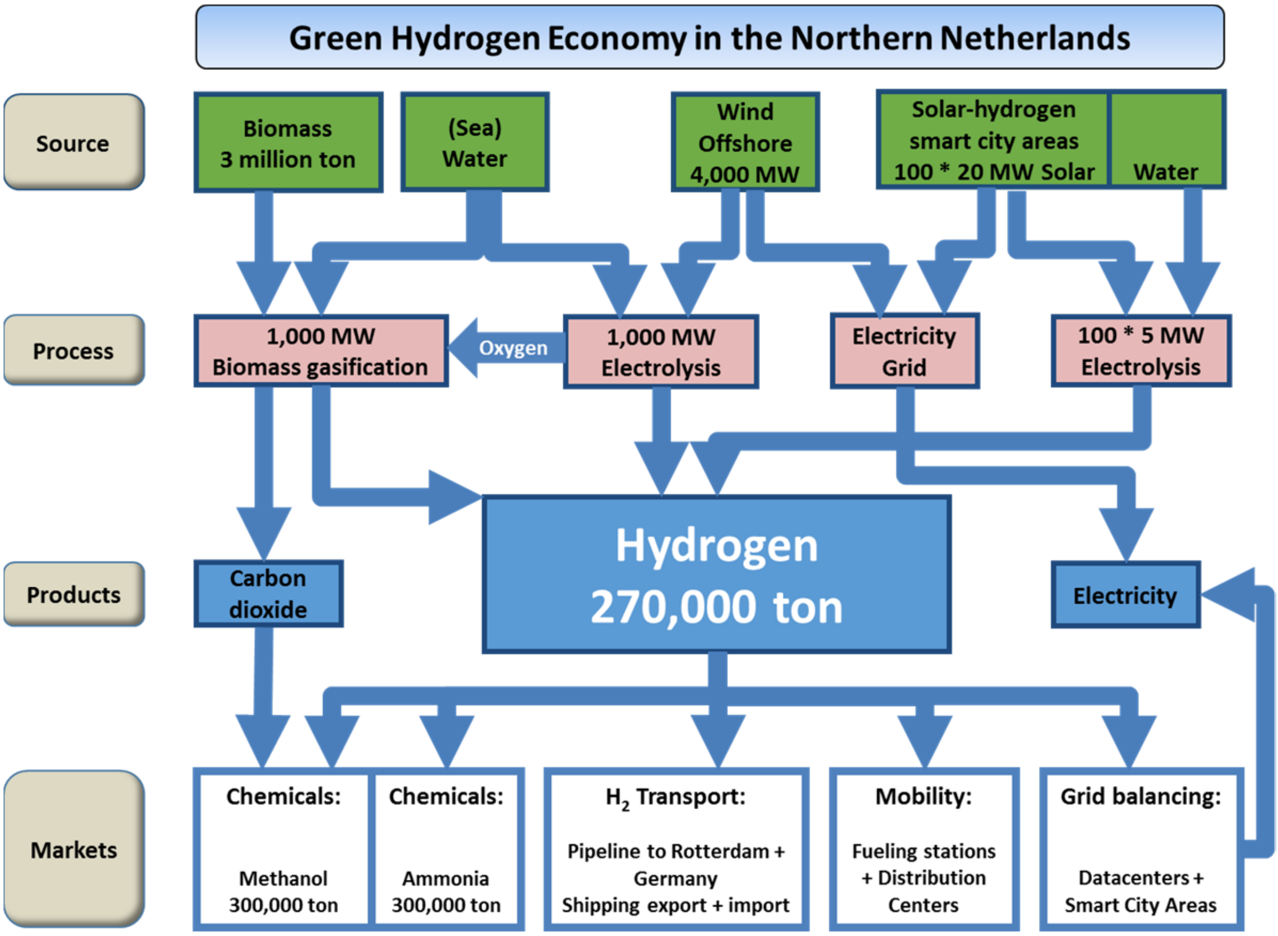


Through the realization of these projects, activities and systems, in the period 2017-2030 about 270,000-ton hydrogen (=38 PJ) per year will be produced in the Northern Netherlands. This large-scale hydrogen production is necessary to realize low hydrogen production cost between €2-3 per kg, which is more or less competitive with present fossil-based hydrogen prices. However, the emerging markets for hydrogen in mobility and grid balancing can by no means absorb this hydrogen volume. The main markets for hydrogen lies in the chemical and the petro-chemical industry. It is therefore necessary to further develop these hydrogen markets. In the Northern Netherlands, the existing chemical industry can realize ammonia and methanol production using large quantities of hydrogen. Furthermore, hydrogen transport facilities need to be developed, hydrogen pipelines to Rotterdam and Germany together with harbor facilities for worldwide hydrogen import and export by ship. These facilities can only be realized and economically operated when a sufficiently large volume of hydrogen is produced. On the other hand, however, the realization of these large hydrogen production volumes will only take place if there is both access to these markets and trading opportunities.

This integral plan for a green hydrogen economy will not only generate green hydrogen, but many other green energy products, such as green electricity, green syngas, green carbon-dioxide, green char (85% carbon), bio-pellets, pure water and oxygen. About 18 billion kWh green electricity per year will be generated, contributing to a green electricity supply. All basic green chemicals are generated which enable the production of any green chemical required; methanol, ammonia and many others. By-products such as char could be used in the agricultural sector and in the chemical industry. New and clean mobility could be developed based on fuel cell hydrogen technology in the maritime sector, in road and rail transport and in new applications such as robots and drones. Green electricity and green hydrogen are the basic elements to realize clean energy and mobility systems in smart city areas. The flow chart below shows the basic interactions and system integration.
A more elaborated business plan, roadmap with initial commitments of interested partners, a financing structure and organizational framework, will be ready by March 2017.



4. The total investments for the development of a green hydrogen economy in the Northern Netherlands up to 2025 is estimated to be 17,5 to 25 billion Euro. About 75-80% is dedicated to the production of renewable electricity. This in turn is combined with hydrogen production by offshore wind and electrolysis to hydrogen, biomass gasification to produce a syngas (hydrogen, carbon monoxide and carbon dioxide) and local solar hydrogen energy systems in smart city areas. National, regional and local governments should create the conditions in which companies, investors, financial institutions and consumers will invest. The conditions in the Northern Netherlands are uniquely suited for green hydrogen and syngas production at world competitive prices, with an industry that could produce green chemicals, materials and products for competitive prices and local communities that are clean and prosperous, generating their own green electricity and using hydrogen for clean transport and balancing the electricity system.

Green Hydrogen Economy in Northern Netherlands	Investments (million €)
Production	**15,000-20,000**
- 4,000 MW Wind Offshore	12,000-15,000
- 1,000 MW Electrolysis hydrogen production	500-1,000
- 1,000 MW biomass-gasification	500-1,000
- 100 solar-hydrogen smart city areas	2,000-3,000
Markets	**1,000-1,800**
- 300,000 ton green methanol + 300.000 ton green ammonia	600-1,000
- 100 H_2 Fueling stations in Northern Netherlands	100-200
- 5 Hydrogen fuel cell balanced Data Centers	200-400
- 3 Hydrogen Innovation/Start-up Community	100-200
Infrastructure	**700-2,000**
- Hydrogen pipeline to Rotterdam + Germany	200-1,000
- Hydrogen Trading Platform	50-100
- Hydrogen Harbor Facilities Eemshaven	400-800
- 5 Hydrogen Distribution Centres	50-100
Society	**800-1,200**
- Zero Emission Public Transport	800-1,200
- Hydrogen Trade Fair and Exhibition	0-10
- Hydrogen Regulatory Framework	0-10
- Green Hydrogen Certificates	0-10
TOTAL	**17,500-25,000**

