HyChain 3

Analysis of the current state and outlook of technologies for production

Hydrogen Supply Chain - Technology Assessment

Hydrohub

TITLE
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PUBLICATION DATE
April 30th, 2019

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PUBLISHED BY
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ABOUT THIS REPORT

This project report is part of a set of three parallel projects carried out in the period June 2018 till May 2019:

- HyChain 1 :
  Assessment of future trends in industrial hydrogen demand and infrastructure
- HyChain 2:
  Cost implications of importing renewable electricity, hydrogen and hydrogen carriers into the Netherlands from a 2050 perspective
- HyChain 3:
  Hydrogen Supply Chain – Technology Assessment

All three project reports can be found on www.ispt.eu/projects/hychain.

THE HYCHAIN PROJECT

The HyChain project is initiated by the Institute for Sustainable Process Technology (ISPT) and is part of the Hydrohub Innovation Program. Its mission is 'Largescale electrolysis-based production of sustainable, low cost, hydrogen as a driver for circular industrial chains'. The project is part of the ISPT's cluster System Integration. The HyChain central research focuses on the question: '*How can we make an optimization for all the full value chain to deliver the lowest cost, carbon-neutral hydrogen to Dutch industry (domestic and global production) and what barriers and bottlenecks stand in the way?*'.

PUBLIC FUNDING

The project received public funding from The Netherlands Enterprise Agency (RVO) under Grant TSE-18-17-01- Topsector Energiestudies.

CONSORTIUM PARTNERS

Summary

This project represents the outcomes of half a year of research on hydrogen supply chain technologies. In a collaborative effort between industry parties and research institutions, key information was collected into 59 fact sheets on technologies for production, conversion, storage, transportation, and reconversion of hydrogen. In addition to quantitative information, the project also explored qualitative risks or opportunities that are known to be associated with specific technologies.

This represents the largest single repository in the public domain on this topic and can be a key reference manual to serve as a starting point for other analysis on hydrogen supply chains. Accompanying this document is also an Excel collection of the key data and uncertainty. Together, this information serves a key supporting function for reaching the ambitions of the RVO and industry in the efforts towards decarbonizing industry.

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Introduction

The Increasing Importance of Renewable Hydrogen

The importance of hydrogen in decarbonization cannot be understated. Not only is hydrogen expected to play an important role in the transition to a renewable energy system, but it is also a key component of decarbonization pathways for industry.

Hydrogen is one of the few carbon-free energy carriers for excess renewable energy. It can be converted to different energy carriers (such as ammonia), or simply pressurized and transported for use. As a flexible energy carrier, hydrogen is being explored for use as a cost-effective buffer to manage the intermittency that is inherent in a fully renewable energy supply. It can be used as a fuel for vehicles, heating, or electricity generation, but also as an efficient long distance transportation or long-term storage medium. Hydrogen is expected to play an important role in the wind energy sector which is expected to quintuple it's capacity by 2050, where power-to-gas is required to enable the development of planned far-offshore-wind and floating-wind platforms.

Beyond use as an energy carrier, hydrogen is important as a feedstock for industry applications. The largest applications are the refining industry and the fertiliser sector. Other important applications for decarbonization pathways are in the steel sector, where hydrogen is required for Direct Reduced Iron (DRI). Also, as we move away from fossil fuels towards other energy feedstocks such as solid waste, biomass, or waste gas, hydrogen will be a key input, as it allows us to shift CO_2 to CO to produce syngas which is a key chemical feedstock. This also means that hydrogen is a prerequisite for carbon capture and utilization (CCU).

The Netherlands expects to demand anything between 2 and 14 megatons of H_2 annually by 2050 (CE Delft 2018), which is significantly more than the current domestic demand of 0,8 Mt (Berenschot & TNO 2017) and a quarter of current global industrial H_2 consumption (Gigler & Weeda, 2018 "Contouren van een Routekaart Waterstof").

Currently the demand for industrial feedstocks account for 95% of total hydrogen demand in the Netherlands. Growth of other applications like the mobility sector, electricity production, and heating applications will cause a growth in total demand. Different studies expect the shares of each of these applications to grow to anything between 5-20% of the total. Studies agree that mobility will show the biggest increase.

Reliable and Centralized Information on Hydrogen Supply Chains and Technologies

Not only will enormous volumes of hydrogen be required as an energy source and as a feedstock, but in order to support decarbonization on the long term, hydrogen will need to be produced using renewable energy, rather than natural gas. This so-called "green hydrogen" can be made using electrolysis. Electrolysis is far from a new technology; in the 50s and 60s, electrolysers with capacities of more than 100 MW were built near hydro power plants around the world to produce renewable hydrogen. However, since this period, steam methane reforming (SMR) has outcompeted electrolysis largely due to the low cost of natural gas. This remains the current main production method today. Innovation in electrolysis technologies slowed down until the last decade when interest was renewed alongside the growing urgency of climate change.

Carbon-neutral H_2 production (e.g. green H_2 from water electrolysis or SMR-H_2-production combined with carbon capture) is still prohibitively expensive, which makes meeting the growing demand an enormous challenge. In the coming decades, a significant capacity scale-up will be necessary. Innovation in electrolysis will play a key role in this scale-up, but there are other issues along the supply chain to be considered. These considerations include the locations for production, supplies of inputs for electrolysis (energy and water), the byproducts (e.g. O_2) and the market for these, the type of H_2-containing energy carriers which can be used the most effectively (e.g. $NaBH_4$, NH_3, pure H_2 gas, etc), how they will be transported and stored.

To work towards solving these problems, the Institute for Sustainable Process Technology (ISPT) initiated the HyChain program under its System Integration cluster which addresses the larger H_2 supply chain issues. This program is working to bring together actors from the entire supply chain: current and future users or producers of hydrogen, logistics and storage, parties, research institutions, and other stakeholders. The mission of this program is to understand what future H_2 supply chains will ideally look like and how to get there together. In HyChain 1, likely demand volumes for hydrogen in the future was explored, as well as tipping points which would change the picture. In HyChain 2, (international) sources of hydrogen were mapped to examine how attractive import from different regions could be.

This project, HyChain 3, plays a key role in ensuring that we have enough information on the technologies needed to build the renewable energy supply chains of the future. The focus here is on collecting this information and presenting it in a way that can be used in the HyChain program to map out optimal supply chain scenarios and provide guidance to industry and logistics organizations on the next steps to take towards decarbonization pathways that rely on hydrogen. However, this information can also be used in other research or development projects or to guide strategy development by other organizations outside of HyChain.

Synthesizing Information on Technologies

While different research groups and industry parties have worked to gather information on hydrogen supply chain technologies separately, there is currently no central repository to collect this information in a way that can be used for deeper supply chain analysis to support decision makers. The primary aim of HyChain 3 is to create that central repository of information.

The main research questions for this project include:

- What are the main technologies in the full value chain of hydrogen generation, conversion, storage, and transportation?
- What parameters (social, economical, technological, and environmental) will determine the future use of these technologies in the value chain?
- How do the technologies score on each of these parameters?

In this project, the project team (TU-Delft, Metabolic, Frames, ECN part of TNO) defined a set of environmental, social, economic, and technological indicators (both quantitative and qualitative) to assess the hydrogen supply chain technologies. Working with research institutions (TU Delft, ECN part of TNO) and industry partners (Frames, Vopak, Nouryon, Yara, GasUnie, Proton Ventures, Stedin, and OCI Nitrogen), the project team has collected data on 59 technologies. In this report, these are presented as data sheets, and an Excel database has been created that provides only the quantitative Key Performance Indicators (KPIs) and an evaluation on their uncertainty.

In addition to containing these data sheets, this report also documents the general approach that was used to develop the data sheets, the reasoning behind that approach, how to use the information provided in the data sheets (or how not to use it), and what some of the conclusions were that came out of this process.

General Approach

At the beginning of HyChain 3, the partners involved in the project developed a long list of technologies to be assessed and identified the parties who had previous knowledge on these options to provide key knowledge. In consultation with the full HyChain consortium, this list has been adjusted over time. In the end, a total of 59 technologies were assessed. The technologies are divided into five categories: Production of hydrogen (P), Conversion to energy carriers (C), Transportation (T), Storage (S), and Reconversion to hydrogen (R). An overview of the technologies assessed is provided in Table 1.

In addition to establishing which technologies would be assessed, at the beginning of the project the team also developed a list of **Key Performance Indicators (KPIs)** to evaluate for each technology, which are explained in the section “Explanatory Notes”. In order to ensure that these were evaluated in the same manner for each technology, a guide was created to explain which definitions and methods of evaluating different KPIs should be used. Alongside the outputs of KPIs, information was collected on the **process flows** of technologies, **CAPEX as a function of capacity**, and **additional explanatory information** on the parameters of the assessment, where relevant.

Beyond the quantitative KPIs, we asked for inputs on any relevant qualitative information regarding any known potential risks or opportunities of specific technology options (e.g. technological, economic, political, social, or environmental issues). This contextual information on technologies is also important to capture as it gives an indication of where there may be additional barriers or incentives to the adoption of a certain technology.

Finally, each of the data sheets was assessed for uncertainty related to the input data, modeling, or outcomes. This supplementary information is crucial to report alongside the quantitative information in order to ensure the data sheets are interpreted in a suitable manner.

Production	Conversion	Transportation		Storage	Reconversion
P1: Electrolysis – PEM	**C1**: High-pressure H_2	**T1a**: Pipeline H_2 gas - High pressure backbone	**T8b**: Road Fuel truck liquid LOHC (onshore)	**S1**: Gaseous storage - geologic bulk storage (salt caverns)	**R1**: $NaBH_4$
P2: Electrolysis - Alkaline	**C2**: Liquefied H_2	**T1b**: Pipeline H_2 gas - Regional grid	**T9**: Road Fuel truck liquid Formic acid (onshore)	**S2**: Gaseous storage - geologic bulk storage (gas field)	**R2**: LOHC (Dehydrogenation)
P3: Electrolysis: SOEC	**C3a**: NH_3 - small scale	**T1c**: Pipeline H_2 gas - Existing Hydrogen network	**T10**: Road Truck bulk metal hydrides ($NaBH_4$)	**S3**: Liquid storage: Liquid (cryogenic) H_2 tank	
P4: Steam methane reforming, with carbon capture	**C3b**: NH_3 - large scale	**T2**: Pipeline liquids general	**T11**: Shipping - $NaBH_4$	**S4**: Liquid storage (LOHC)	
P5: Autothermal reforming (ATR), with carbon capture	**C4**: CH_3OH	**T3**: Road cryogenic truck for liquefied & slurry H_2 (onshore)	**T12**: Shipping cryogenic tanker for liquefied H_2 (offshore)	**S5**: Liquid storage (NH_3)	
P6: Battolyser	**C5**: CH_4 (synthetic)	**T4**: Road Gas H_2 - compressed gas tanks (tube trailers)	**T13**: Shipping liquid NH_3 (offshore)	**S6**: Liquid storage (Formic Acid)	
P7: Dry reforming of methane	**C6**: LOHC (Hydrogenation)	**T5a**: Road Gas Ch_4 (syn) - ISO container compressed gas tube trailers	**T14a**: Shipping liquid Methanol, LOHC (offshore)	**S7**: Liquid storage (Methanol)	
P8: POX (partial oxidation)	**C7**: $NaBH_4$	**T5b**: Road Gas Ch_4(syn): Compressed gas in cylinder modules	**T14b**: Shipping DBT	**S8**: Solids storage - $NaBH_4$ hydrides	
P9: Gasification processes	**C8a**: CHOOH (Formic Acid - electrochemical)	**T5c**: Road Gas LNG	**T15**: Shipping liquid formic acid (offshore)	**S9a**: Liquid storage - DME Spherical tank	
P10: Overview production of H_2 as a by-product	**C8b**: CHOOH (Formic Acid - Thermochemical route)	**T6**: Road Gas DME,: ISO containers/fuel tankers	**T16**: Shipping DME	**S9b**: Liquid storage - DME Iso container	
P11: Low TRL production methods	**C9**: DME-OME	**T7**: Road Fuel truck liquid NH_3 (onshore)	**T17**: Shipping CH_4 Liquified (LNG)	**S10**: Liquid storage - LNG	
		T8a: Road Fuel truck liquid Methanol	**T18**: Rail Liquid NH_3		

Table 1: Overview of technologies assessed in HyChain 3

Data Sheets: What is Included?

Each data sheet follows the following format:

- **Name of technology**
- **Technology Description**
- **Key Performance Indicators (KPIs)**

Technological		**Economic**				**Environmental**	
		Year	**Base year**	**2030**	**2050**		
TRL (scaled to Nth of a kind)		Equipment Cost (M€)				Water consumption (m^3/GJ)	
Round trip efficiency (%)		CAPEX (M€)				Water withdrawal (m^3/GJ)	
Capacity (TJ/y)		Annualized CAPEX (M€/y)				Heat (MJ/GJ)	
Capacity (ktonne/y)		Annualized CAPEX (€/GJ)				Electricity (kWh/GJ)	
Capacity (ktonne H_2-eq/y)		Annualized CAPEX (€/kg H_2-eq)				GHG emissions (kg CO_2-eq/GJ)	
Product concentration, purity (wt.%)		OPEX (M€/y)				Land footprint (m^2/GJ)	
Volumetric energy density (GJ/m^3)		OPEX (€/GJ)					
Losses during storage (%)		OPEX (€/kg H_2-eq)					

Key Performance Indicators (KPIs) for Transport Options

Technological		Economic				Environmental	
		Year	**Base year**	**2030**	**2050**		
TRL		Transportation costs (€/t .km)				Fuel type	
Capacity (TJ/y)		Transportation costs (€/t H2-eq.km)				Fuel consumption (L/t.km)	
Capacity (ktonne/y)						Heat (MJ/t.km)	
Capacity (ktonne H2-eq/y)						Electricity (kWh/t.km)	
Concentration of transported product (wt.%)						GHG emissions (kg CO2-eq/t.km	

CAPEX as function of capacity

	ktonne/y		M€		M€
Capacity 1		Equipment cost 1		CAPEX	
Capacity 2		Equipment cost 2		CAPEX	
Capacity 3		Equipment cost 3		CAPEX	

Equipment	ktonne/y	Scaling factor

Quality Assessment

The following matrix shows the scores on quality assessment of data inputs and indicators grouped as total system.