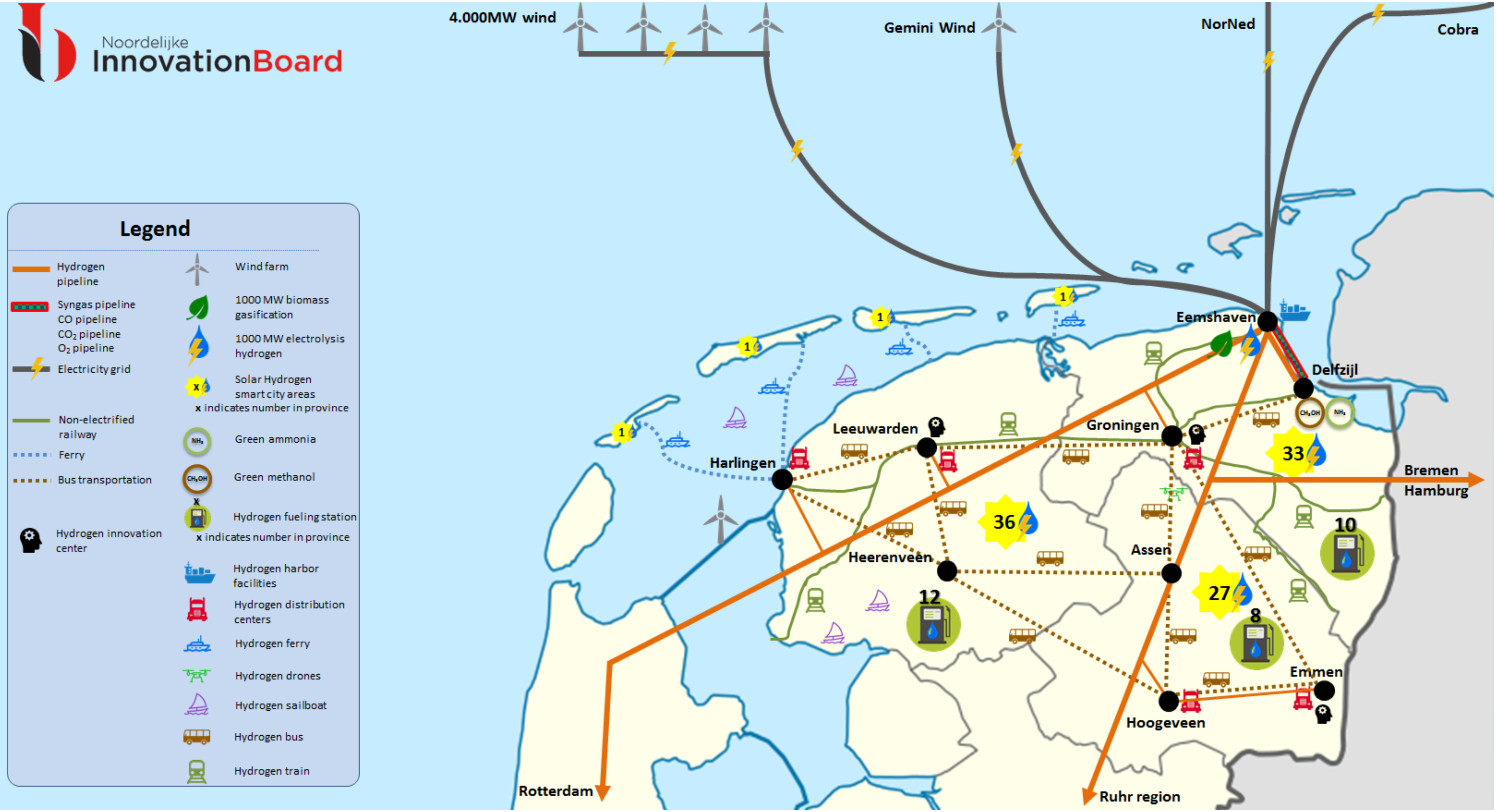
5. The realization of a green hydrogen economy in the Northern Netherlands, will contribute to the economic growth and employment in all regions, cities and communities in the Northern Netherlands. Investments and economic activities will be both on a large scale as well as small scale in local communities. Large scale green hydrogen production together with harbor transport and storage facilities will be located at Eemshaven, with green chemicals production in Delfzijl. Small scale solar-hydrogen production will be in numerous cities and villages throughout the Northern Netherlands. Hydrogen distribution centers and fueling stations are located strategically to be able to supply hydrogen fuel cell to public transport and cars in all parts of the Northern Netherlands. Hydrogen innovation centers will be developed in Leeuwarden, Groningen and Emmen. Hydrogen pipelines will connect and supply Rotterdam and the Ruhr area in Germany with green hydrogen produced and/or transported via the Northern Netherlands.
   On the map below, the locations of the different projects, pipelines, infrastructure, distribution centers, hydrogen fueling stations, solar-hydrogen smart city areas and other activities are shown. In the table below a possible roadmap for the development of all these projects, transport developments, infrastructure and activities in time up to the year 2030, is presented.

The Northern Netherlands Innovation Board

December 2016

Prof. Dr. Ad van Wijk

Green hydrogen economy in the Northern Netherlands



	Roadmap Green Hydrogen Economy in the Northern Netherlands												
	2017	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**
Wind offshore	*600 MW Gemini*				800 MW		1000 MW		1000 MW		1000 MW		
Electrolysis			**20 MW**		**480 MW**		500 MW			(1,000 MW)			(1,000 MW)
Biomass gasification					**20 MW**		480 MW		500 MW				
Solar-hydro areas		**Ameland**	**1 icon areas**	**2 icon areas**		5 areas	5 areas	10 areas	10 areas	15 areas	15 areas	15 areas	20 areas
Offshore cable	*600 MW Gemini*		*700 MW Cobra*		800 MW wind		1000 MW wind		1000 MW wind		1000 MW wind		(1,000 MW NorNed 2)
Ammonia						**150,000 ton**		150,000 ton					
Methanol								150,000 ton		150,000 ton			
Pipeline					**Rotterdam Harlingen**		Ruhr area Emmen	Bremen-Hamburg					
Fueling stations	**Delfzijl**	**2**	**4**	**6**	**8**	**10**	10	10	10	10	10	10	10
Distribution centers					**Harlingen i.e. trains**	Groningen i.e. trains	Emmen	Leeuwar-den		Hoogeveen		Electrolysis Harlingen	Electrolysis Emmen
Fuel cell balancing									100 MW	100 MW	100 MW	100 MW	100 MW
Harbor Facilities			**Truck loading**		Eemshaven-Delfzijl pipelines		Biomass Import			Hydrogen offshore pipeline	Hydrogen shipping		
Busses	**2**	**6**	**10**	**100**	**100**	**100**	150	150	150	150	150	150	150
Trains		**Groningen-Bremen**			**10**	**20**	**20**						
Trucks	**2**	**6**	**10**	**20**	**30**	**50**	50	50	50	100	100	100	100
Cars		20	100	500	1,000	3,000	6,000	10,000	10,000	15,000	15,000	20,000	20,000
Boats			**Ecolution**	**Sail boats**	Sail boats	First Ferry	First Yacht	First Fisher Boat	First Freight Ship				
Others (Drones,.)		forklifts	drones	robots	Mobile								
Innovation Centre	Entrance	Wetsus	Emmen										
Trading platform													established
Trade Fair		shows	shows	First time	1	1	1	1	1	1	1	1	1
Green Certificates					Established NL	Established Germany			Established Europe				
Regulations		**Provisionally established**			Fully implemented								
Education		MBO, HBO, Universities, High schools, Basic schools Etc.											
Training		Automotive. Fire-men, Police, Installers, Builders, Technicians, Regulators, Etc.											

Legend

Italic; Under construction

Bold and Normal; Included in investments

Bold; Priority to Realize

(Between brackets); Not included in investments

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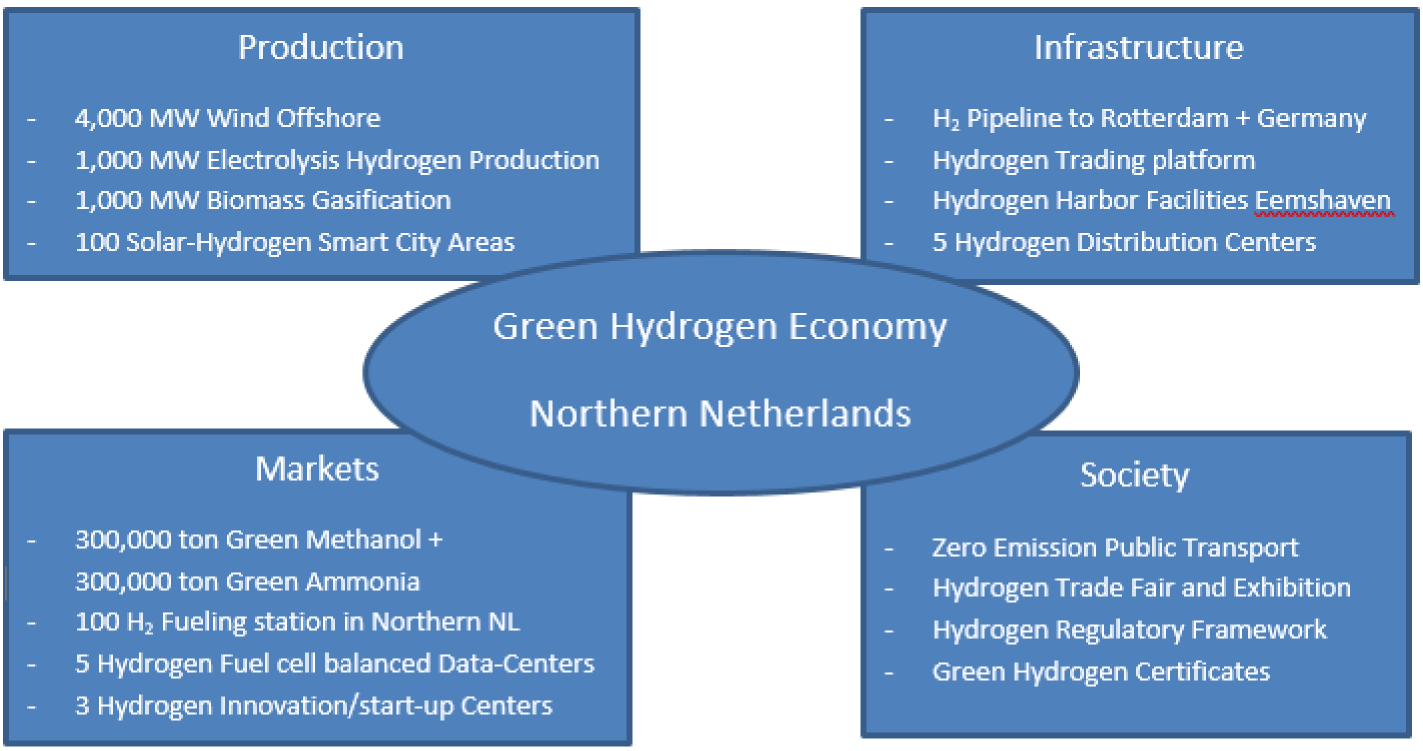
Green Hydrogen Economy in the Northern Netherlands