Uncertainty for Data Inputs				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical				
Economic				
Environmental				

Uncertainty for Key Performance Indicator Outcomes				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical				
Economic				
Environmental				

Process flow diagram

Risks and opportunities

	Risks	Opportunities
Technological		
Economic		
Political		
Social		
Environmental		

References:

Explanatory Notes

The following sections explain the shared definitions of Key Performance Indicators and other inputs to the data sheets and mirrors the guidance document that was shared with parties working on the data sheets to ensure consistency across the different technology assessments.

Quantitative Indicators: Technological KPIs

Technology readiness level (TRL): The definition is based on that provided by the European Commission (2016).

- **TRL 1**: basic principles observed
- **TRL 2:** technology concept formulated
- **TRL 3:** experimental proof of concept
- **TRL 4:** technology validated in lab
- **TRL 5:** technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)
- **TRL 6:** technology demonstrated in a relevant environment (industrially relevant environment in the case of key enabling technologies)
- **TRL 7:** system prototype demonstration in an operational environment
- **TRL 8:** system complete and qualified
- **TRL 9:** actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space)

Round trip efficiency, (or conversion ratio): Round trip efficiency is defined as the ratio of energy delivered in the final product to the energy inputs considered in the system (Roskosch, Venzik & Atakan, 2018).

Capacity: Capacity is defined here as the total amount of product that the technology can deliver in a given year. The capacity can be provided in energy basis (e.g., TJ/y) in mass basis (e.g., ktonne/y) and/or mass of hydrogen equivalents (e.g., ktonne/y) of main product. To convert mass flows to energy flows the lower heating value of the main product is used. The lower heating value is defined as the heat released by combusting the product (which initially is at 25 ºC) and returning the products to 150 ºC.

Product concentration, purity: Product concentration refers to the state of the final product and how much it is diluted with other substances. For instance, formic acid is generally delivered at 85 wt% where the remaining 15 wt.% is water. This parameter is relevant to determine the energy content of the main product.

Volumetric energy density: Defined as the energy contained in the final product per unit volume expressed in GJ per m^3.

Losses during storage: Indicator defined as self-discharge loses and loses occurring during storage included within the system boundaries, expressed in percentage of energy stored (%).

Quantitative Indicators: Economic KPIs

Cost data includes base year and projections to 2030 and 2050. The base year should be specified, as well as the assumption for cost projections for 2030 and 2050, if available.

Equipment cost: Equipment costs refers to the plant/process/technology equipment costs excluding installation factors before installation. Most approaches for estimating capital investment are based on equipment costs. By providing this parameter, it should be easier to understand the contribution of installation (or the approach followed to consider it) on fixed capital investment.

CAPEX: The Capital Expenditure (CAPEX) refers to the fixed capital investment of the technology, which includes typical investment aspects such as equipment installation, instrumentation and control, piping, electrical systems, buildings, yards improvements and service facilities representing direct costs. Aspects such as engineering and supervision, construction expenses, legal expenses, contractor's fee and contingency are typically accounted for in fixed capital investment as indirect costs. CAPEX is expressed in million euros (M€).

Annualized CAPEX: Capital expenditure over the economic lifetime calculated as shown in equation (1). Plant life time (*t*) and interest rate (*i*) are input parameters to estimate the annualized capex. Generally, plant lifetime is 20 years, however, it is indicated if this is not the case. Interest rates used in the assessment are noted.

$$Annualized\ CAPEX\left(\frac{€}{year}\right) = CAPEX\ (€) \cdot \frac{i}{1-\frac{1}{(1+i)^t}} \tag{1}$$

Annualized CAPEX per product unit: This indicator is estimated by dividing the annualized capital expenditure with the production capacity of the final product in energy basis. This indicator is expressed in €/GJ of final product. CAPEX is also expressed in €/kg H_2 equivalents of final product.

OPEX: The Operational Expenditure (OPEX) is defined as the sum of raw materials costs, utilities costs, maintenance, labor costs, fixed & general and overheads expressed M€/y. Where possible, information is provided on the contribution of utilities costs in order to understand the costs related to energy use as a footnote. Location is assumed as north west Europe, unless otherwise mentioned.

OPEX per product unit: This indicator is estimated dividing the annual operational expenditure by the production capacity of the final product in energy basis. This indicator is expressed in €/GJ of final product. OPEX is also expressed in €/kg H_2 equivalents of final product

Quantitative Indicators: Environmental KPIs

As default, environmental indicators are expressed per main product output in GJ. However, these indicators can also be expressed per unit of hydrogen equivalents (e.g., GHG emissions expressed in CO_2-eq/kg H_2-eq). Depending on user choice proper units should be provided for the KPIs. Explanations below are analogous in the case kg H_2-eq is used as the functional unit.

Water consumption: Water consumption is defined as the fraction of water use in the process that is not returned to its original source after withdrawal. Consumption is generally occurring when water is embodied into a product, converted and/or evaporated. This indicator aims to report the gate-to-gate direct water consumption per final product unit (e.g., m^3/GJ or m^3/kg H_2-eq). Water consumption for cooling purposes is accounted for in this indicator. Water embodied in other inputs are excluded.

Water withdrawal: Water withdrawal is defined as net water withdrawn from surface water or groundwater source. This indicator aims to report the gate-to-gate direct water withdrawal per final product unit (e.g., m^3/GJ or m^3/kg H_2-eq). Water withdrawal for cooling purposes should be accounted for in this indicator. Water embodied in other inputs are excluded.

Heat requirements: This indicator is defined as the gate-to-gate direct heat requirements to obtain the final product. Heat requirements are generally referring to steam and/or direct fired requirements in GJ per GJ of final product or in GJ per kg H_2-eq of final product. Heat requirements for producing raw materials are excluded.

Electricity requirements: This indicator is defined as the gate-to-gate direct electricity requirements to obtain the final product expressed in kWh per GJ of final product or in GJ per kg H_2-eq of final product. Energy inputs for producing raw materials are excluded.

GHG emissions: GHG emissions are defined as the gate-to-gate emissions resulting from direct energy use in the plant/technology in the form of heat and power for producing the final product, and to the gate-to-gate direct emissions released to air in the production process. Emissions related to the production of raw materials, other inputs and end of life are excluded.

Land footprint: This indicator is defined as gate-to-gate the land required to produce the final product. Following a gate to gate approach this indicator refers to the land occupied by the technology/process to obtain the final product. Upstream land requirements (e.g., land for PV) is excluded.

CAPEX as a Function of Capacity

In order to understand better how CAPEX can vary as a function of capacity, data sheets can include values for three different capacities. The assumptions on how the technology was scaled should be stated, as well as whether the base case system corresponds to a Nth of a kind or first of a kind. Some data sheets may include equipment lists and scaling factors for the equipment considered. In case scale parameters are unknown, this should be stated in the explanatory notes. Finally, the base year assumed for scaling the technology should be noted.

Quality Knowledge Base

In HyChain3, quality assessment is based on a series of matrices, which were specifically developed by the project team for this purpose. These matrices were based on pedigree matrices available in literature and projects previously developed by TUDelft, which were adapted or modified for a better representation of the HyChain3 project. The pedigree matrices are defined for 4 quality criteria: proxy, empirical basis, methodological rigour and validation. The scores range from 0 to 4, where 4 represents the best possible quality. This approach would allow assessing the robustness and uncertainties of data inputs and outputs/key performance indicators for the groups of indicators representing technical, economic and environmental aspects.

Definitions of the 4 quality criteria are based on van der Spek, Ramirez & Faaij (2016), and defined as follows:

Empirical basis: Empirical basis refers to which extent direct observations, measurements and statistics are used to estimate the parameter. When the parameter is based upon good quality observational data, the pedigree score will be high. Sometimes directly observed data are not available and the parameter is estimated based on partial measurements or calculated from other quantities. Parameters determined by such indirect methods have a weaker empirical basis and will generally score lower than those based on direct observations.

Proxy: Proxy refers to how good or close a measure of the quantity that is modeled is to the actual quantity is represented. Sometimes it is not possible to represent directly the aspect of interest by a parameter, thus a proxy measure is used.Think of first order approximations, oversimplifications, idealizations, gaps in aggregation levels, differences in definitions, non-representativeness, and incompleteness issues. If the parameter were an exact measure of the quantity, it would score four on proxy. If the parameter in the model is not clearly related to the phenomenon it represents, the score would be zero.

Methodological rigour: Some method will be used to collect, check, and revise the data used for making parameter estimates. Methodological quality refers to the norms for methodological rigor in this process applied by peers in the relevant disciplines. Well-established and respected methods for measuring and processing the data would score high on this metric, while untested or unreliable methods would tend to score lower.

Validation: This metric refers to the degree to which one has been able to cross-check the data and assumptions used to produce the numeral of the parameter against independent sources. When these have been compared with appropriate sets of independent data to assess its reliability it will score high on this metric. In many cases, independent data for the same parameter over the same time period are not available and other data sets must be used for validation. This may require a compromise in the length or overlap of the data sets, or may require the use of a related, but different, proxy variable for indirect validation, or perhaps use of data that has been aggregated on different scales. The more indirect or incomplete the validation, the lower it will score on this metric.

The pedigree matrix used for both inputs and outputs is depicted in Table 2.

Pedigree matrix for technical, economic, and environmental knowledge base

Criterion / ***Score***	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
4	A direct measure of the desired quantity	Controlled experiments and large sample, direct measurements	Best available practice in well-established discipline	Compared with independent measurements of the same variable over long domain
3	Good fit to measure	Historical/field data, uncontrolled experiments, small sample, direct measurements	Reliable method common within established discipline; best available practice in immature discipline	Compared with independent measurements of closely related variable over shorter period
2	Well correlated but not measuring the same thing	Modelled/derived data, indirect measurements	Acceptable method but limited consensus on reliability	Measures are not independent, include proxy variables or have limited domain
1	Weak correlation but commonalities in measure	Educated guesses, indirect approximation, rule of thumb estimate	Preliminary methods, unknown reliability	Weak and very indirect validation
0	Not correlated and not clearly related	Crude speculation	No discernible rigour	No validation performed

Qualitative Indicators

For the qualitative indicators, any important technological, economic, political, social, or environmental **risks** or **opportunities** associated with the technology that the parties contributing to the work are aware of or come across in the research should be noted. Within risks and opportunities, five different dimensions are included: Technological, Economic, Political, Social, and Environmental.

Parties contributing to the work were given a list of example aspects that could be noted as relevant, but were free to note other things of interest. If nothing relevant to note was uncovered during the work, this section was left blank. Example aspects for each of the five dimensions include:

Technological: Operational flexibility, compatibility with existing infrastructure, dependence on external feedstocks, scalability

Economic: Potential job implications, current demand or supply

Political: Facility safety classification and zoning, safety measures and risk, incentive frameworks, policy

Social: Sound, odor, or visual pollution, public perception or acceptance

Environmental: Toxic pollution or risk, scarcity of required inputs, recyclability

Database: How to use

In the database, two parts from the data sheets are duplicated: the quantitative KPIs and the quality assessment matrices that are associated with these KPIs. These are placed in the database to make it easy to work with the values contained here, but any use of these values should remain coupled with the more detailed information provided in the data sheets. The data sheets generally provide all of the contextual detail around how the values were calculated, which is necessary for proper interpretation of the outcomes. Therefore, this information cannot be considered standalone.

In the database, the first sheet contains an index, organized by technology type. Clicking on one of the technologies will automatically take you to the relevant tab where the information is stored. To return to the index, click on the link back to the index under the technology name at the top of each sheet. The second sheet in the file contains a basic overview of a few of the KPIs, where available.

Results

The following sections include the main body of this document: the data sheets for each technology category. While care was taken to ensure the data sheets are as consistent as possible, through dealing with varying degrees of information availability, some are missing information.

For each data sheet, the author and organization responsible for the contribution is cited. In most cases, Delft University of Technology has reviewed the data sheets to identify any clear problems with the information or places where additional explanation was necessary to interpret the information provided. These were revised in accordance with the comments made. However, some data sheets have not gone through this review process. Where this is the case, this is mentioned on the data sheet.

Hydrogen Production

P1: Electrolysis - PEM

Data sheet prepared by/owner: Frames

Data sheet reviewed by: Jonathan Moncada & Andrea Ramirez, Delft University of Technology.

Technology Description: A PEM electrolyser is a system which converts electricity and ultrapure water into hydrogen and oxygen. The electrochemical process is driven by applying electrical potential between two electrodes: anode and cathode. Water molecules are split into oxygen and hydrogen ions. The oxygen ions combine at the anode to form oxygen gas, while the hydrogen ions permeate through the membrane to the cathode where they form hydrogen gas.

The stack is provided with ultrapure demi water at the anode. The reaction produces heat which needs to be removed from the stack. This can either be done by a separate cooling circuit within the stack, or by surplus supply of ultrapure water to the anode.

The proton exchange membrane allows crossover of water and gases, hence the produced hydrogen will contain water and traces of oxygen. The produced oxygen will contain traces of hydrogen. Crossover is determined by the design of the stack and membrane, and the operating conditions.

The product oxygen at the anode needs to be removed from the process; this is done with a gas/liquid separation device. The produced hydrogen needs to be purified to meet product quality requirements. This purification includes removal of oxygen (deoxo) and drying by means of e.g. silica-gel towers or molecular sieves.

The reaction is driven by the supplied current to the stack. The power electronics convert the supplied electrical energy (potentially high voltage AC) to the required stack specifications (low voltage high current). Turndown of the system is realized by limiting the supplied current to the stack, resulting in an increased efficiency of the electrochemical conversion at lower currents.

Key Performance Indicators (KPIs)

Technological		Economic				Environmental	
		Year	2019	2030 (6)	2050		
TRL (scaled to Nth of a kind)	7	Equipment Cost (M€) (3)	27.2	16.5		Water consumption (m^3/GJ)	0.093
Round trip efficiency (%)	0.66	CAPEX (M€)	49	29.8		Water withdrawal (m^3/GJ)	0.14
Capacity (TJ/y) (1)	502	Annualized CAPEX (M€/y)	3.93	2.39		Heat (GJ/GJ)	0.34
Capacity (ktonne/y)	4.19	Annualized CAPEX (M€/GJ)	0.00000783	0.00000476		Electricity (kWh/GJ)	446
Capacity (ktonne H_2-eq/y)	N/A	Annualized CAPEX (M€/kg H_2-eq)	N/A	N/A		GHG emissions (kg CO_2-eq/GJ) (5)	0
Product concentration, purity (wt.%)	99.9995	OPEX (M€/y) (4)	10.3	9.92		Land footprint (m^2/GJ)	0.00598
Volumetric energy density (MJ/Nm^3)	10.8	OPEX (M€/GJ)	0.0000205	0.0000198			
Losses during storage (%)	N/A	OPEX (M€/kg H_2-eq)	N/A	N/A			

Notes:

- Annualized capex calculated for a period of 20 years and interest rate of 5%
- (1) Calculation based on 25 x 1 MW stack: BOL (beginning of life) 25,6 MW, EOL (end of life) 28,7 MW. Each 1 MW stack consisting of 140 cells, each cell producing 1,55 Nm^3/hr. 98% availability.
- (2) Closed loop water cooling assumed. Water recovery of 67% assumed to produce ultrapure water for process.

- (3) Includes all process, instrumentation, mechanical and electrical equipment. Cost does not include material cost for installation (eg. civil works)
- (4) Based on 0.02 of CAPEX for routine maintenance plus electricity cost of EUR 0.04 / kWh.
- (5) Excludes GHG emissions during fabrication, assembly, construction, commissioning, maintenance, decommissioning
- (6) Based on the development of system costs as per report "Study on development of water electrolysis in the EU", 2014

CAPEX as function of capacity

	ktonne/y		M€		M€
Capacity 1	3.15E-01	Equipment cost 1	2.3	CAPEX	5.0
Capacity 2	3.94E+00	Equipment cost 2	27.0	CAPEX	49.0
Capacity 3	1.58E+01	Equipment cost 3	90.0	CAPEX	160.0

Notes:

- Equipment cost figures for 2 MW and 25 MW based on 2019 actual market prices. 100 MW is pure estimation.

Quality Assessment

The following matrix shows the scores on quality assessment of data inputs and indicators grouped as total system.

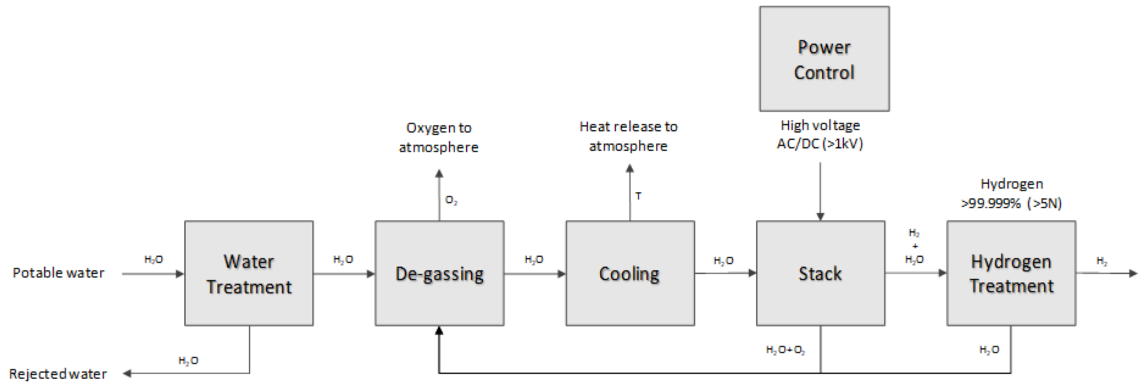
Uncertainty for Data Inputs				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	4	3	3	2
Economic	2	2	3	2
Environmental	4	2	2	2

Uncertainty for Key Performance Indicator Outcomes				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	**4**	**3**	**3**	**2**
Economic	**2**	**2**	**3**	**2**
Environmental	**4**	**2**	**2**	**2**

Notes:

- PEM Electrolysis is a very mature technology, however, field experience at the scale of > 25 MW is not available. Therefore the quality assessment generally contains level 2 to 3 with an exceptional 4 to represent the quality level of the assessment.

Process flow diagram



Risks and opportunities

	Risks	Opportunities
Technological	Stacks are easily damaged by inappropriate operation and cell design. Sensitive to imperfections, dust, impurities. Long term stability is a challenge (> 60,000 hrs).	PEM is a relatively new technology, which can still be improved (reduction of electrocatalysts (Platinum Group Metals), reduction of thickness of membranes, higher operating pressures). PEM technology improvements can result in higher efficiency, higher stack capacity (1 MW to 10MW scale) and reduction of noble metal catalysts. PEM's main USP is its ability to respond to rapid load changes.
Economic	Many of the reports assume economies of scale to reach 40 - 50% price reduction over the period till 2050. This may not materialize.	Valorization of oxygen and heat from the electrolysis process may be interesting. Eg. 70 deg C heat in combination with heat pump to reach temperatures above 100 deg C may be interesting. Mass manufacturing of standardized building blocks for larger scale plants. PEM electrolysis has opportunity to be operated at higher power densities, reducing plant footprint.
Political	Dependence on countries with an abundance of green electricity required for the production of green hydrogen. Geo-political changes.	Development of GW scale electrolyzers to use existing gas distribution systems in the country.
Social	A hydrogen technology related accident, is a risk for the entire hydrogen value chain including electrolysis.	The use of natural gas is generally accepted in The Netherlands' public domain and hydrogen can be used as a "drop-in" replacement using a large part of the existing infrastructure.
Environmental	Most of the PEM designs (2019) rely heavily on platinum group metals. Mining of these PGMs has large impact on the environment.	Recent research shows quite some research into the usage of earth-abundant catalysts (EACs) for the membrane-electrode assemblies. Furthermore recycling of PGM should be considered in a total lifecycle approach.

References:

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- Xinwi, S., Kaiqi, X., Fleischer, C., Bjørheim, T.S., Liu, X., Norby, X., Grandcolas, M., Ragnar, S., Chatzitakis, A. (2018) Earth-Abundant Electrocatalysts in Proton Exchange Membrane Electrolyzers.
- Internal pricing for 2 MW and 25 MW electrolysis plants offered by Frames in 2019 to various customers.

P2: Electrolysis - Alkaline

Data sheet prepared by/owner: Thijs de Groot, Nouryon

Data sheet reviewed by: Jonathan Moncada, Delft University of Technology.

Technology Description:

Alkaline water electrolysis has a long history in the chemical industry and has been applied at large scale (up to 200 MW). It is a type of electrolyzer that is characterized by having two electrodes operating in a liquid alkaline electrolyte solution of potassium hydroxide (KOH) or sodium hydroxide (NaOH). These electrodes are separated by a diaphragm, separating the product gases and transporting the hydroxide ions (OH^-) from one electrode to the other. Both atmospheric as well as pressurized alkaline electrolyzers exist.

Compared to other electrolysis technologies classic alkaline electrolysis is operated at low current densities (2 kA/m^2), which means that the hydrogen output per m^2 is smaller than for other technologies. Therefore alkaline electrolyzers are typically large. On the other hand, a major advantage of alkaline electrolysis is that it does not require the use of noble metals, which makes the technology cheap.

Developments in alkaline technology are currently focused on increasing the current density, while retaining the low cost and the good efficiency. Promising developments especially take place in the area of the diaphragm.

Suppliers of alkaline water electrolysis include NEL (Norway), PERIC (China), Suzhou Jingli (China), Hydrogen-Pro (Norway-China), thyssenkrupp (Germany), AKC (Japan) and McPhy (France,Germany,Italy). Currently, the largest market for the technology is China.

Key Performance Indicators (KPIs)

Technological		Economic				Environmental	
		Year	Base year	2030	2050		
TRL (scaled to Nth of a kind)	8	Equipment Cost (M€)	49	32	23	Water consumption (m^3/GJ)	0.075
Round trip efficiency (%)	0.73	CAPEX (M€)	136	81	51	Water withdrawal (m^3/GJ)	6.04
Capacity (TJ/y)	1667	Annualized CAPEX (M€/y)	21.8	12.9	8.1	Heat (MJ/GJ)	0.25
Capacity (ktonne/y)	13.9	Annualized CAPEX (€/GJ)	0.000013	0.0000077	0.0000049	Electricity (kWh/GJ)	450
Capacity (ktonne H_2-eq/y)	13.9	Annualized CAPEX (€/kg H_2-eq)	0.0000016	0.00000093	0.00000058	GHG emissions (kg CO_2-eq/GJ)	0
Product concentration, purity (wt.%)	0.9995	OPEX (M€/y)	40	28	16	Land footprint (m^2/y.GJ)	0.0063
Volumetric energy density (GJ/m^3)	0.198	OPEX (€/GJ)	0.000024	0.000017	0.0000096		
Losses during storage (%)	N/A	OPEX (€/kg H_2-eq)	0.0000029	0.000002	0.0000012		

CAPEX as function of capacity

	ktonne/y		M€		M€
Capacity 1	1.9	Equipment cost 1	9	CAPEX	23
Capacity 2	13.9	Equipment cost 2	49	CAPEX	136
Capacity 3	92.7	Equipment cost 3	274	CAPEX	766

Notes:

- Numbers are for 2020

Equipment	ktonne/y	Scaling factor
Electrolyser		0.9-1
Balance of plant		0.6-0.8
Power train		0.6-0.8

Quality Assessment

The following matrix shows the scores on quality assessment of data inputs and indicators grouped as total system.

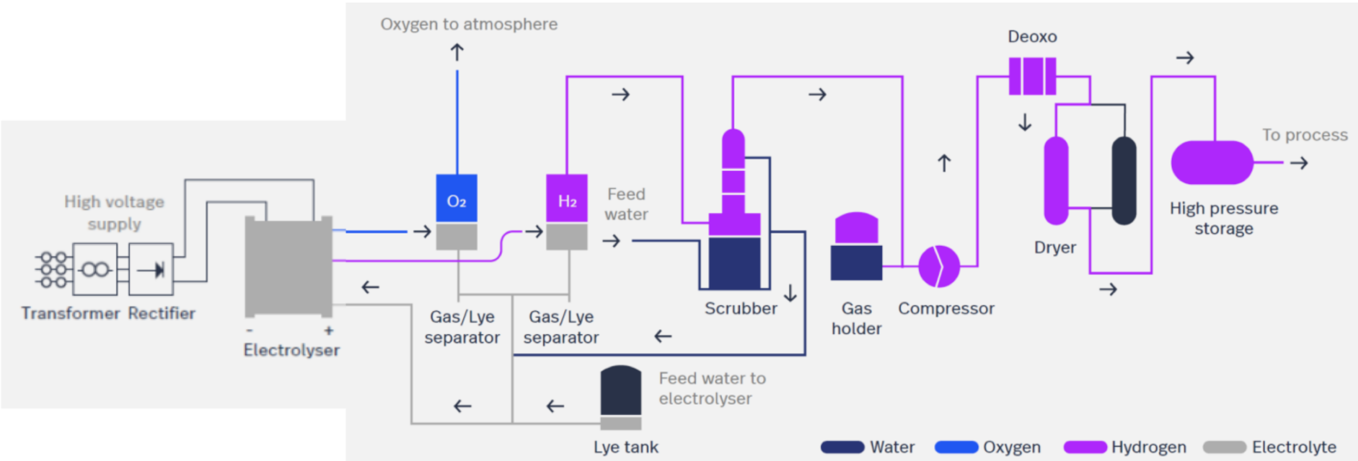
Uncertainty for Data Inputs				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	4	4	3	3
Economic	3	3	3	3
Environmental	3	3	2	2

Uncertainty for Key Performance Indicator Outcomes				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	4	4	4	3
Economic	3	3	3	2
Environmental	3	3	2	2

Notes:

- In general inputs score high as the majority of information to represent the system was gathered from technology developers and certainty of performance and features that compose the technology are well known.
- To complete the analysis some economic inputs were gathered from reports widely available in literature. The system is well known and supported in several studies and in-house experience. Thus outputs score high.

Process flow diagram



Risks and opportunities

	Risks	Opportunities
Technological	Lack of innovation and low speed of rollout could make that we do not make our 2030 cost targets for electrolyzers.	"Pimping" the Chinese technology can potentially even lead to lower prices (the Chinese are already quite close to our targets).
Economic	High electricity prices reduce economic competitiveness of green hydrogen compared to grey/blue hydrogen.	Partnering with windparks can take uncertain electricity prices out of risks.
Political	Changing government support schemes lead to increased uncertainty for green hydrogen business cases that require government support. Slowdown in rollout of offshore wind would also slow down electrolysis.	Growing political support for green hydrogen can help bringing in the right support schemes that are needed for alkaline electrolysis to be rolled out on a significant scale and hence reach the cost reductions.
Social	Hydrogen can be perceived as dangerous. Possible preference to go for "all electric" option. Climate sceptics that try to undermine societal support for green hydrogen.	Growing societal support for green hydrogen can help in creating the right political support schemes Possible willingness to pay more for green products will help the business case.
Environmental	KOH leakage into environment (highly unlikely).	Alkaline green hydrogen is truly green: green electricity has no footprint and materials needed are abundantly available from developed countries (eg. Nickel from Australia and Canada).