Products, Markets, Infrastructure, Society



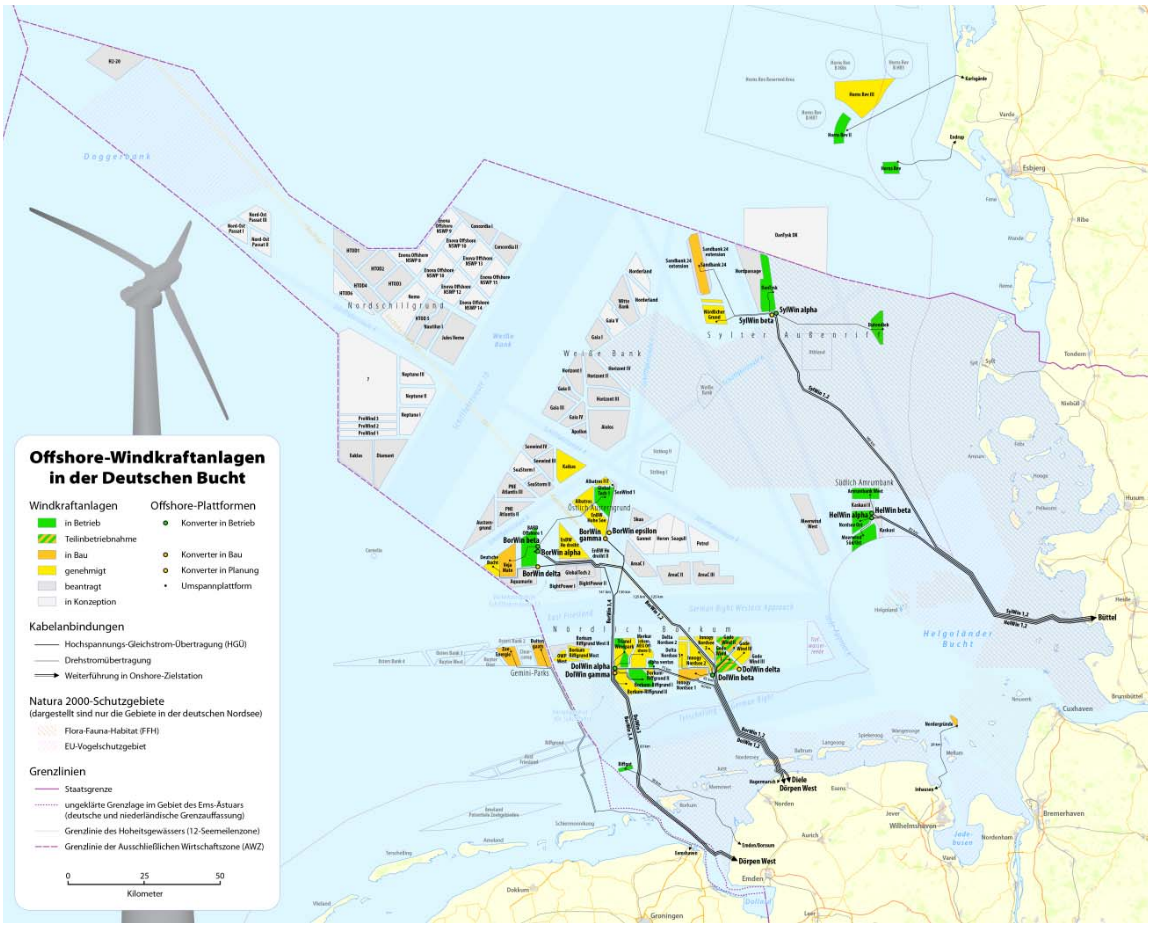
Production: 4.000 MW Offshore Wind Energy

At the North Sea in the German part a huge amount of offshore wind is in planning, under construction or foreseen. Below the German projects are shown. It is foreseen that in 2020 about 6.500 MW offshore wind is installed. Total plans include over 25.000 MW offshore wind energy.

At this moment in the Dutch part of the North Sea above the Wadden islands, the 600 MW Gemini wind farm with a grid connection to Eemshaven has been realized. Next to the Gemini windfarm an area for wind offshore is available of about 800 MW. The other areas above the Wadden islands are now excluded for offshore wind, because they are military zones. Even using a small part of this area above the Eemshaven would be sufficient to install 4.000 MW wind offshore.

Even when no wind offshore in the Dutch part above the Wadden islands will be realized, the electricity grid cable to the shore would for many German offshore wind farms be favorable to connect to the Eemshaven in the Netherlands. Tennet is the transport grid company active in both the German and Dutch part of the country and needs to connect the offshore wind farms to the grid. A capacity of at least 4.000-6.000 MW could be favorable connected to the Eemshaven.

A realistic estimate is that 4.000 MW wind offshore capacity will be realized in the next 10 years that will be connected to the onshore grid at the Eemshaven. The investment costs today for offshore wind are around 3.5 million Euro for 1 MW, which include the grid cable and connection. The recent tender procedures for offshore wind in the Netherlands and Denmark, has shown that electricity prices for these offshore windfarms have come down to 7,3 €ct/kWh in the Netherlands and 6,0 €ct/kWh in Denmark. Recently, November 2016, it is announced that a new offshore wind farm will be build delivering electricity for 4,99 €ct/kWh, also in Denmark



Production: 1000 MW electrolysis hydrogen production

In the Eemshaven an offshore electricity cable from Norway, the NorNed cable with a capacity of 700 MW, comes on land. The Cobra cable, with a capacity of 700 MW, from Denmark is foreseen to connect at the Eemshaven to the onshore grid. The Gemini wind farm is connected to the grid in the Eemshaven with a capacity of 600 MW. Within 10 years it is foreseen that another 4.000 MW offshore wind will have their electricity cable to the Eemshaven. There is already a lot of onshore wind turbine capacity in the Eemshaven (>275 MW). And there is over 5.000 MW fossil fired power plant capacity; a new coal fired power plant owned by RWE (1.560 MW), the NUON new Magnum power plant (1.320 MW), which they want to fuel with green ammonia, and the rather old gas fired power plants owned by Engie (700 MW and 5*350 MW = 2.450 MW). It is already announced by Engie that some of the old gas fired power plants will be closed, but still there will be a substantial amount of large power plant capacity, eventually fired by biomass and green ammonia, operational in the coming years.

Therefore, it can be concluded that the Eemshaven will develop in a green electricity hub where more than 8.000 MW green electricity is available. The inland grid cable from the Eemshaven, however, has at this moment a capacity of about 4.000 MW. Expansion of the grid capacity is foreseen to 5.610 MW in several tranches. Even with such an expansion of the grid capacity there will be a substantial excess green electricity production capacity. A small part can be absorbed by data centers, but there is at least a 1.000 MW green electricity available for green hydrogen production via electrolysis.

A 1.000 MW electrolysis plant that runs 8.000 hours a year, uses 8 billion kWh and 1,5 million m^3 pure water to produce 160 million kg Hydrogen. A reverse osmosis plant has to produce the 1.5 million m3 pure water, using sea water or surface water as input. If an electricity price of 2-2,5 €ct/kWh and a total investment between 500 million and 1 billion Euro with a 10 year life time is assumed, a green hydrogen cost price around 2-3 €/kg will be the result. This is about competitive with present hydrogen prices, produced from natural gas by steam reforming. At present the fossil hydrogen prices are between 1-2 €/kg. Certainly, when the green character of the hydrogen could be valued properly a market for green hydrogen as a feedstock in industry and for mobility could be developed.

SILYZER 200 basic system *Technical data*
Electrolysis type / principle: PEM (Proton Exchange Membrane)
Rated stack capacity: 1.25 MW
Skid dimensions: 6.30 m x 3.10 m x 3.00 m
Startup time: < 10 sec
Output pressure: Up to 35 bar
Hydrogen purity (dep. on operating point): 99.5% – 99.9%
Hydrogen quality 5.0: Optional DeOxo dryer
Hydrogen production under nominal load: 225 Nm³/h
Life cycle design: > 80,000 h
Weight: 17 t
CE conformity: Yes
Fresh water demand: 1.5 l / Nm³ H_2

Production: 1000 MW biomass gasification

Green hydrogen can be produced by electrolysis using green electricity, but can be produced also from biomass via gasification. Biomass gasifiers use solid biomass as an input and deliver a green syngas, a mixture of hydrogen, carbon-monoxide (CO) and carbon-dioxide (CO_2), and char as an output. The CO could be used, together with water (H_2O), to produce extra hydrogen. The resulting products from biomass gasification are green hydrogen and CO_2. However, from CO_2 and green hydrogen every chemical product could be produced. Therefore, the combination of green hydrogen and CO_2 or green syngas creates the opportunity for a fully green chemical industry in the Northern Netherlands.

Biomass gasification is a technology still in its development phase. In Groningen, the company Torrgas develops a biomass gasifier using torrified biomass as an input. Torrefaction is a process to create a unified biomass product from all kinds of solid biomass residues, such as wood residues, straw, coconut shells, etc. Torrefaction is the same process as coffee beans roasting, it makes the biomass water resistant and breaks the fibers. Gasifying torrified biomass is a lot easier and therefore this process looks promising both technologically as well as economically. It is expected that within 2-5 years this technology, as well as other gasification technologies, are commercially available on the market.

The idea is to install a 1.000 MW biomass gasification plant next to the electrolysis plant. This gives the opportunity to use the oxygen which is released at the electrolysis plant in the biomass gasifier which saves cost. A 1.000 MW biomass gasification plant uses 166 ton torrified pellets per hour. With 8.000 hours, full load operation time per year an amount of 1,3 million ton torrified biomass pellets are needed. To produce this number of pellets about 3-3,5 million ton of wood residues is needed. The yearly output is 300.000-ton char (carbon content 85%), 1,3 million ton CO_2 and 90.000-ton green hydrogen.

The investment in a torrefaction plant are between 1 and 2,5 million per ton torrified biomass output, which includes a total investment of 200-400 million Euro. The investment in a 1.000 MW gasification plant will be between 300-600 million Euro. Resulting in an investment between 500-1.000 million Euro. Char is a valuable product on the market, as a soil enhancer, feedstock for activated carbon or to replace petcoke. For example, the company ESD SIC in Delfzijl could use char to replace low sulfur petcoke (80.000-90.000 ton). If char is sold to the world market and the CO_2 is not valued, the resulting hydrogen price, based on 8 €/GJ (=180 €/ton) biomass price, will be around 1,5-2,5 €/kg.

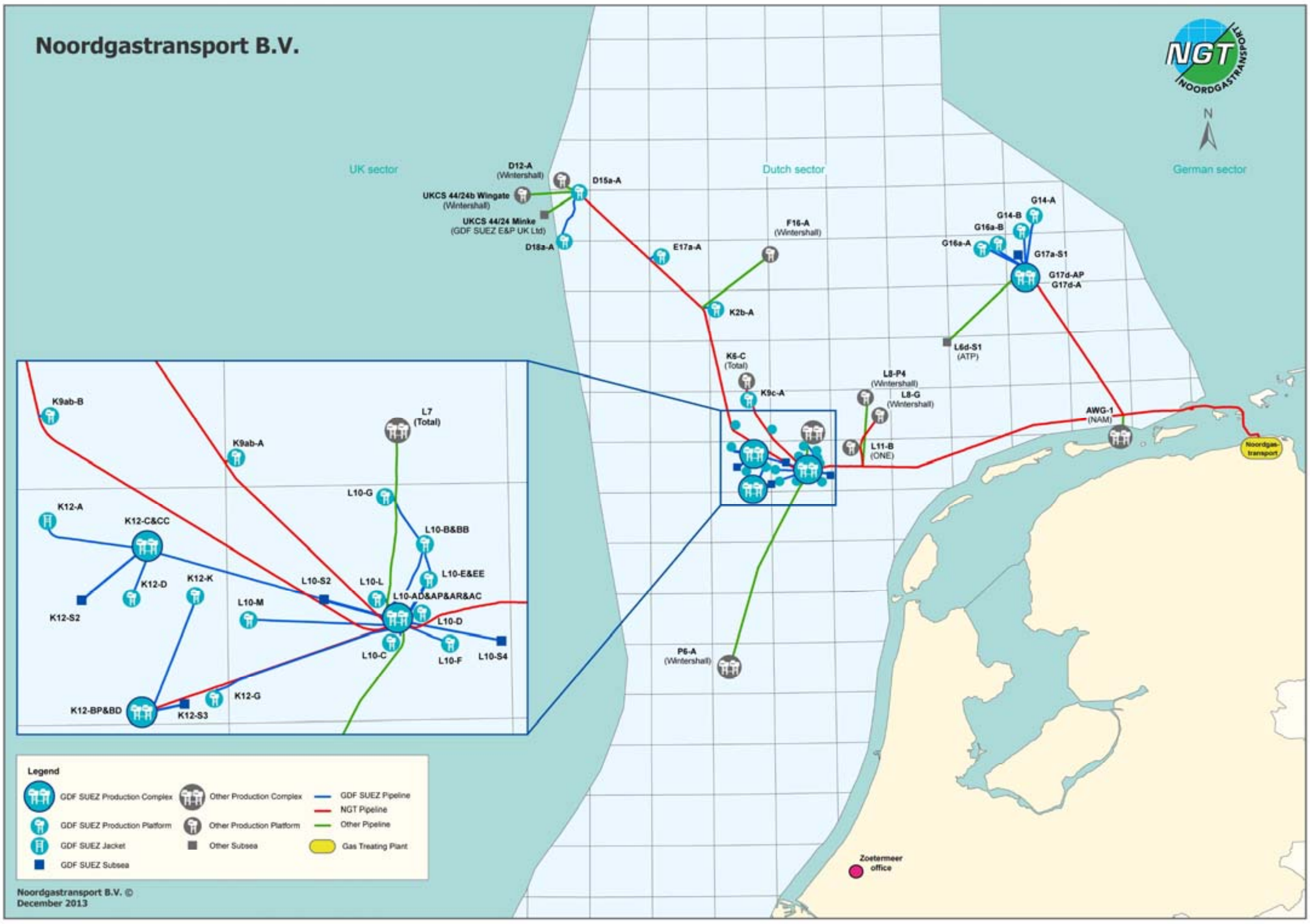
Torrgas biomass gasification pilot plant, Groningen the Netherlands

Production: Offshore hydrogen production from far offshore wind farms

Offshore wind farms produce electricity which can be brought onshore via an electricity cable. Such an offshore electricity cable is expensive. The farther offshore the wind farm is located the more expensive the electricity cable cost. At the North Sea, an alternative solution for these wind farms is to convert the electricity into hydrogen at an existing oil/gas platform and to transport this hydrogen eventually mixed with gas via an existing gas pipeline. Onshore the hydrogen is separated from the natural gas and cleaned to be transported via pipeline, ship or truck to the markets.

The company Noordgastransport a daughter company of Engie, operates an offshore gas grid in the Dutch part of the North Sea with a total length of 470 km. The transport capacity of these pipelines is 42 million Nm^3 natural gas per day. The onshore landing of this pipeline is in the Emmapolder nearby Eemshaven. Engie is operating some of these gas fields and offshore platforms.

Recently a detailed study is performed by Energy Delta Institute together with ECN into offshore green hydrogen production on existing platforms using the gas infrastructure for hydrogen transport. The conclusion is that in 2020 the calculated hydrogen cost is about 4-5 Euro per kg hydrogen. Because the wind farm is not a base load plant, the electrolyser capacity is not utilized all the time. Therefore, the calculated hydrogen price is not fully competitive with present hydrogen prices (2-3 Euro/kg hydrogen). In future (2025-2030), however, it is expected that electrolyser prices come done and that offshore wind turbines could be adjusted to higher load factors. At that time, certainly competitive hydrogen prices can be realized.