References:

- PERIC (2017) Development of AEL and PEM technology. Conference presentation.
- Suzhou Jingli (2018) Hydrogen Production equipment. Company presentation.
- Thyssenkrupp (2018) Hydrogen from large-scale electrolysis. Brochure by Thyssenkrupp.
- NEL (2017) Hydrogen electrolyzer, world's most efficient and reliable electrolyzer, brochure by NEL.
- Hirano et al. (2016) Advanced alkaline water electrolyzer for renewable hydrogen production.
- Hydrogen-Pro (2017) Company brochure.
- McPhy (2018) Presentation at the Hannover Messe.

P3: Electrolysis: SOEC

Data sheet prepared by/owner: Marija Saric & Yvonne van Delft, ECN part of TNO

Data sheet reviewed by: Jonathan Moncada & Andrea Ramirez, Delft University of Technology

Technology Description:

Solid oxide electrolysis cell (SOEC) is a technology that operates at relatively high temperatures (700-1000°C) to split water to produce hydrogen. The solid oxide electrolyser is the most commonly used high temperature electrolyzer (ref. 1). Due to the higher temperature, the technology has better efficiency than electrolysis technologies using lower operating temperatures. The electrical input required at 800°C is 25% lower than at 100°C , therefore the electrical efficiency is higher. However, to be considered a sustainable technology both electricity and heat have to come from renewable sources (ref. 2). Another advantage of SOEC is the possibility to co-electrolyse hydrogen and carbon dioxide to produce syngas which can be further processed to methane and other hydrocarbons (ref. 3).

A disadvantage of the higher operating temperature is the need to find specific materials that are durable but also cost effective. In order to be commercialized this issue needs to be resolved (ref. 4). In SOFC, ceramics are used as a solid electrolyte. Further research is however needed.

Key Performance Indicators (KPIs)

Technological		Economic				Environmental	
		Year	Base year	2030	2050		
TRL (scaled to Nth of a kind)	5-6	Equipment Cost (M€)	2.65	1.12 - 2.25 (ref. 6)	1.57 (ref. 5)	Water consumption (m^3/GJ)	$9.26 \cdot 10^{-2}$
Round trip efficiency (%)	82%	CAPEX (M€)	3.44	1.45 - 2.92	2.04	Water withdrawal (m^3/GJ)	$1.92 \cdot 10^{-2}$
Capacity (TJ/y)	16.1	Annualized CAPEX (M€/y)	0.27	0.11-0.23	0.16	Heat (MJ/GJ)	200
Capacity (ktonne/y)	0.13	Annualized CAPEX (€/GJ)	16.8	6.9-14.3	10	Electricity (kWh/GJ)	386
Capacity (ktonne H_2-eq/y)	0.13	Annualized CAPEX (€/kg H_2-eq)	2.07	0.84-1.77	1.23	GHG emissions (kg CO_2-eq/GJ)	154.4
Product concentration, purity (wt.%)	99.999	OPEX (M€/y)	1.44 (0.22 utility)	0.5-0.65 (0.27 utility)	0.52 (0.31 utility)	Land footprint (m^2/GJ)	$1.75 \cdot 10^{-3}$
Volumetric energy density (GJ/m^3)	0.01 (at pressure of 1 bar]	OPEX (€/GJ)	89.5	31-40	33		
Losses during storage (%)	N.A.	OPEX (€/kg H_2-eq)	11	3.8-5	4		

Notes:

- 1. Installation factor of 1.3 assumed to take into account connection to electricity grid, engineering, civil works.
- 2. Assuming 8000h of electrolyser operation.
- 3. Assumed plant lifetime 20 years, interest rate 5%. The stack replacement is included in OPEX.

- 4. To produce steam at 3 bar and 150 °C.
- 5. System electricity use (stack + BOP).
- 6. Assuming electricity mix CO2 emission of 0.40 kg CO2 eqv./kWh electricity for 2016.
- (land footprint, round trip efficiency) Regarding OPEX: 1.5% Capex for maintenance, 3% for administration/permits, labor costs (1 operator 75 k€/year), electricity costs based on NEV for 2018 and 2030 and 2050 is an assumption. Respectively electricity costs are: 34 €/MWh, 44 €/MWh and 50 €/MWh. Assumed that stack is 50% of equipment cost with a lifetime of 10,000, 50,000 and 80,000 h for 2018, 2030 (ref. 6) and 2050 respectively.

CAPEX as function of capacity

	ktonne/y		M€		M€
Capacity 1		Equipment cost 1		CAPEX	
Capacity 2		Equipment cost 2		CAPEX	
Capacity 3		Equipment cost 3		CAPEX	

Equipment	ktonne/y	Scaling factor
SOE (0.75 MW)	0.13	1

Quality Assessment

The following matrix shows the scores on quality assessment of data inputs and indicators grouped as total system.

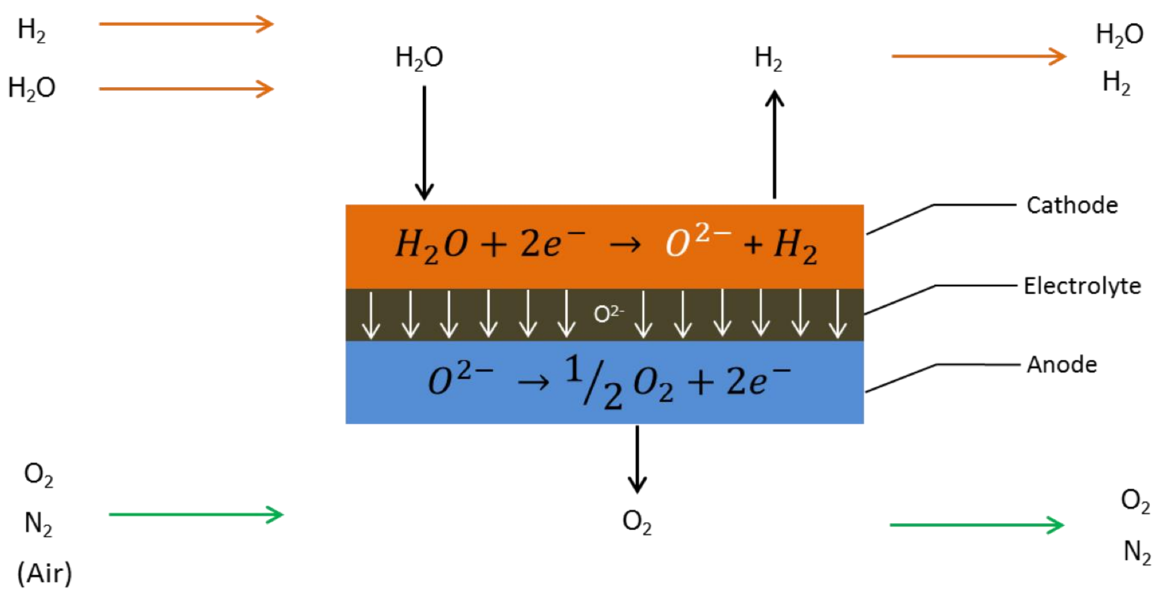
Uncertainty for Data Inputs				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	3	2	3	3
Economic	1	2	1	1
Environmental	3	3	3	3

Uncertainty for Key Performance Indicator Outcomes				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	3	2	3	3
Economic	1	2	1	1
Environmental	3	3	3	3

Notes:

- No correlations were used to estimate KPI.
- Max. 3 references available, no data for large scale SOE.
- For technical KPI's methods are well established and validated.
- There is a large deviation on the CAPEX values in literature for future, due to low TRL.

Process flow diagram



Risks and opportunities

	Risks	Opportunities
Technological	Severe material degradation as a result of the high operating temperatures results in the short stack lifetime.	Due to operation at high temperature, higher current efficiency can be achieved compared to the low T electrolysis.
Economic	SOE electrolyzer are costly because of required special materials and sealing for operation at higher temperatures.	These electrolysers are more efficient, thus production capacity is higher.
Political	N.A.	Emphasis on the limitation of CO_2 emissions and the role of electrification in different sectors .
Social	N.A.	N.A.
Environmental	Limited availability of materials as (Ni and Zr) that can be used for electrodes and electrolytes	Decrease of CO_2 emissions if green electricity is used.

References:

- IEA. (2017). Global Outlook and Trends for Hydrogen
- Gigler, J. & Weeda, M. (2018). *Outlines of a Hydrogen Roadmap*. TKI Nieuw Gas. Retrieved from: https://www.topsectorenergie.nl/sites/default/files/uploads/TKI%20Gas/publicaties/20180514%20Roadmap%20Hydrogen%20TKI%20Nieuw%20Gas%20May%202018.pdf
- De Vita et al (2018). Sectoral integration- long term perspective.
- Pesonen, O., & Alakunnas, T. (2017). Energy storage
- Mathiesen,B.V., Skov, I.R., Connolly, D., Nielsen, M. P., Vang Hendriksen,P, Bjerg M.M,Højgaard J. S., Dalgaard E.S., (2013). Technology data for high temperature solid oxide electrolyser cells, alkali and PEM electrolysers.
- Schmidt, Gambhir, Staffell, Hawkes, Nelson, Few, (2017). Future cost and performance of water electrolysis: An expert elicitation study. International Journal of H2 energy, 42
- Sunfire (2019). Hylink. Retrieved from https://www.sunfire.de/en/products-and-technology/sunfire-hylin
- NEV (2017). Tabellen NEV 2017 variant 'Vastgesteld en voorgenomen beleid, zonder nieuwe SDE+ openstellingen na 2019'

P4: Steam methane reforming, with carbon capture

Data sheet prepared by/owner: Emile Herben, Yara in collaboration with Gasunie

Data sheet reviewed by: Jonathan Moncada & Andrea Ramirez, Delft University of Technology

Technology Description:

Steam methane reforming (SMR) involves catalytically reacting natural gas with steam to produce hydrogen and carbon monoxide (a mixture known as syngas). A subsequent reaction involving more steam produces further hydrogen while also converting carbon monoxide (CO) to CO_2.

Most hydrogen produced today is made via steam-methane reforming, a mature production process in which high-temperature steam (700°C–1,000°C) is used to produce hydrogen from a methane source, such as natural gas. In steam-methane reforming, methane reacts with steam under 3–25 bar pressure (1 bar = 14.5 psi) in the presence of a catalyst to produce hydrogen, carbon monoxide, and a relatively small amount of carbon dioxide. Steam reforming is endothermic—that is, heat must be supplied to the process for the reaction to proceed.

Subsequently, in what is called the "water-gas shift reaction," the carbon monoxide and steam are reacted using a catalyst to produce carbon dioxide and more hydrogen. In an optional final process step called "pressure-swing adsorption," carbon dioxide and other impurities are removed from the gas stream, leaving essentially pure hydrogen. Steam reforming can also be used to produce hydrogen from other fuels, such as ethanol, propane, or even gasoline.

Key Performance Indicators (KPIs)

Technological		Economic				Environmental	
		Year	**Base year (2019 - 2034)**	**2030**	**2050**		
TRL (scaled to Nth of a kind)	8-9	Equipment Cost (M€)	234			Water consumption (m^3/yr/GW H_2)	921,811
Round trip efficiency (%)	79.5 %	CAPEX (M€)	1223			Water withdrawal (m^3/kg H_2)	0.03
Capacity (TJ/y)		Annualized CAPEX (M€/y)	102.5			Heat (MJ/GJ)	
Capacity (ktonne/y)		Annualized CAPEX (€/GJ)				Electricity (MW/GW H_2)	23.7
Capacity (ktonne H2-eq/y)	329	Annualized CAPEX (€/kg H_2-eq)	0.31			GHG emissions (g CO_2-eq/kWh H_2)	20.5
Product concentration, purity (wt.%)	0.975	OPEX (M€/y)				Land footprint (ha/GW H_2)	25-30
Volumetric energy density (GJ/m3)	?	OPEX (€/GJ)					
Losses during storage (%)	N/A	OPEX (€/kg H_2-eq)					

Notes:

- Costs are based on a multi-year investment proposal
- GBP to EUR exchange rate 1,13
- Capex is excluding CO_2 transport and storage
- TRL 9 for ATR and capture of CO_2, 8 for integration with transport and storage of CO_2
- Roundtrip efficiency is defined in this case as HHV of H2 output/HHV of NG and electricity needed for production. HHV is used because part of the heat from water condensation is reused in the process.
- A product concentration of >99,9 can be achieved by installing a PSA, but this will reduce overall efficiency to about 75% while increasing capex and opex.
- The volumetric energy density is uncertain, costs are based on 97,5% H_2 @ 80 bar and unknown temp.
- The GHG emissions are a result of CO_2 emissions that are not captured. In case the electricity consumed is from a non-renewable source, that will lead to additional (Scope 2) emissions as well.
- Annualized capex assumes 40yr lifetime and 8% interest rate.