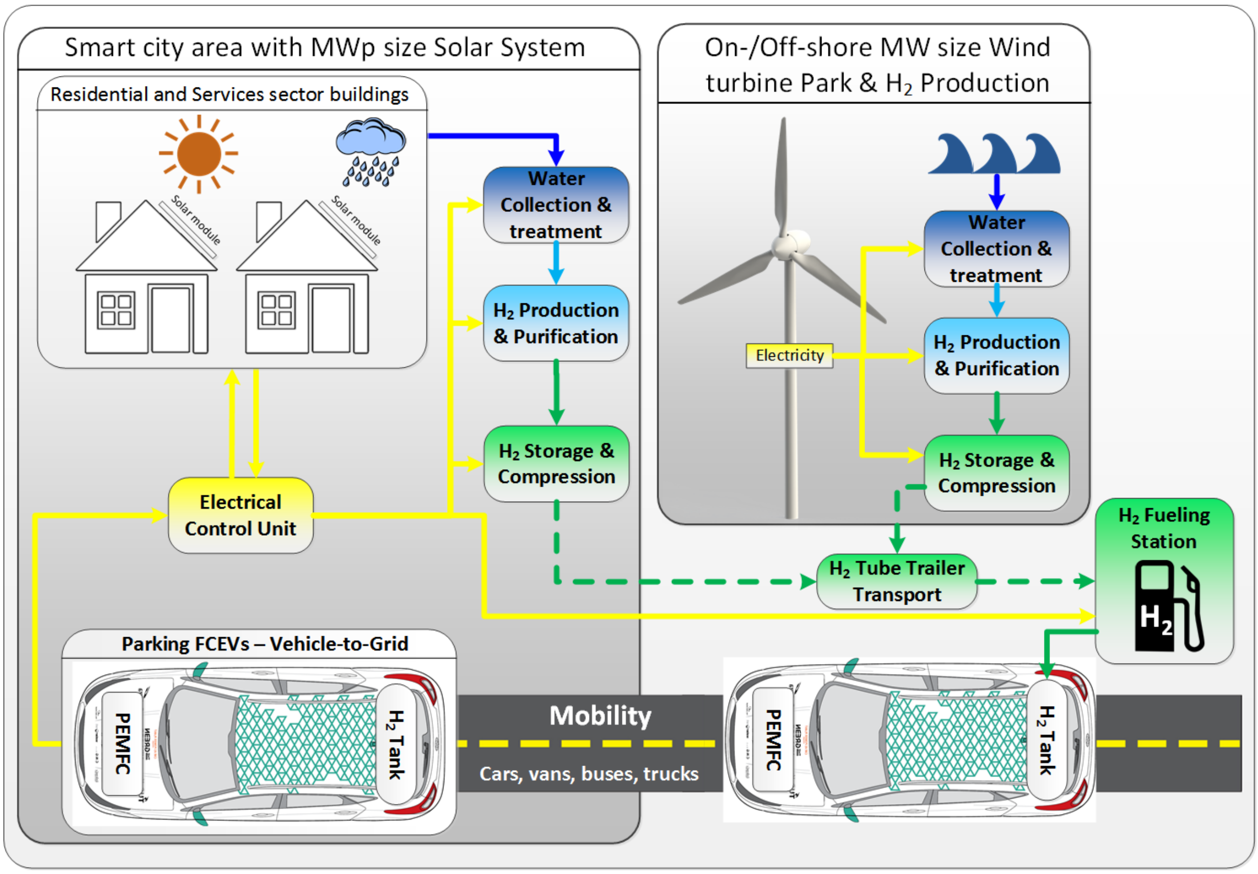
Production: 100 solar-hydrogen smart city areas.

Future smart city areas need to become fully sustainable in many ways, also in energy. Reducing the energy demand for heating and cooling, for appliances and lighting, changing to all electric and generating all the electricity with solar is one of the system concepts to realize a zero-energy smart city area. However, not at every moment it is zero energy, in summer more electricity is produced than consumed and in winter more electricity is consumed than produced by solar. Besides that, the energy consumption for transport is not considered.

In a fully sustainable smart energy system, electricity system balancing can be done by batteries for day/night balancing and hydrogen for seasonal balancing. During the summer time, excess electricity can be converted to hydrogen by installing an electrolyser. In winter time a fuel cell (stationary or in a car) could supply the electricity needed, by converting hydrogen in electricity. There is a need for extra renewable energy for driving and balancing, which could be supplied to the smart city area as hydrogen produced from wind, biomass, biogas or large solar.

An average city area or village in Europe with a population of 4.500 people contains 2.000 houses, 1 shopping mall, 1 fueling station, schools, offices, 2.300 cars, some busses and trucks. In such an area, about 20 MWp solar can be installed at roofs. A 5 MW electrolyser is needed to convert the excess electricity into hydrogen. The investments in solar and electrolyser capacity, hydrogen compression and storage is estimated to be 25 million for each smart city area.

Local energy cooperatives or local energy companies can realize and operate such fully renewable energy systems for heating and cooling, electricity and transport. They can produce, distribute, sell and buy electricity in the smart city area and they can produce, distribute, sell and buy hydrogen for transport and balancing the electricity system. In other words, the smart city area community is fully in control of its own sustainable energy system.



Markets: 300,000-ton green methanol + 300,000-ton green ammonia

Hydrogen (H_2) and Carbon-dioxide (CO_2) can be used in chemical processes to produce a wide variety of chemical products. Two of the main building blocks in chemistry are methanol and ammonia. Methanol can be produced from H_2 and CO2. Ammonia is produced from H_2 and nitrogen (N_2), captured from the air.

Methanol is primarily used to produce other chemicals such as formaldehyde for plastics and paints, DME, olefins (ethylene, propylene), acetic acid, etc. In Delfzijl at the chemical industry site there is already a methanol production plant. In the past natural gas was used to produce methanol but today there is already a bio-methanol production plant. The company name is BioMCN owned by OCI. Green methanol production could be easily expanded on this chemical site. And in the Northern Netherlands there is already an existing chemical industry situated that uses methanol as a feedstock (e.g. ChemCom, AkzoNobel). But methanol is also a fuel that can be used in gasoline combustion engines, direct or blended. And because it is a liquid it could be easily shipped all over the world.

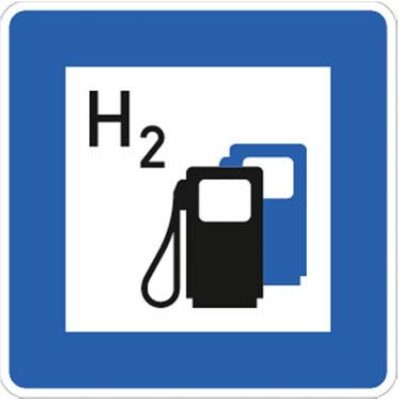
Ammonia is primarily used to produce fertilizers, but it is used in a variety of other pharmaceutical and chemical products. Ammonia is used to produce ethylene amines, produced in Delfzijl by Delamine. The ammonia is now imported, but can be produced from green hydrogen and nitrogen. The other product to produce ethylene amines is ethylene dichloride, also imported. But this product could be produced totally green on the Delfzijl site. Ethelyne production could be done based on green hydrogen and carbon-dioxide. But ethylene production could be done also based on ethanol, which could be produced from sugar beets. Sugar beets is one of the agricultural products produced on a large scale in the Northern Netherlands with the company Cosun that process sugar beets. Application of ethylene and polyethylene are numerous, for example at companies on the Emmtec industrial site in Emmen.

Ammonia can also be used as a fuel, direct in diesel engines, for example in ships and trucks. It is studied to use the ammonia as a fuel in the Magnum power plant in the Eemshaven to produce electricity. Because it is a liquid with a high-energy density it is ideal for energy storage and it could be easily shipped all over the world.

It is assumed that based on competitive green hydrogen prices and cheap carbon-dioxide, green methanol production expansion with 300.000-ton green methanol is realistic. 300.000-ton methanol consumes about 60.000-ton hydrogen and 360.000-ton carbon-dioxide. A 300.000-ton green ammonia plant can also be realized in the Northern Netherlands, using another 60.000-ton green hydrogen. Both a 300.000-ton methanol plant as well as a 300.000-ton ammonia plant will need an investment between 50-60 million Euro. The methanol and ammonia production will generate follow up investments in plants that use methanol or ammonia as a feedstock. An investment multiplication factor of 4 is assumed. So, a total methanol + ammonia production related investment between 500-600 million Euro is expected.

Chemical site Delfzijl the Netherlands

Markets: 100 Hydrogen Fueling stations in the Northern Netherlands



For refuelling vehicles in the northern Netherlands, hydrogen fueling stations (HRS) need to be installed. These fueling stations will be able to fuel passenger cars, commercial light and heavy duty vehicles with pressurized hydrogen at 700 bar and in some cases busses at 350 bar. However, busses will mostly be fueled at the bus depot as is current practice for bus operators. Therefore, dedicated hydrogen fueling stations will need to be installed at bus depots.

Fueling stations will be supplied with hydrogen by truck, mostly. In some cases, near the hydrogen fueling station, local hydrogen production will be present. It is assumed that in 10 percent of the cases there will be local production by means of electrolysis, using green power. In some cases, fueling stations can be connected to a pipeline (example Rhoon/Rotterdam). From cost perspective, this is the most attractive supply method, however from (financial) planning perspective this will be an exception in the early years of infrastructure development. Once demand is becoming mature and the hydrogen grid will be denser, this supply method may start to give more opportunities.