Quality Assessment

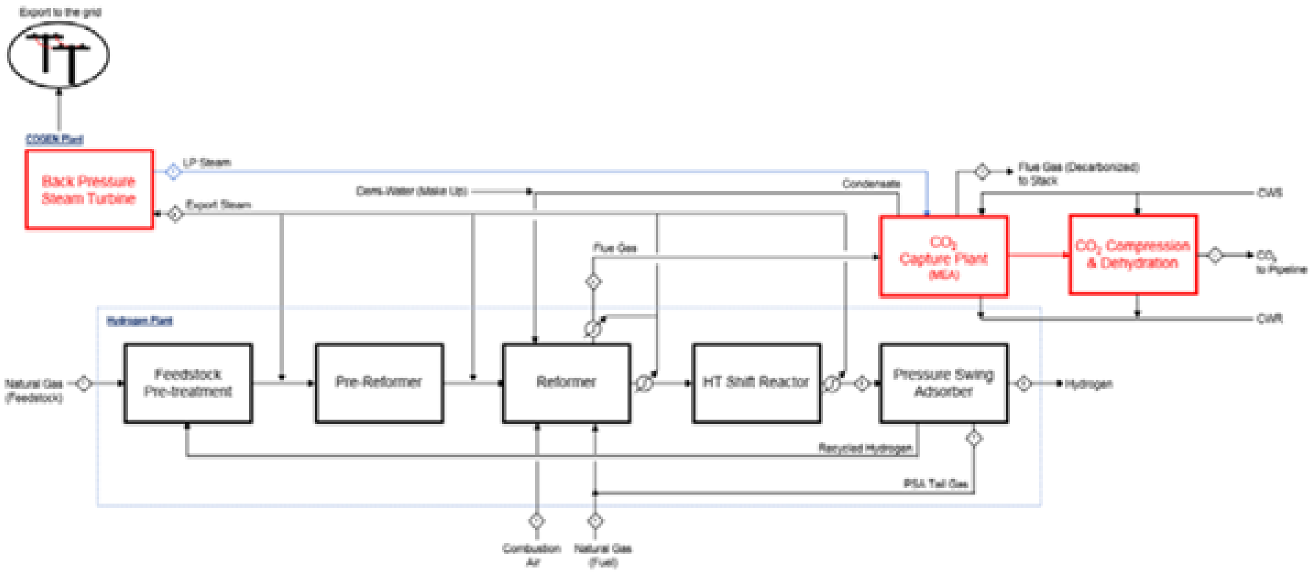
The following matrix shows the scores on quality assessment of data inputs and indicators grouped as total system.

Uncertainty for Data Inputs/KPIs				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	4	2	4	1
Economic	4	2	4	1
Environmental	3	2	4	1

Notes:

- There is quite a lot of data available on SMR, but not on SMR with high % CO2 capture. That's why the validation and the empirical data scores rather low.
- Data used is primary data, hence no KPI uncertainty.

Process flow diagram



Risks and opportunities

	Risks	Opportunities
Technological	Not flexible. Designed for 24/7, single capacity operation. CO_2 transport and storage infrastructure is missing This technology highly depends on natural gas and water.	Mature technology, large existing asset base. There is already a large existing natural gas and SMR infrastructure. so this technology can be used today, at low risk.
Economic		For now the most economical way to produce low carbon hydrogen. Scalable to very large sizes, in fact, only economical at very large scale.
Political	Public opinion on CCS can be quite negative, depending on the location of storage.	
Social	Same as above.	
Environmental	CCS will not get you to net-zero emissions, but 95% at best.	

References:

- H21 North of England (2018) H21 NoE Report. Retrieved from: https://www.northerngasnetworks.co.uk/h21-noe/H21-NoE-26Nov18-v1.0.pdf
- IEAGHG (2017). Techno-Economic Evaluation of SMR Based Standalone Hydrogen Plant with CCS. Retrieved from: https://ieaghg.org/exco_docs/2017-02.pdf

P5: Autothermal reforming (ATR), with carbon capture

Data sheet prepared by/owner: Emile Herben, Yara in collaboration with Gasunie

Data sheet reviewed by: Jonathan Moncada & Andrea Ramirez, Delft University of Technology

Technology Description: ATR is a catalytic technology, essentially a combination between steam reforming (SR) and partial oxidation (POX). The heat generated from the exothermic POX reaction is used for supplying the heat needed for the endothermic SR reaction during operation.

The main difference between SMR and ATR is how heat is supplied to the reforming reactions. In the SMR reactor heat is transferred from a separate combustion section, whilst in the ATR reactor heat is generated by partial combustion of the reformer feed (natural gas) with oxygen. This means that a more CO_2-rich syngas is produced in the ATR than in the SMR since the combustion products (H_2O and CO_2) end up in the syngas. In an SMR, this CO_2 stream is released to the atmosphere. This is an important difference between ATR and SMR regarding the ability to capture CO_2.

Key Performance Indicators (KPIs)

Technological		Economic				Environmental	
		Year	**Base year (2019 - 2034)**	**2030**	**2050**		
TRL (scaled to Nth of a kind)	8-9	Equipment Cost (M€)	224			Water consumption (m^3/yr/GW H2)	460905
Round trip efficiency (%)	79.9 %	CAPEX (M€)	1070			Water withdrawal (m^3/kg H_2)	0.03
Capacity (TJ/y)		Annualized CAPEX (M€/y)	89.7			Heat (MJ/GJ)	
Capacity (ktonne/y)		Annualized CAPEX (€/GJ)				Electricity (MW/GW H_2)	48.4
Capacity (ktonne H_2-eq/y)	329	Annualized CAPEX (€/kg H_2-eq)	0.27			GHG emissions (g CO_2-eq/kWh H2)	13.1
Product concentration, purity (wt.%)	97.50%	OPEX including CO_2 costs (M€/y)	3060			Land footprint (ha/GW H_2)	15-20
Volumetric energy density (GJ/m^3)	?	OPEX (€/GJ)					
Losses during storage (%)		OPEX including CO_2 costs (€/kg H_2-eq)	1.1				

Notes:

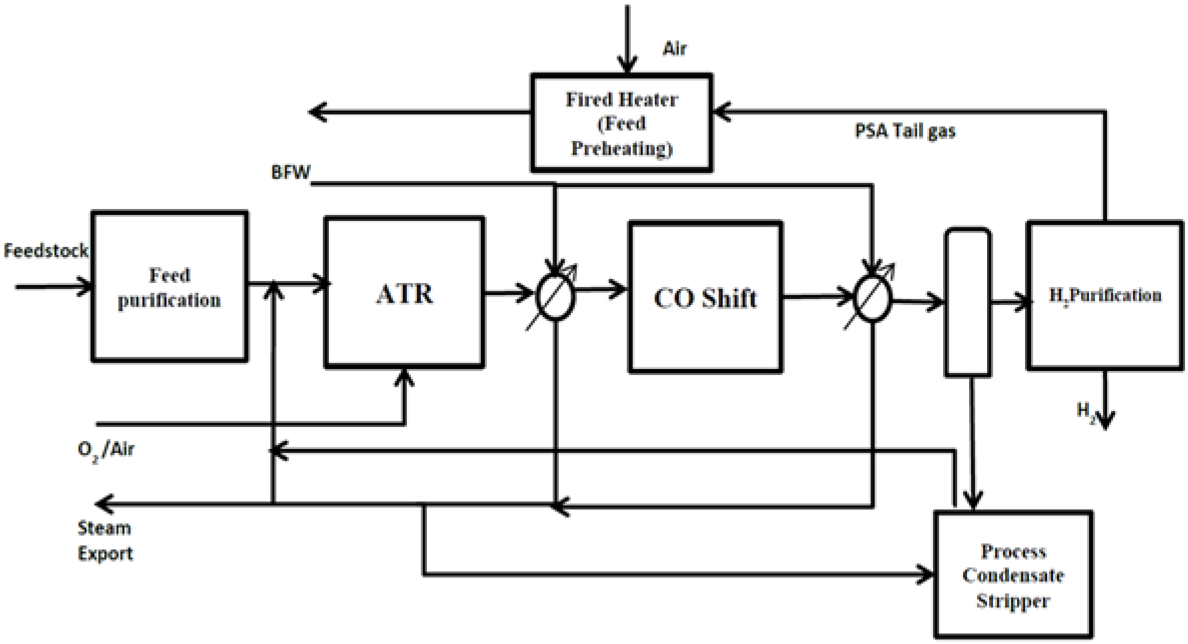
- Costs are based on a multi-year investment proposal
- GBP to EUR exchange rate 1,13
- Capex is excluding CO_2 transport and storage
- Opex is including CO_2 transport and storage
- TRL 9 for ATR and capture of CO_2, 8 for integration with transport and storage of CO_2
- Roundtrip efficiency is defined in this case as HHV of H_2 output/HHV of NG and electricity needed for production. HHV is used because part of the heat from water condensation is reused in the process.
- A product concentration of >99,9 can be achieved by installing a PSA, but this will reduce overall efficiency to about 75% while increasing capex and opex.
- The volumetric energy density is uncertain, costs are based on 97,5% H_2 @ 80 bar and unknown temp.
- OPEX including CO_2 costs is based on a 12 GW plant
- The GHG emissions are a result of CO_2 emissions that are not captured. In case the electricity consumed is from a non-renewable source, that will lead to additional (Scope 2) emissions as well.
- Annualized capex assumes 40yr lifetime and 8% interest rate.

Quality Assessment

The following matrix shows the scores on quality assessment of data inputs and indicators grouped as total system.

Uncertainty for Data Inputs/KPIs				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	4	2	4	1
Economic	4	2	4	1
Environmental	3	2	4	1

Process flow diagram (without CCS)



Notes:

- The diagram above does not include CCS. CCS would basically add a CO_2 capture unit after the fired heater, followed by CO_2 transportation and storage.
- CCS is still included within the system boundaries and part of CAPEX and OPEX

Risks and opportunities

	Risks	Opportunities
Technological		Mature technology, so this is ready for large scale commercial exploitation today.
Economic		For now the most economical way to produce low carbon hydrogen on a large scale.
Political	CCS requires a higher carbon price than any country has today to make it economically attractive. It also requires government support for building CO_2 transport and storage infrastructure that is shared by several industrial users.	
Social	Public opinion on CCS can be quite negative, depends on the location of storage	Same as for technology, this is a technology that can be used at low risk already today, and that can reduce a very large amount of emissions.
Environmental		

References:

- H21 North of England (2018) H21 NoE Report. Retrieved from: https://www.northerngasnetworks.co.uk/h21-noe/H21-NoE-26Nov18-v1.0.pdf
- Croezen & Rooijers (2018). Feasibility study into blue hydrogen - CE Delft, Retrieved from https://www.cedelft.eu/en/publications

P6: Battolyser

Data sheet prepared by/owner: Bob Weehuizen, Proton Ventures BV

Data sheet reviewed by: Jonathan Moncada & Andrea Ramirez, Delft University of Technology

Technology Description: The Battolyser™ is a new development utilizing turn of the 19th century technology of Edison, the Ni-Fe battery. This battery still remains in a few niche markets. Battolyser Bv.'s reinvention of this battery takes its losses, predominantly due to the production of hydrogen and oxygen and uses this as a positive attribute. In a new hydrogen economy and e-refinery, this loss is welcomed! Lab tests have shown that not only does the production of hydrogen increase battery capacity utilization and regeneration due to overcharging, but also has the potential of increasing electrolyser efficiencies above industrial standards.

The Battolyser™ is the first multicell NiFe battery on the market; the first to make hydrogen continuously for production; and the first alkaline electrolyser to run below the 10% capacity threshold. Thus the unit will bring industry a unique combination of electrical storage and transmission, as well as hydrogen production in one unit. With such novelty in one unit it is expected that the Battolyser™ can stand alone on the future energy and hydrogen market.

Key Performance Indicators (KPIs)

Technological		Economic				Environmental	
		Year	Base year (2019 - 2034)	2030	2050		
TRL (scaled to Nth of a kind) [6]	3	Equipment Cost (M€)				Water consumption (m^3/GJ)	6
Round trip efficiency (%)	85-90% [2]	CAPEX (M€)	0.3 [1, 12]			Water withdrawal (m^3/GJ)	0.6
Capacity (TJ/y)	0.315 [3]	Annualized CAPEX (M€/y)	0.02 [1]			Heat (MJ/GJ)	100-150
Capacity (ktonne/y)	0.204 [4]	Annualized CAPEX (€/GJ)	63.5			Electricity (kWh/GJ)	0.0036
Capacity (ktonne H_2-eq/y)	N/A	Annualized CAPEX (€/kg H_2-eq)	0.000098			GHG emissions (kg CO_2-eq/GJ) [13]	0 [13]
Product concentration, purity (wt.%) [6]		OPEX (M€/y)	0.04 [14]			Land footprint (m^2/GJ)	4 [8]
Volumetric energy density (GJ/m^3)	0.09	OPEX (€/GJ)	0.011 [7]				
Losses during storage (%) [6]		OPEX (€/kg H_2-eq)	N/A				

Notes:

- (1) Target price 250 euros/kWh. A 1 kWh unit can produce 1kW$_{pk}$ Hydrogen production and 0,25kW efficient production. The size given is for a 1MWh unit in a 20ft container. This excludes auxiliary equipment and utilities and the electrical substation. The lifetime of the plant is 20 years and a 3% interest rate. This excludes gas purification which can vary dramatically.
- (2) 80% electrical energy to electrical energy (losses are converted to H_2)
- (3) 25% charge time and 75% discharge.
- (4) Continuous H2 production (no discharge of the battery).
- (5) Only electrolyte needs changing every 2 years. Excludes labour and feed costs, this is project and size dependent and the Battolyser can be used in several configurations.
- (6) 99,7-99,99999%mol H_2 - Hydrogen gas can be purified to client specifications with normal industrially standard purification equipment. Concentration from the battolyser itself is dependent on the delivered pressure.
- (7) For battery only and without hydrogen energy included.
- (8) Battery storage only and without hydrogen production; 1MW/1MWh = 20ft container.
- (9) For battery only and without hydrogen energy included.
- (10) Hydrogen production is the reason for battery energy depreciation. Therefore the numbers are difficult to provide.
- (11) Data Model is derived from the primary source and values obtained during the design of a pilot plant.
- (12) Target price is 2022/23 The picture today is 600euros/kWh (with current prices with NO OPTIMISATION) for the supply mentioned.
- (13) We are not using hydrocarbons It uses water, electricity and limited nitrogen. We are not calculating the power station behind the electricity production. The power station is not the technology assessed.
- (14) Labour and feed costs are excluded because electrical prices are fluctuating in a green future. This and water are the only feedstock.
- (15) Scales are difficult to fill in. Scales are always relative to the person making the assessment.

Quality Assessment (15)

The following matrix shows the scores on quality assessment of data inputs and indicators grouped as total system.

Uncertainty for Data Inputs				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	4	4	3	2
Economic	4	4	3	2
Environmental	4	4	3	2

Uncertainty for Key Performance Indicator Outcomes				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	**4**	**4**	**3**	**2**
Economic	**3**	**4**	**3**	**2**
Environmental	**3**	**4**	**3**	**2**

Risks and opportunities

	Risks	**Opportunities**
Technological	Lower efficiencies obtained from the pilot plant built in June due to ionic leak currents from the multicell configuration Houses are not built for Hydrogen as a replacement for Natural gas.	Technology can be used for only battery without hydrogen use and quickly adapted to start/increase capacity at a later date with increase of users. Efficiencies are increased at lower capacity (larger battery) which competes with PEM and Alkaline Electrolysers
Economic	Difficulties to obtain large funds to be competitive with the existing battery market which is fully assembly line ready.	Clients can buy a battery for minimal investment and future expand into hydrogen when funding and markets become available. This expansion can be accomplished in a faster time. Materials are cheaper than common batteries since only Ni and Fe are the main components. Electricity can be traded as well as hydrogen (best of both worlds) this provides a constraint revenue and allows you to sell electricity at the highest price.
Political	Not enough government investment is taking place to build 1-GWh battery installation, or does not have the right strategies to spark investment at the levels needed to bring the cost of the battery lower (this is changing)	The stopping of coal/gas/nuclear power stations is a requirement for society and an objective of the government. The battolyser enables this transition.

Social	Hydrogen and KOH (electrolyte) are both hazardous products. An accident in the hydrogen industry in general when it is used in transportation could trigger the end of its use, particularly as a compressed gas.	Neighborhoods can implement their own renewable grid, with electricity and hydrogen to replace NG, as well as for energy storage. Remote areas and islands can generate and store their own electricity. Hydrogen can be produced for all industrial applications. No CO_2 is produced and Coal/gas/nuclear power stations can be shut down and finally replaced.
Environmental	None	Reduction of CO_2.

Notes:

- Hydrogen can be made from green energy source without CO_2 production. Therefore energy sources such as wind and solar become more favorable than fossil fuels, nuclear, land clearing biofuels, tree-felling energy sources or environment altering sources such as hydroelectric.

References:

- Mulder, F.M., Weninger, B. M. H. , Middelkoop, J., Ooms, F. G. B., and Schreuders, H. (2017). *Efficient electricity storage with a battolyser, an integrated N-Fe battery and electrolyser.* Energy Environ. Sci., 2017.10 page 756-764.
- Radersma, S. (2018). Eemshaven krijgt een Battolyser. RTVNoord. Retrieved from: https://www.rtvnoord.nl/nieuws/195167/Eemshaven-krijgt-een-Battolyser

P7: Dry reforming of methane

Data sheet prepared by/owner: Marija Saric & Yvonne van Delft, ECN part of TNO

Data sheet reviewed by: Jonathan Moncada & Andrea Ramirez, Delft University of Technology

Technology Description:

Dry reforming, or CO_2 reforming of methane, refers to the production of syngas (a mixture of hydrogen and carbon monoxide) from the reaction of carbon dioxide in methane. The reaction scheme is shown below

(1)$CH_4 + CO_2 = 2CO + 2H_2 (\Delta H_{298K} = +247\ KJ\ mol^{-1})$

DRM is not considered an industrially mature process.The extremely high endothermic reaction, coupled with rapid carbon formation eventually leads to the catalyst deactivation. In addition, the long reaction time and the requirement for pure CO_2, renders DRM an impractical process that still needs further developments. In 2015 the Linde Group officially opened a dry-reforming based pilot facility at Pullach near Munich, with plans to commercialize the technology. Based on developments such as this and ENEA Consulting's comparison with the hydrogenation of $CO_2$to methanol a TRL of 4–6 is assigned to dry reforming.

Key Performance Indicators (KPIs)

Technological		Economic				Environmental	
		Year	Base year (2019 - 2034)	2030	2050		
TRL (scaled to Nth of a kind)	4-6 (ref 2.)	Equipment Cost (M€)				Water consumption (m^3/GJ)	-
Round trip efficiency (%)	70%	CAPEX (M€)	442			Water withdrawal (m^3/GJ)	0.017
Capacity (TJ/y)	21136	Annualized CAPEX (M€/y)	35.33			Heat (MJ/GJ)	-
Capacity (ktonne/y)	176	Annualized CAPEX (€/GJ)	1.67			Electricity (kWh/GJ)	-
Capacity (ktonne H_2-eq/y)	176	Annualized CAPEX (€/kg H_2-eq)	0.2			GHG emissions (kg CO_2-eq/GJ)	45.54
Product concentration, purity (wt.%)	5.62% dry (the rest is CO_2	OPEX (M€/y)	331 (ref 3.)			Land footprint (m^2/GJ)	
Volumetric energy density (GJ/m^3)	0.4 (for H_2 at 50 bar)	OPEX (€/GJ)	15.7				
Losses during storage (%)	N.A.	OPEX (€/kg H_2-eq)	1.8				

Notes:

- Round trip efficiency taking into account CO and H_2 product
- Regarding CAPEX, please note, there is no info found in literature on economics of dry reforming to H_2 route, data are extracted from economic data on dry reforming to MeOH route, thus WGS reactor, product gas compression and gas cleaning section is not included.
- Regarding OPEX, the natural gas price of 5 €/GJ assumed, costs of CO_2=20 €/t, maintenance = 3% CAPEX and 5 operators X 3 shifts for 40 k€/year assumed.

Quality Assessment

The following matrix shows the scores on quality assessment of data inputs and indicators grouped as total system.

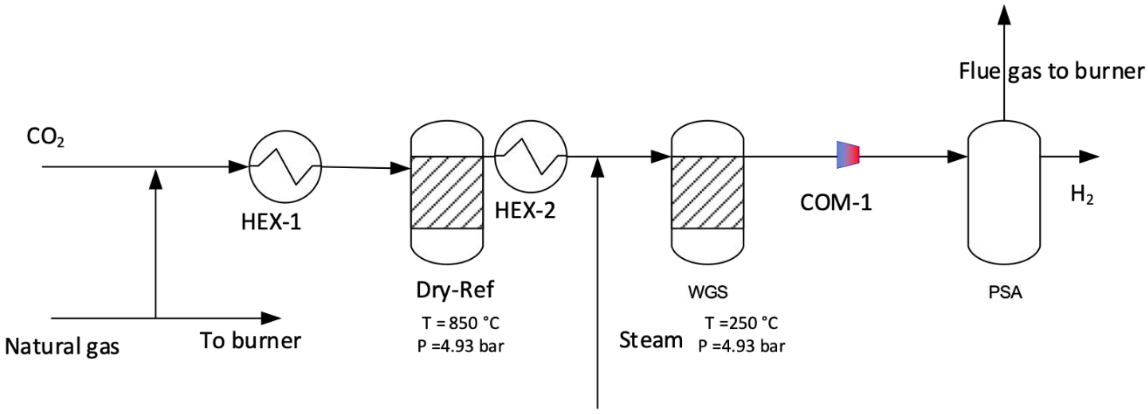
Uncertainty for Data Inputs				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	1	1	1	1
Economic	1	1	1	1
Environmental	1	1	1	1

Uncertainty for Key Performance Indicator Outcomes				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	1	1	1	1
Economic	1	1	1	1
Environmental	1	1	1	1

Notes:

- Economic proxy data based on one reference

Process flow diagram



Risks and opportunities

	Risks	Opportunities
Technological	Catalyst deactivation due to C formation	Options to use alternative way of heating: microwave, solar.
Economic	N.A.	The dry reforming process offers cost efficiencies relative to partial oxidation – the conventional method used up to now to produce CO-rich synthesis gases. These would be of particular interest to small and medium-sized plants.
Political	N.A.	N.A.
Social	N.A.	N.A.
Environmental	Uses natural gas as a raw material and fuel.	Decreases water use compared to steam methane reforming and has a potential to decrease carbon footprint

References:

- Aramouni N.A.K., Touma J. G., Tarboush B. A., Zeaiter J., Ahmad M. N., (2018). Catalyst design for dry reforming of methane: Analysis review, Renewable and Sustainable Energy Reviews 82(3), 2570-258
- Jarvis S. M., Samsatli S., (2018). Technologies and infrastructures underpinning future CO2 value chains: A comprehensive review and comparative analysis, Renewable and Sustainable Energy Reviews 85 46–68

P8: POX (partial oxidation)

Data sheet prepared by/owner: Albert van den Noort & Nicolien van der Sar, Gasunie

Data sheet reviewed by: Jonathan Moncada & Andrea Ramirez, Delft University of Technology

Technology Description: Partial oxidation is a technically mature process in which natural gas or a heavy hydrocarbon fuel is mixed with a limited amount of oxygen in an exothermic process

General reaction:

$$C_nH_m + \frac{n}{2}O_2 \rightarrow n\ CO + \frac{m}{2}H_2$$

Water may be added to lower the combustion temperature and reduce soot formation. Yields are below stoichiometric due to some fuel being fully combusted to carbon dioxide and water. A distinction is made between thermal partial oxidation (TPOX) and catalytic partial oxidation (CPOX).

It seems that in the Netherlands POX is mainly used for hydrogen production from heavy fractions of the oil distillation (residual oil) in refineries.

Key Performance Indicators (KPIs)

Technological		Economic				Environmental	
		Year	**Base year (2019 - 2034)**	**2030**	**2050**		
TRL (scaled to Nth of a kind)	9	Equipment Cost (M€)				Water consumption (m^3/GJ)	0.093
Round trip efficiency (%)	82.7	CAPEX (M€)	4160	2952	2341	Water withdrawal (m^3/GJ)	-
Capacity (TJ/y)	89,520	Annualized CAPEX (M€/y)	334	237	188	Heat (GJ/GJ)	1.598
Capacity (ktonne/y)	746	Annualized CAPEX (€/TJ)	0.004	0.003	0.002	Electricity (kWh/GJ)	-
Capacity (ktonne H_2-eq/y)	746	Annualized CAPEX (€/kg H_2-eq)	0.45	0.32	0.25	GHG emissions (kg CO_2-eq/GJ)	158
Product concentration, purity (wt.%)	0.999	OPEX (M€/y)				Land footprint (m_2/GJ)	
Volumetric energy density (GJ/m^3)		OPEX (€/GJ)					
Losses during storage (%)		OPEX (€/kg H_2-eq)					

Notes:

- (2017/base year)H_2 capacity 2840 MW ->
- 2840 MW system costs 3782 Mpounds->*1.1=4160 M€
- Study mentions CAPEX for 2025 -> assumed the same for 2030
- (2025/2030)3060MW system costs 2891 Mpound ->2891*(2840/3060)*1.1= 2952 M€
- (2050)2693MW system costs 2018Mpound ->2018*(2840/2693)*1.1= 2341 M€
- Annualized capex is calculated with a plan lifetime of 20 years and a 5% interest rate

- With Coal gasification, Water consumption: 0.286 litres/kWh H_2 HHV (H_2 supply chain evidence base) -> 0.286/1000*3600*1000000*(120/141)=0.093 m^3/GJ LHV
- With Coal gasification, heat requirement is 1.36 kwh/kwh H_2 HHV -> 1.36 GJ/GJ H_2 HHV -> 1.36/(120/141)=1.598 GJ/GJ H_2 LHV
- With Coal gasification, CO_2 emission capture at 90% capture rate is 17.1 kg/kg H_2 (H_2 supply chain evidence base) -> at 100% is 19 kg/kg H_2 -> 158 kg/GJ H_2 LHV

Quality Assessment

The following matrix shows the scores on quality assessment of data inputs and indicators grouped as total system.

Uncertainty for Data Inputs				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	**2**	**2**	**2**	**3**
Economic	**2**	**2**	**2**	**3**
Environmental	**1**	**2**	**2**	**1**

Uncertainty for Key Performance Indicator Outcomes				
Areas	Proxy	Empirical basis	Methodological rigour	Validation process
Technical	**2**	**2**	**2**	**3**
Economic	**2**	**2**	**2**	**3**
Environmental	**1**	**2**	**2**	**1**

Notes:

- Used same estimates for data input as for KPIs. Rating based on available references (POX is mature technology; economic data hard to find)

Process flow diagram

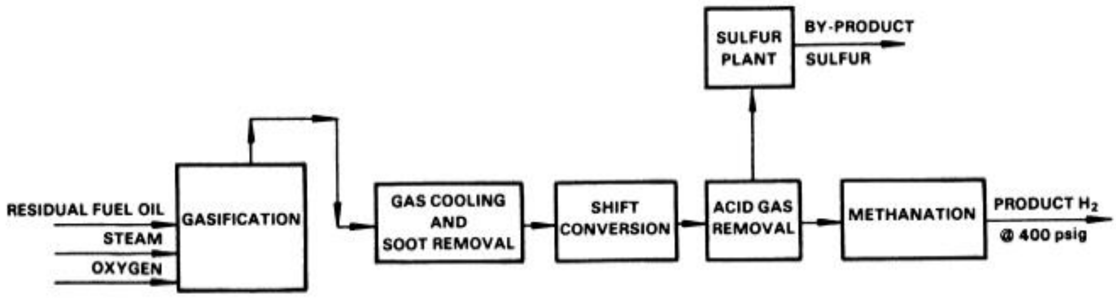


Figure 2. Hydrogen from residual fuel oil partial oxidation—simplified flow diagram

(Source: Smith & Santangelo, 1980)

Risks and opportunities

	Risks	Opportunities
Technological		Proven mature technology
Economic		Creates valuable hydrogen (or syngas) from rest materials
Political	Large point source of CO_2 -> CCS?	CCS?
Social	Large point source of CO_2 -> CCS?	CCS?
Environmental	Uses fossil materials as input of the process. Is therefore grey hydrogen	CCS?