The Netherlands currently has around 4.000 regular fuelling stations. This number is expected to diminish towards 3.000 fueling stations: http://www.tankpro.nl/specials/2014/09/17/aantal-tankstations-in-nederland-licht-gedaald/. When 10% of all public stations offer hydrogen, the coverage is perceived reasonable by users, THRIVE study: https://www.ecn.nl/docs/library/report/2011/e11005.pdf). The Northern Netherlands will need at least 100 hydrogen fueling stations to allow for a station within reach of 20 minutes of driving or a maximum of 30 km distance to a next service point.

Hydrogen dispensers will be integrated in existing or newly built fueling stations featuring other fuels, electric charging, shop, carwash etc. In principle hydrogen, can be integrated into existing sites and business models. The minimum hydrogen supply is about 200 kg per day (40-60 cars), growing to about 1.000 kg per day (200-300 cars). Hydrogen fueling stations needs to be compliant with SAE 2601 and PGS-35.

Hydrogen Fueling stations (HRS) investment costs			
Type	**CAPEX MEuro**	**Number of HRS**	**Investment MEuro**
HRS; Hydrogen supplied by truck	1.5-2	90	135-180
HRS; local hydrogen production by electrolysis	3-5	10	30-50
Total investment			**165-230**

Markets: 5 Green Hydrogen Fuel cell balanced Data Centers.

Google builds a very large data center in the Eemshaven, see picture below. The reasons for Google to choose for the Eemshaven are the existence of an offshore data cable, enough space and green electricity. Google as well as other companies that install and operate data centers wants to run on green electricity. Therefore, Google has signed a power purchase agreement with Eneco to buy green electricity for 10 years. For this reason, Eneco builds an onshore wind farm nearby. On a yearly average this wind farm produces enough electricity to meet the data center demand. However, supply and demand are not at every time in balance. At moments that there is no wind, other power plants must take over the electricity supply. Now, these are fossil fired power plants.

In future, these power plants will be closed and supply and demand needs to be balanced in another way. And of course, that needs to be done with renewable electricity. This can be done by fuel cells fueled with green hydrogen. Fuel cells can follow demand and supply variations very fast with high efficiencies. Fuel cells are quiet and have no emissions, except very clean, demineralized, water.

These fuel cells could be placed at data centers for balancing, but in fact they can do that for the electricity grid. As an assumption at 5 data centers in the Northern Netherlands in total 500 MW fuel cell systems are placed for grid balancing. At an investment cost between 400.000 to 800.000 Euro per MW, this implies a total investment between 200-400 million Euro.

Eemshaven the Netherlands, with Google data center at the forefront

Markets: Hydrogen Innovation/Start up Centers

To develop the green hydrogen economy innovation will be crucial. Innovation is necessary in technology, systems and products: New and better conversion, storage, transport and distribution technologies for green hydrogen. But also in applying green hydrogen in chemical processes, materials and products, in mobility over land, water and air, in new products and systems such as drones, robots, wireless appliances, for electricity grid balancing and remote electricity production, etc. And in all kinds of related technologies and systems, for example sensor technology, demi-water production technology, safety control, fueling systems, compression technology, smart IT systems, smart city/village design, Internet of Things, etc. Innovation is not only technological innovation, but innovation in business models, safety procedures, social embracement, regulatory framework and procedures and institutional organization is equally important.

In the Northern Netherlands, a well-established research, education, innovation and start-up infrastructure exists, that can play a leading position in the crucial innovation for the green hydrogen economy. There is a good knowledge and education infrastructure in the Northern Netherlands in natural gas, which could be easily extended to hydrogen, in the Energy Academy Europe, Groningen University, in the Applied Universities van Hall Larenstein and Hanze Hogeschool and in the secondary education centers. Especially the Energy Academy Europe and 3 research and innovation centers could play a crucial role in green hydrogen innovation, start-up and new business development.

- Entrance http://en-tran-ce.org/ in Groningen is the hotspot of applied sciences for businesses and innovations in energy. Innovation in green hydrogen production, conversion, storage, transport and distribution can and will be a main area in Entrance.
- Wetsus https://www.wetsus.nl/ in Leeuwarden is a European center of excellence for sustainable water technology. Pure water production by reverse osmosis with membranes is crucial for electrolysis of water to hydrogen. Especially membrane technology is crucial, not only in reverse osmosis, but also in electrolysis, fuel cells, hydrogen gas cleaning and gas compression. Wetsus could be leading in membrane technology application.
- API, Applied Polymer Innovations http://www.api-institute.com/ in Emmen is a leading institute and facilitator for the chemical industry to develop new and bio-based chemical products. API can play a role in developing new and better chemical processes and applications for green hydrogen in combination with biomass syngas and bio-based chemicals.

Next to these institutes there are many developments and innovative industries that could integrate green hydrogen in their products, systems or activities. To mention a few;

- Airport Eelde will be redeveloped in a drone airport ‘Drone Hub GAE’. Hydrogen with fuel cell technology will be crucial for longer flight times with drones.
- There is a maritime industry cluster http://www.maritiemclusterfriesland.nl/ that can integrate fuel cell and hydrogen technology for propulsion in the maritime sector, sailing boats, yachts, ferries, ships, etc.
- There is a manufacturing industry cluster, High-Tech Systems and Materials, that can manufacture sensors, products and materials for the hydrogen industry as well as using fuel cell and hydrogen technology in products such as busses, drones and planes.

Infrastructure: H_2 Pipeline to Rotterdam + Germany

The Market for Hydrogen is not only in the Northern Netherlands. In Rotterdam, large volumes of hydrogen are consumed in the chemical and especially the petro-chemical industry. From the Rotterdam area, there is a hydrogen pipeline infrastructure to Antwerp and other parts of Belgium, to Terneuzen in the Netherlands up to the northern part of France, operated by Air Liquide. Also in Germany, especially in the Ruhr area and near Bremen and Hamburg the chemical industry uses hydrogen too.

For the transport over land of large quantities of hydrogen over longer distances a hydrogen pipeline is a cost-effective solution. An hydrogen pipeline at 120 bar, with an input pressure of 35 bar cost between 0,04 and 0,16 €/100km/kg H_2 For a very large hydrogen pipeline with a maximum capacity of 1.5 million ton hydrogen per year from the Eemshaven to Rotterdam, 275 km, the investment cost is between 300 and 400 million Euro. This excludes the cost for compression of about 50-100 million Euro. A similar amount needs to be invested for the pipelines to Germany. In total this will cost about 1 billion Euro for new pipelines.

Another option is to use one of the existing gas transport pipelines and adjust these pipelines for hydrogen use. This could be done by refurbishing the existing natural gas pipelines or by putting a new hydrogen pipeline in the existing gas pipeline. The cost for such adjustments are at least a factor of 10 less than for new pipelines. And even more important the permitting procedure will be much and much shorter. In the end this will be the preferred option, because existing natural gas infrastructure will be used less in future and the gas infrastructure does not need to be removed and demolished but can get a second life.

Natural gas transport Pipelines in the Netherlands

Infrastructure: Hydrogen Trading Platform

Over the years Gasunie and Gasterra have developed the international gas-trading platform TTF. It has become Europe's biggest gas-trading platform. The TTF success is based on three pillars:

- Transport is secured for all the natural gas available in the Netherlands gas network via a standardized entry and exit system.
- There are electronic trading platforms at trading exchanges and brokers where standard contracts could be traded
- There are enough market parties that want to trade via the TTF and therefore create liquidity in the market.

The production of hydrogen differs from the production of natural gas. Hydrogen can be produced using another energy source as an input (gas, coal, biomass or electricity), on large, medium and small scale and in principle everywhere. Natural gas is extracted from large underground reservoirs and put in a pipeline for distribution. However, today natural gas is also liquefied, LNG, and transported by ship and truck.

The market for hydrogen at this moment is based on specialized contracts between hydrogen suppliers and hydrogen consumers. In the chemical and petro-chemical industry large volumes of hydrogen are produced on site or supplied via a privately-owned pipeline. On the other hand, there is a market for very small volumes of hydrogen that is supplied via hydrogen bottles to specific customers.

In future, the markets for hydrogen will be diversified, not only feedstock for industry but also fuel for transport and fuel for electricity system balancing. There will be many producers and customers, producing and demanding, small, medium and large volumes of hydrogen. The transport and distribution will be both by pipeline and by ship/truck. Even hybrid transport and distribution systems could be envisaged in future. In such a market a trading platform for hydrogen, green hydrogen certificates and maybe related products such as methanol or ammonia could be an enabler for growth for the green hydrogen markets.

To realize such a hydrogen trading platform, the following needs to be developed;

1. A group of transporters and distributors who collect the hydrogen from the producers and deliver this to consumers. There is not a direct relation between producer and client. All hydrogen fulfills specific predefined quality criteria. Producers pay an entry fee to the transporter/distributor. All customers pay an exit fee to the transporter/distributor. Both pipeline transporters/distributors as well as ship/truck transporters/distributors could be partners in this group.
2. Independent parties that organize the trading. These parties should develop the software for these trading systems and the standard contracts with standard products for trading. Finally, there needs to be a clearing organization, to finalize all financial transactions. In gas these organizations are ICE, Trayport or APX. The standard contracts in gas are the EFET contracts.
3. Trading companies that want to take positions at a starting hydrogen trading platform. As a start a large hydrogen producer or consumer must be prepared to be a first mover on this platform and take the lead as a market maker.