References:

- Element Energy Ltd. (2018). Hydrogen supply chain evidence base, Nov 2018.
- *H21 North of England (2018) H21 NoE Report. Retrieved from:* https://www.northerngasnetworks.co.uk/h21-noe/H21-NoE-26Nov18-v1.0.pdf
- Mirabal, S.T. (2003). An Economic Analysis of Hydrogen Production Technologies Using Renewable Energy Resources. Master Thesis, University of Florida. Retrieved from: http://etd.fcla.edu/UF/UFE0002060/mirabal_s.pdf
- Smith and Santangelo (1980). Hydrogen: Production and Marketing ACS Symposium Series; American Chemical Society: Washington, DC. Retrieved from: https://pubs.acs.org/doi/pdfplus/10.1021/bk-1980-0116.ch001
- Wikipedia (2019). Hydrogen Production - Partial Oxidation. Retrieved from: https://en.wikipedia.org/wiki/Hydrogen_production#Partial_oxidation

P9: Gasification processes

Data sheet prepared by/owner: Albert van den Noort & Nicolien van der Sar, Gasunie

Data sheet reviewed by: Jonathan Moncada & Andrea Ramirez, Delft University of Technology

Technology Description: Gasification is the thermal conversion of biomass in a flammable gas, volatile compounds and ashes in a closed reactor in the presence of an externally added oxidant (air, oxygen, water). Gasification is an intermediate step between pyrolysis and combustion, it is an endothermic reaction.

Gasification of biomass results in the production of a mixture of hydrocarbons, hydrogen, carbon monoxide, carbon dioxide and water vapour. This mixture is known as syngas. Syngas is purified and used for the conversion of chemical products or the production of heat and power. Besides the produced gasses also ashes are reaction products: char, ashes and tar. The reaction products, their composition and quantities are determined by the oxidants, temperature, pressure, heating and fuel characteristics (composition, water content, grain size distribution). The technology can handle a broad range of biomass flows, but for the stability of the process the input needs to be as homogeneous as possible in terms of C-H ratio, water content, ashes and mineral content.

There are four main technology principles that determine the applied reactor types: counter current fixed bed reactors, co-current fixed bed reactors, (circulating) fluidized bed reactors, and entrained flow gasifiers.

Key Performance Indicators (KPIs)

Technological		Economic				Environmental	
		Year	Base year (2019 - 2034)	2030	2050		
TRL (scaled to Nth of a kind)	6-7	Equipment Cost (M€)				Water consumption (m^3/GJ)	
Round trip efficiency (%)	65	CAPEX (M€)	6,597,222		1,736,111	Water withdrawal (m^3/GJ)	
Capacity (TJ/y)	37.5	Annualized CAPEX (M€/y)	0.53	0.00	0.14	Heat (MJ/GJ)	
Capacity (ktonne/y)	0.3125	Annualized CAPEX (€/GJ)	0.014	0.000	0.004	Electricity (kWh/GJ)	
Capacity (ktonne H_2-eq/y)	0.3125	Annualized CAPEX (€/kg H_2-eq)	1.69		0.45	GHG emissions (kg CO_2-eq/GJ)	
Product concentration, purity (wt.%)	99.9	OPEX (M€/y)	10.00%	6.9%	5.0%	Land footprint (m^2/GJ)	
Volumetric energy density (GJ/m^3)		OPEX (€/GJ)	0.0014	0.0000	0.0002		
Losses during storage (%)	0	OPEX (€/kg H_2-eq)	0.169	0.000	0.022		

Notes:

- TRL: demonstration in operational environments available. Product purity: depending on gas purification specs of the plant

- Round trip efficiency: 75-90% thermal efficiency for conversion to syngas; 65% overall efficiency due to pre- and postconditioning steps (e.g. torrefaction, purification etc)
- Capacity: 1000 kg/day; 7500 hours/year -> 0.3125 ktonne/year -> LHV = 120 MJ/kg -> 37.5 TJ/year
- Capex (base year) for 1000kg/day ->1,389 kW H_2 output -> @80% thermal efficiency =1,736 kWth_input -> 3800 €/kW$_{th_input}$ = €6,597,222
- Capex(2050) for 1000kg/day ->1,389 kW H_2 output -> @80% thermal efficiency =1,736 kW$_{th_input}$ -> 1000 €/kW$_{th_input}$ (ambitious) = €1,736,111.
- Annualized capex is calculated with a plant lifetime of 20 years and a 5% interest rate
- OPEX 10% (6% opex, 4% maintenance)
- Water consumption (depends on technology, but limited), Electricity: substantial, depending on technology); CO_2 is biogenic; land footprint: unknown.

Quality Assessment

The following matrix shows the scores on quality assessment of data inputs and indicators grouped as total system.

Uncertainty for Data Inputs				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	3	3	2	3
Economic	2	2	2	3
Environmental	0	0	0	0

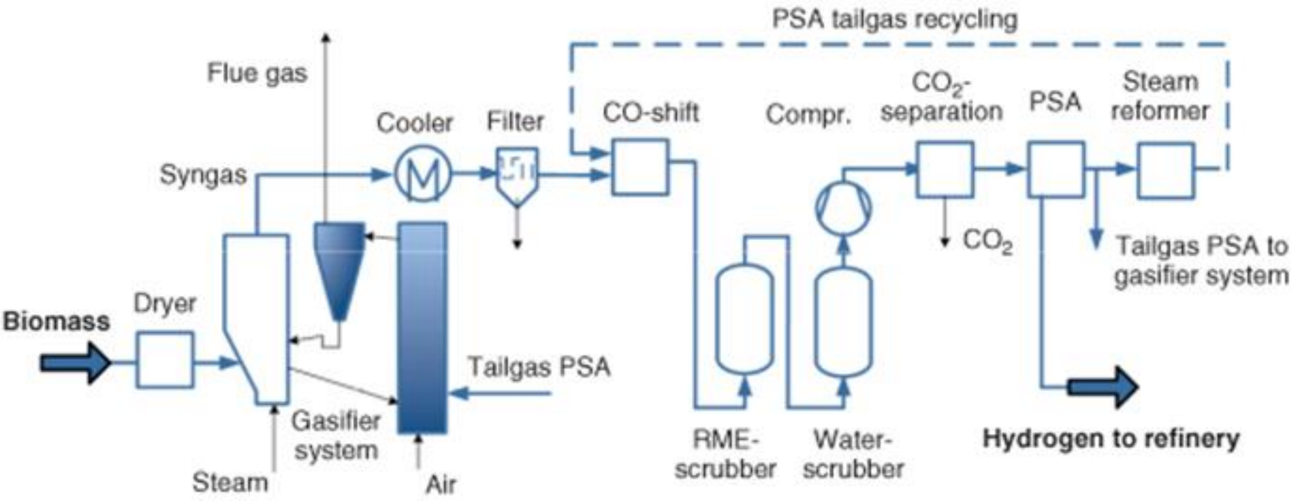
Uncertainty for Key Performance Indicator Outcomes				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	3	3	2	3
Economic	2	2	2	3
Environmental	0	0	0	0

Notes:

- Same assessment for data input and KPIs. Use 0 when no data is available.

- Technical data is available for, but given TRL level still not at quality levels; rated at 3. For economic factors even more uncertainty (hence 2).

Process flow diagram



Risks and opportunities

	Risks	Opportunities
Technological	There is a question of whether there is enough biomass for large production.	
Economic	Competition with other applications of biomass (feed, food, fuel).	Create valuable products (CO/H_2/C) from biomass.
Political		
Social		
Environmental		Biomass gasification with ccs -> negative CO_2 emissions.

References:

- Element Energy Ltd. (2018). Hydrogen supply chain evidence base, Nov 2018.
- Rauch, R. (2013). Biomass gasification for synthesis gas production and applications of syngas.

P10: Overview production of H_2 as a by-product

Data sheet prepared by/owner: Albert van den Noort & Nicolien van der Sar, Gasunie

Data sheet reviewed by: Jonathan Moncada & Andrea Ramirez, Delft University of Technology

Technology Description: There are a number of chemical processes that produce hydrogen as a byproduct. The Roads2Hy study made an inventorisation of the quantities of hydrogen in these processes that have no further use in the process or on the site. Only this category can be made available for other applications such as fuel cell electric vehicles.

The major processes that produce hydrogen as a byproduct are:

1. Chlorine production (electrolysis of NaCl to Cl_2, NaOH and H_2): 270 m^3 H_2/t chlorine in state-of-the-art electrolysers
2. Ethylene production (190 m^3 H_2/t ethylene)
3. Acetylene production (approx 3500 m^3 h_2/t acetylene)
4. Cyanide production (BMA process, 2470 m^3 H_2/t HCN)
5. Styrene production (220 m^3 H_2/t of styrene)
6. Coke oven (450 m^3 H_2/t of product)

Key Performance Indicators (KPIs)

Technological		Economic				Environmental	
		Year	**Base year (2019 - 2034)**	**2030**	**2050**		
TRL (scaled to Nth of a kind)	9	Equipment Cost (M€)				Water consumption (m^3/GJ)	not relevant
Round trip efficiency (%)	not relevant	CAPEX (M€)				Water withdrawal (m^3/GJ)	not relevant
Capacity (TJ/y)	16,488	Annualized CAPEX (M€/y)				Heat (MJ/GJ)	not relevant
Capacity (ktonne/y)	137	Annualized CAPEX (€/GJ)				Electricity (kWh/GJ)	not relevant
Capacity (ktonne H_2-eq/y)	137	Annualized CAPEX (€/kg H_2-eq)				GHG emissions (kg CO_2-eq/GJ)	not relevant
Product concentration, purity (wt.%)	Varies	OPEX (M€/y)				Land footprint (m^2/GJ)	not relevant
Volumetric energy density (GJ/m^3)		OPEX (€/GJ)					
Losses during storage (%)		OPEX (€/kg H_2-eq)					

Notes:

- H_2 as by-product is difficult to quantify in terms of CAPEX and OPEX. The hydrogen is in principal a waste stream, with a certain waste stream value depending on the (local) demand.
- Capacity estimates for the Netherlands:
  - Chlorine production capacity: 583.000 m^3 H_2/day
  - Ethylene production capacity: 2.000.000 m^3 H_2/day

  - Styrene production capacity: 1.225.000 m^3 H_2/day
- Total production capacity as by-product = 4.187.000 m^3 H_2/day = 1.5 E9 m^3/year = 1.5 bcm/year
- With lower heating value (10,78852 MJ/m^3) and density (0.089941) this is equal to 16488 TJ/y and 137 ktonne/y
- Environmental KPIs are not relevant because impacts are associated to the main product and not hydrogen as a byproduct

Quality Assessment

The following matrix shows the scores on quality assessment of data inputs and indicators grouped as total system.

Uncertainty for Data Inputs				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	3	3	2	1
Economic	3	0	2	1
Environmental				

Uncertainty for Key Performance Indicator Outcomes				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	3	3	2	1
Economic	3	0	2	1
Environmental				

Notes:

- Same assessment for data input and KPIs.
- Rated at 3 where technical data is available. For economic factors, empirical data is not available because of different processes; capacities are listed (3). Method and proxy are 3 and 2.

Risks and opportunities

	Risks	Opportunities
Technological	Quality of H_2 depends on main product route.	
Economic	Quantities dependent on production of the main products.	H_2 is the byproduct which could be valorized if enough demand (otherwise it should be vented/flared).
Political		
Social		
Environmental		Valorization of byproducts lowers the emissions of the main product process.

References:

- Roads2Hy.com (2007). Deliverable 2.1:: PART II: Industrial surplus hydrogen and markets and production

P11: Low TRL production methods

Data sheet prepared by/owner: Albert van den Noort & Nicolien van der Sar, Gasunie

Data sheet reviewed by: Jonathan Moncada & Andrea Ramirez, Delft University of Technology

Technology Description: Besides the mean stream production technologies for hydrogen, new novel production methods are being developed. These methods are still at low TRLs. This datasheet is generated to keep these technologies in the back of our minds and monitor them in the future, and not to give a full description of the technologies. KPIs are difficult to get at this stage.