Infrastructure: Hydrogen Harbor Facilities Eemshaven

The Eemshaven Harbor has a crucial role in the development of a green hydrogen economy. It is the place where 1.000 MW electrolysis and 1.000 MW biomass gasification plant should be installed. The output of these two plants is hydrogen, syngas and/or carbon-dioxide, oxygen and by-products such as char. The input for the electrolysis plant is green electricity from offshore wind, the NorNed and Cobra cable. This electricity could be supplied to the electrolysis by a DC-cable from the sea cables, which avoids DC-AC and AC-DC conversions. The input for the biomass gasification plant is 3-3.5-million-ton wood chips or other solid biomass residues. A torrefaction plant at the Eemshaven needs to torrify this biomass, resulting in 1,3 million pellets, which will be feed into the biomass gasifier. To a large extend, this biomass will be imported with ships.

Eemshaven Foto; Pieter Broertjes

The Eemshaven is a deep-sea harbor where ships with a water depth up to 11 meter can enter in four basins. For biomass import, quays for transshipment with storage facilities for biomass and pellets could easily be realized in the Eemshaven. Such quay's cost about 50.000 Euro per meter. A quay of about 500 meter is needed to facility the largest ships, which means a total investment of about 25 million. A same investment amount is necessary for biomass storage?

The Hydrogen produced at the Eemshaven must be transported to the hydrogen markets, by pipeline, ship and truck. To facilitate these different transport modes, the following must be realized:

- Delfzijl industrial site, at about 25 km, houses several large chemical companies, such as AKZO and OCI. At this chemical site, it is relatively easy to realize chemical plants to produce ammonia, methanol and other chemical products. Therefore hydrogen, oxygen, syngas, CO_2, must be transported from the Eemshaven to Delfzijl by pipelines. Such a pipeline street has been studied already in the past and could be realized within a reasonable time.
- The hydrogen must be transported to other places where there is a need for green hydrogen as a feedstock or fuel, such as Rotterdam, Antwerp in Belgium, Ruhr area, Bremen and Hamburg in Germany. A transport pipeline from the Eemshaven to these areas needs to be realized, preferably by using an existing natural gas pipeline
- To transport hydrogen to fueling stations a hydrogen filling stations for bottles and tubes under pressure must be realized together with a logistics center to load and off load container racks with hydrogen tubes and trucks.
- A dedicated hydrogen harbor basin must be built to facilitate the import and export of (liquefied) hydrogen. Such a hydrogen harbor basin is like a LNG harbor facility with roughly similar investment cost between 40-60 million Euro. Besides this harbor basin, a large-scale hydrogen liquefaction plant must be realized with a capacity of 50-100-ton hydrogen per day. And also a facility to feed imported (liquefied) hydrogen into the hydrogen transport pipeline.

Main impex terminal LNG, Source: Wärtsila

- Hydrogen can also be transported from offshore electrolysis platforms via an existing gas offshore pipeline to Eemshaven. This could be liquefied or remain compressed hydrogen for further distribution. A facility needs to either ship this for export, or put it in a pipeline or truck for further inland transport.

All these facilities together are the main hub for hydrogen transport by ships, pipelines and trucks. A first rough estimation is that these facilities together needs an investment of roughly 400-800 million Euro.

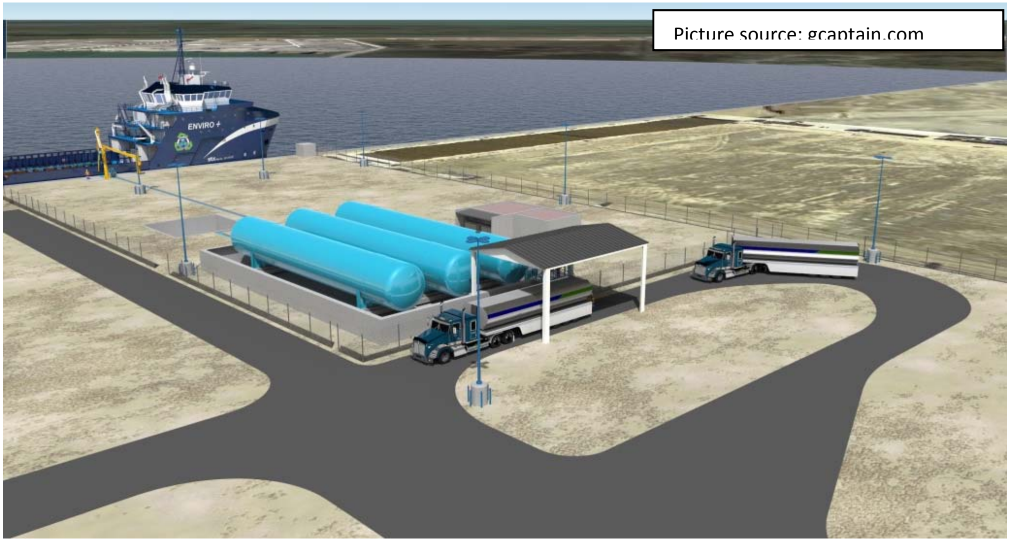
Infrastructure: 5 Hydrogen Distribution Centers

The Northern Netherlands is a wide geographical area that needs distribution hubs for intermediate storage and distribution of hydrogen when not distributed in pipelines. This is quite comparable to the small-scale infrastructure in use for liquid natural gas (LNG). Liquid natural gas and liquid hydrogen are quite similar from handling point of view, both are cryogenic gas, liquefied by low temperature, and stored in thermal insulated storages.

Larger quantities of hydrogen can be shipped to these hubs by inland vessels or trucks. Alternatively, by pipeline and thereafter filled in tube trailers. It could also be liquefied for transport by liquid hydrogen truck to individual demand centres like public fuelling stations, bus depots, train depots, forklift fleets etc. The hubs will therefore feature truck loading bays. The inlet will feature a high pressure (50-120 bar) hydrogen pipeline or inland vessel offloading facility.

The location of the small-scale hubs is proposed in Harlingen, Leeuwarden, Groningen, Emmen, Hoogeveen, equally distributed over the whole area and close to larger demand areas.

The investment for a small-scale hydrogen hub including truck loading bays is estimated at 10-20 Million Euro each, leading to 50-100 Million Euro for 5 small-scale distribution hubs.



Picture source: gcaptain.com

Liquid hydrogen truck loading bay, Source: Iwatani

Society: Zero Emission Public Transport

Governments are responsible for public transport by busses, taxis, trains and ferry's. They issue public tenders on the basis where companies can make an offer. In these tenders, they can require that zero emission transport is an obligation. The expectation is that for busses and trains, such a requirement will lead to fuel cell hydrogen busses and trains.

In the Northern Netherlands, approximately 1.300 city busses are daily operated. City bus means city and rural use. Operators are mainly ARRIVA and QBuzz. When all these busses are replaced by fuel cell hydrogen busses, this means an investment of about 715 million Euro with the bus prices of today. The total hydrogen consumption is about 10.000 ton.

Fuel Cell Busses

- Total busses in the Northern Netherlands approximately. 1.300 units
- Hydrogen consumption 9-10kg H_2/100km in city/country mix
- 2/3 of the buses is operated in city area (200km per day) and 1/3 of the buses in rural/mixed area (300km per day). On average 225 km per day
- Bus operations average 6 days per week, 330 days per year, which means 74.250 km per year

CAPEX per bus today app. 550.000 Euro. 1.300 Units → 715 Million Euro.

#	Daily km	Yearly km	Yearly H_2 consumption (tons)
1	225	74.250	7,4
1.300	292.500	96.525.000	9.600

In the Northern Netherlands, 50 diesel trains are daily operated on non-electric lines. These trains, operated by ARRIVA have two or three carriages and a power of 450-600KW supplied by Diesel-Electric engines. Fuel cell-electric hydrogen trains could replace these diesel trains. Alstom is a company that builds these fuel cell hydrogen trains and will perform a test next year on the line Groningen-Bremen. Because the depreciation time for trains is 25 years, not all trains will be bought new. Some trains may need to be retrofitted with fuel cell-electric power supply, which is technically feasible. When all these 50 diesel trains are replaced an investment in new and retrofitted trains of about …? Million Euros is needed. The total hydrogen consumption of these trains is about 5.000 ton.

Fuel Cell Trains

- Total (diesel) trains in the Northern Netherlands is 50 units
- Hydrogen consumption approximately 25 kg H_2/100km
- Train operations average 6 days per week. Train is operated approximately 1.200 km per day, based on two times per hour per trajectory of 50km.
- Train operations average 6 days per week. 330 days per year.

CAPEX per train approximately …. ? 50 Units → …? Million Euro

#	Daily km	Yearly km	Yearly H_2 consumption (tons)
1	1.200	396.000	100
50	60.000	19.800.000	5.000

Society: Hydrogen Trade Fair and Exhibition

In the Northern Netherlands, an international green hydrogen trade fair and exhibition both for business and professionals as well as for an interested public need to be established. Such a trade fair and exhibition serves several goals:

- It puts the Northern Netherlands on the map as the center for green hydrogen.
- It creates a platform for business, information exchange and what is happening in the world.
- To inform about ongoing research, development and innovation.
- To show all who is interested, companies, organizations, politicians, civil servants and the public, what are the new products, systems and services in the green hydrogen economy.
- To generate societal embracement and involvement.

At such a green hydrogen trade fair and exhibition, the integrated green hydrogen chain must be presented. It is about

- Renewable energy production and conversion to hydrogen.
- Hydrogen storage, transport and distribution via pipelines, ships and trucks.
- Hydrogen utilization in the chemical industry and industry in general.
- Hydrogen use in transport, cars, buses, trucks, trains, boats, planes, etc.
- Hydrogen for balancing the electricity system.
- Hydrogen for new applications; drones, robots, 3D printers, computers, mobile devices, etc.
- Hydrogen safety and environmental impacts.
- Hydrogen economics and financing.
- Hydrogen policies and societal aspects.
- Hydrogen training and education.
- Etc.

To develop a green hydrogen economy such a trade fair and exhibition is an imperative to create business attention, international reach and societal awareness in the Northern Netherlands. Every year a large trade fair and exhibition needs to be organized in one of the Northern Netherlands cities. In between a mobile green hydrogen exhibition to inform a public could travel around in the Northern Netherlands. To develop this activity an initial budget for startup and budget to cover the losses in the first years is needed.

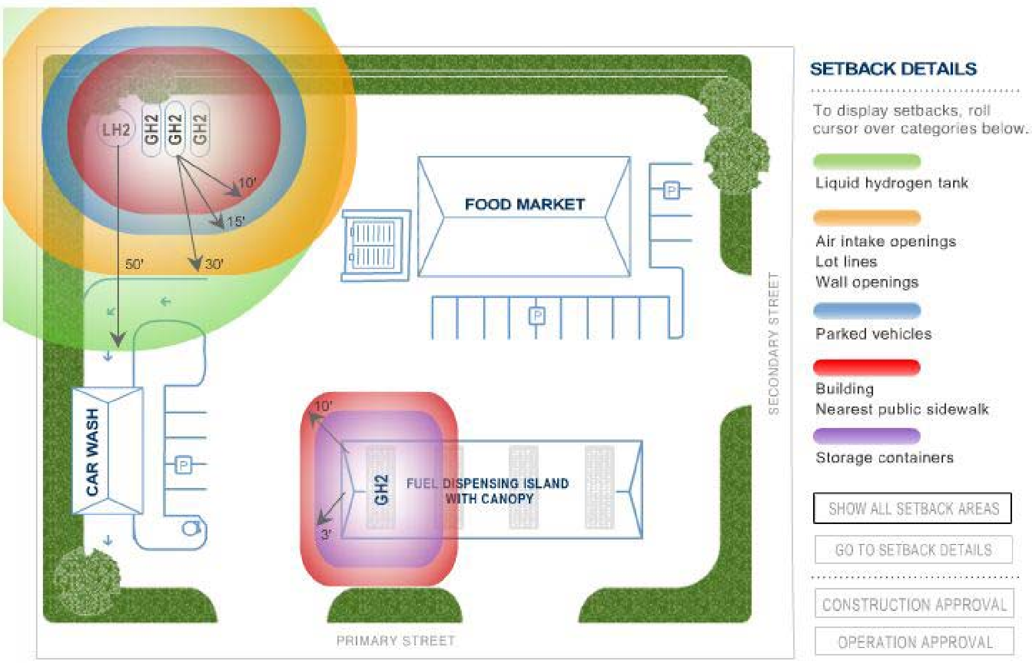



Society: Hydrogen Regulatory Framework

Within the present regulatory framework (standards, regulations, permitting procedures, safety, environmental regulations and spatial planning), hydrogen is not included, except for large scale industrial production. This regulatory framework for hydrogen needs to include:

- Large scale hydrogen and syngas production via steam reforming, electrolysis and biomass gasification.
- Hydrogen use at a large scale to produce chemicals, materials, steam, etc.
- Small scale hydrogen production via electrolysis and steam reforming in city areas, near fueling stations, farms, waste water treatment plants, hospitals, etc.
- Hydrogen storage; large scale in harbors and small scale in city areas, near farms, etc.
- Hydrogen transport and distribution via pipelines, ships and trucks.
- Hydrogen fueling stations, distribution stations and hydrogen bottle/tubes changing stations.
- Hydrogen bus depots, train depots, car parks and other transport parking places.
- Hydrogen use in vehicles, vessels, trains and appliances (drones, robots,).

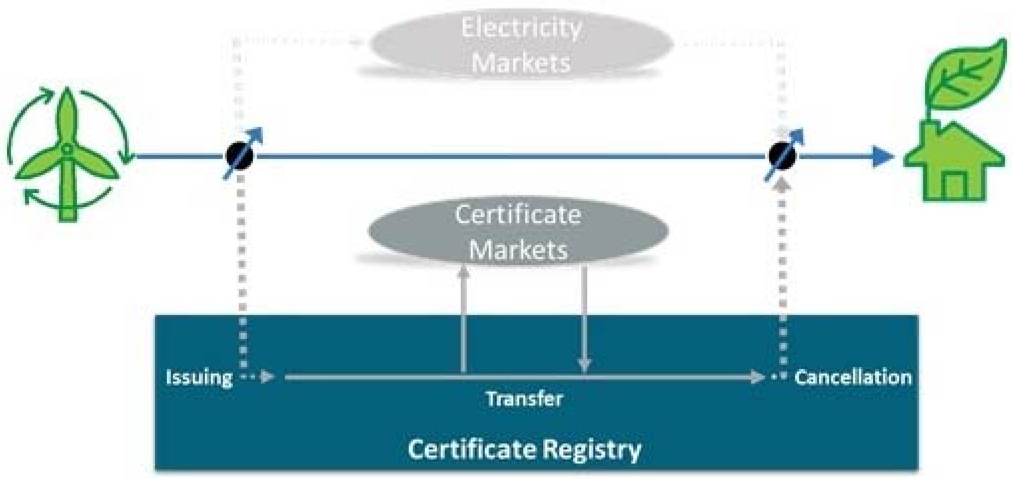
To develop and implement such a regulatory framework for hydrogen via regular procedures it will take tens of years and could very well be fragmented and not harmonized among cities and provinces. Therefore, there is a need to develop this regulatory framework in a non-traditional way. Maybe a task force with all relevant public bodies needs to develop a procedure for fast permitting in the first years together with a road map to develop the formal regulatory framework for hydrogen. Learning and copying regulatory frameworks and procedures from other countries, especially Germany and the US is maybe a good method to speed up the development.



Society: Green Hydrogen Certificates

To value the production of clean and green energy over fossil fuels different kind of emission pricing and/or value clean and green production systems are in place. In Europe, the Emission Trading System ETS, is established to reduce carbon dioxide emissions. The EU ETS works on the ‘cap and trade’ principle. A cap is set on the total amount of certain greenhouse gases that can be emitted by installation that are in the system. The cap is reduced over time so that emissions are reduced. Within the cap, companies receive and buy emission allowances which they can trade with each other as needed. This emission trading system will work if the cap is low enough to bring the carbon emission allowance price to a price level that companies will invest in clean and green energy production. Now, this carbon emission allowance price is around 6 Euro’s per ton CO_2. Many companies and organizations argue that a price of about 50 €/ton CO_2 is needed to accelerate investment in clean and green energy.

This Emission Trading System and the carbon prices in this system, creates a basis to value the green character of the production of electricity and fuels. But how do you guarantee that energy is produced from renewable sources and how is it possible to trade green energy. In the European Union for electricity production this is organized via issuing GO Guaranties of Origen. In short, a GO is a ‘green label or green certificate’ which ensures that a certain amount of electricity has been produced from renewable energy sources. Via these green certificates, it is possible to uncouple the green character from the physical produced electricity. Both the green certificate and the electricity can be traded and sold separately, which makes it possible to buy green electricity everywhere by buying physical electricity and green certificates.



This green certificate system is in place in the European Union for electricity, but can be expanded to all other fuels. In the Netherlands Vertogas https://www.vertogas.nl/ a daughter company of Gasunie, is mandated by the Dutch government to issue Guaranties of Origin or green gas certificates based on the production of green gas. It is relatively easy to develop a similar system for green hydrogen. Such a green hydrogen certificate system can be developed by Vertogas and adopted by the Dutch government. However, such a system for green hydrogen certificates needs to be established in the European Union and not only in the Netherlands.