The list of technologies is:

1. Methane/biomass pyrolysis: direct conversion of biomass or methane into hydrogen and carbon, using

2. Plasma water splitting: production of hydrogen from water using a plasma (lab scale; Differ)

3. Solid oxide electrolysis: electrolysis with a solid oxide membrane. Operates at high efficiency and high temperatures; currently at lab scale

Key Performance Indicators (KPIs)

Technological		Economic				Environmental	
		Year	Base year (2019 - 2034)	2030	2050		
TRL (scaled to Nth of a kind)	1-4	Equipment Cost (M€)				Water consumption (m^3/GJ)	
Round trip efficiency (%)		CAPEX (M€)				Water withdrawal (m^3/GJ)	
Capacity (TJ/y)		Annualized CAPEX (M€/y)				Heat (MJ/GJ)	
Capacity (ktonne/y)		Annualized CAPEX (€/GJ)				Electricity (kWh/GJ)	
Capacity (ktonne H_2-eq/y)		Annualized CAPEX (€/kg H_2-eq)				GHG emissions (kg CO_2-eq/GJ)	
Product concentration, purity (wt.%)		OPEX (M€/y)				Land footprint (m^2/GJ)	
Volumetric energy density (GJ/m^3)		OPEX (€/GJ)					
Losses during storage (%)		OPEX (€/kg H_2-eq)					

Notes:

- TRL levels are low; technologies are at most on pilot level. It is therefore difficult to give realistic CAPEX/OPEX and other data.

Conversion

C1: High-pressure H_2

Data sheet prepared by/owner: Frames

Data sheet reviewed by: Jonathan Moncada & Andrea Ramirez, Delft University of Technology

Technology Description: Hydrogen compression is a known technology at high TRL level. The main application has been in the refinery sector. It is done using a compressor with an after cooler. Most often the reciprocating piston type is used. New developments include the ionic liquid piston type compressor, electrochemical compressor using membrane electrode assemblies and the guided rotor compressor.

This data sheet is based on reciprocating piston type compressors, non-lubricated type to avoid oil contamination.

Key Performance Indicators (KPIs)

Technological		Economic				Environmental	
		Year	Base year (2019 - 2034)	2030	2050		
TRL (scaled to Nth of a kind)	9	Equipment Cost (M€)	1.04			Water consumption (m^3/GJ)	0.42
Round trip efficiency (%)	96.8%	CAPEX (M€)	2.61			Water withdrawal (m^3/GJ)	0
Capacity (TJ/y)	476	Annualized CAPEX (M€/y)	2.10E-01			Heat (GJ/GJ)	0
Capacity (ktonne/y)	4	Annualized CAPEX (M€/GJ)	4.40E-07			Electricity (kWh/GJ)	100
Capacity (ktonne H_2-eq/y)	NA	Annualized CAPEX (M€/kg H_2-eq)	N/A			GHG emissions (kg CO_2-eq/GJ)	6.21
Product concentration, purity (wt.%)	99.99%	OPEX (M€/y)	2.25E-01			Land footprint (m^2/GJ)	0.00021
Volumetric energy density (GJ/m^3)	0.756	OPEX (M€/GJ)	4.73E-07				
Losses during storage (%)	0%	OPEX (M€/kg H_2-eq)	N/A				

Notes:

- Eq. Cost based on 2 x 50% compressor units
- Input boundary conditions: pressure 20 bar; purity 99.99%
- Plant availability 95%; 0.04 EUR / kWh; 20 years depreciation, MAINTEX = 2% of CAPEX

- Roundtrip efficiency calculated based on total energy consumption of 260kW per compressor (excluding cooling); energy density of 1 kg H_2 equals 119.96 MJ
- 2030 and 2050 CAPEX and OPEX are estimated based on improved process design and larger plant as per IDEALHY Plant
- CAPEX based on Langfactor of 2.5
- CO_2 emission based on 0.592 kg CO_2 per kWh
- No after cooling considered, H_2 output at 119 deg C

Quality Assessment

The following matrix shows the scores on quality assessment of data inputs and indicators grouped as total system.

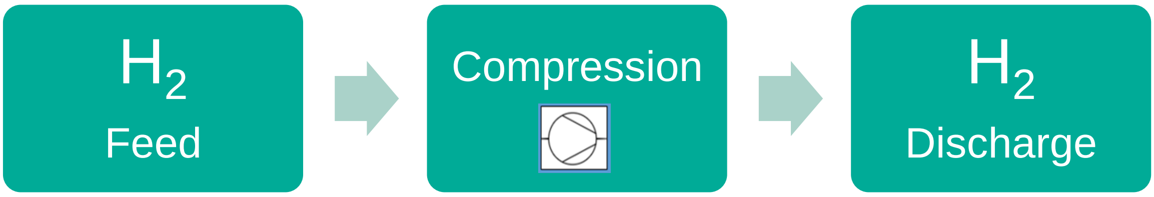
Uncertainty for Data Inputs				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	3	3	3	2
Economic	3	2	2	2
Environmental	3	3	2	2

Uncertainty for Key Performance Indicator Outcomes				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	3	3	3	3
Economic	3	3	3	2
Environmental	3	3	3	2

Notes:

- Compression is considered a mature technology for hydrogen as well as for other gases. Sources for data inputs and key performance indicators are readily available therefore level 3 is generally selected. Some educated assumptions have been made for the For the uncertainty for data inputs on an economic and environmental level and therefore level 2 has been assigned here.

Process flow diagram



Risks and opportunities

	Risks	Opportunities
Technological	Conventional compression technologies require a high degree of operational maintenance, more stringent standards to adhere to, and depending on desired outlet pressure additional cooling/flow control.	New technologies(ionic compression / electrochemical compression) are being developed and gradually penetrating the market.
Economic	Discharge pressure is a significant driver in the costs of hydrogen compression.	Alternatives for small scale compression are not readily available and alternatives for mid-large scale compression are slowly maturing.
Political	Regulatory aspects (standards/norms) are yet to be clarified to full extent for use of (high pressure) hydrogen.	Universal/national standards for compression of hydrogen (to high pressures) are yet to be defined. Doing so will streamline industry progress.
Social	The perception of society on high pressure gas might negatively impact acceptance of such technologies.	CNG (in mobility and urban areas) is a similar and accepted technology. This could be used as a reference for the implementation of hydrogen.
Environmental	Depending on the technology used, pressurization of hydrogen to high pressure (>500 bar) can be an energy intensive process.	Compressed gaseous hydrogen requires a relatively low amount of energy to store.

References:

- Köhler & Hörter Kompressorsysteme
- Makridis, S. (2016). Hydrogen storage and compression. Methane and Hydrogen for Energy Storage. Retrieved from https://digital-library.theiet.org/content/books/10.1049/pbpo101e_ch1

C2: Liquefied H_2

Data sheet prepared by/owner: Frames

Data sheet reviewed by: Jonathan Moncada & Andrea Ramirez, Delft University of Technology

Technology Description:

Hydrogen liquefaction is used to cryogenically store the hydrogen in liquid form at -253 deg C (ie. 20 K). The technology has been developed since the 19th century. The oldest operating plants date from late seventies and eighties of last century. Capacities of the plants in operation vary from 0.3 to 35 tpd. The market is dominated by the large industrial gas suppliers, like Air Products, Air Liquide, Linde and Praxair. Most of the capacity is installed in North America (approx. 300 tpd), besides some smaller plants in Europe with a total capacity of 25 tpd and Asia (total 31 tpd). Most of the liquefied hydrogen is used in aerospace applications, but also to supply hydrogen to the petroleum industry and other industrial users.

The dominating process technology used in the existing plants is the pre-cooled Claude cycle. The typical total energy consumption is around 12.5 to 15 kWh per kg LH_2. The plants consist of a pre-cooling process to cool hydrogen gas to -193 deg C (mostly with liquid nitrogen) and a hydrogen refrigeration system to further cool hydrogen gas to -251 deg C. The last step always consists of a Joule-Thompson valve to cool down to -253 deg C and consequently liquefy the hydrogen.

The most recent work on future technology is the IDEALHY plant design of 2013 which claims to achieve a typical power consumption of less than 6.3 kWh/kg, based on a pre-cooling with a mixed refrigerant to 130 K and two subsequent Brayton cycles (with a mixture of helium and neon called 'Nelium') to cool to 26.8 K. However this process, nor the individual process steps have been demonstrated.

Important aspect of the technology is the para ratio of Hydrogen to minimize boil-off. Typical para-H_2 rates of commercial plants are 95%, IDEALHY claims to provide a minimum of 98% p-H_2.

Improvement of the overall efficiency is proposed by some researchers to improve significantly when liquefaction plant is coupled to LNG regasification plant. Not further considered in this data sheet.

Key Performance Indicators (KPIs)

Technological		Economic				Environmental	
		Year	**Base year (2019 - 2034)**	**2030**	**2050**		
TRL (scaled to Nth of a kind)	9	Equipment Cost (M€)				Water consumption (m^3/GJ)	0
Round trip efficiency (%)	0.735	CAPEX (M€)	39.6	105		Water withdrawal (m^3/GJ)	0
Capacity (TJ/y)	208	Annualized CAPEX (M€/y)	4.7	12.3		Heat (GJ/GJ)	0
Capacity (ktonne/y)	1.8	Annualized CAPEX (€/GJ)	0.0000224	0.0000415		Electricity (kWh/GJ)	100
Capacity (ktonne H_2-eq/y)	N/A	Annualized CAPEX (€/kg H_2-eq)	N/A	N/A		GHG emissions (kg CO_2-eq/GJ)	44.7
Product concentration, purity (wt.%)	0.9999	OPEX (M€/y)	6.4	16.26		Land footprint (m^2/GJ)	0.0902
Volumetric energy density (GJ/m^3)	8.5	OPEX (€/GJ)	0.0000307	0.0000547			
Losses during storage (%)	0.0006	OPEX (€/kg H_2-eq)	N/A	N/A			

Notes:

- 5 TPD unit considered with 12 kWh/kg LH_2 total energy consumption.
- Input boundary conditions: pressure 20 bar; purity 99.99%
- Plant availability 95%; 0.05 EUR / kWh; 20 years depreciation, i = 10%
- Round trip efficiency calculated based on total energy consumption of 12 kWh/kg equals 43.2 MJ/kg LH_2 and energy density of 1 kg equals 119.96 MJ

- 2030 CAPEX and OPEX are estimated based on improved process design and larger plant as per IDEALHY Plant (50 TPD) with target of 6.76 kWh/kg LH_2 total energy consumption
- 0.596 kg CO_2 / kWh electricity

Quality Assessment

The following matrix shows the scores on quality assessment of data inputs and indicators grouped as total system.

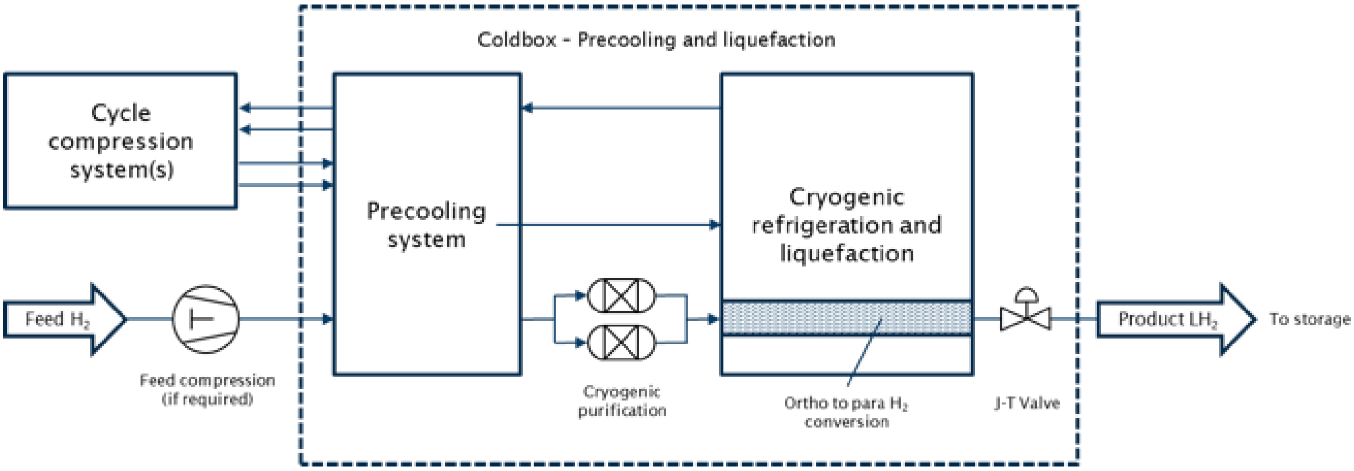
Uncertainty for Data Inputs				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	2	2	3	2
Economic	2	2	2	2
Environmental	2	2	2	2

Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	2	2	3	2
Economic	2	2	2	2
Environmental	2	2	2	2

Notes:

- Liquefaction does not score high in the proxy because the figures used are derived from a small amount of small scale plants.
- These plants rely on relatively 'old' technology and do not provide a solid basis for a scaled up liquefaction plant. These small scale however do provide numbers to base upscaling of the liquefaction on, which makes for a higher technical scoring.
- Empirical data for Liquefaction does not score high as well because most figures are derived from modeled processes for large scale and some measurements are taken from the small scale plants.
- Economic/environmental scoring is based on the above mentioned models.

Process flow diagram



Risks and opportunities

	Risks	Opportunities
Technological	Large scale liquefaction requires new concepts for hydrogen precooling and cryogenic cooling and liquefaction. These technologies are still in the early phase (low TRL) and require significant improvements of compressors, expanders and heat exchangers due to sealing and material embrittlement. Also ortho-para conversion takes a lot of energy which has a great effect on the overall efficiency. Slurry hydrogen has only reached the desks of the space agencies. at TRL-4. It requires improvements in the recycling of Helium and upscaling.	Large scale liquefaction plants are still in the design phase with many studies indicating that energy efficiency can be improved substantially. An energy consumption of 6 kWh per kg LH_2 should be achievable. Cooling the hydrogen further down to a level of 14K will form a slurry of hydrogen which increases the density by 20%.
Economic	Currently 30% of the input energy is used to liquefy the hydrogen. To reach cost per kg LH_2 which are of interest to be used at large scale, large investments in plants are required.	Liquid H_2 is easy to transport in large quantities as it has a relatively high density. Somes studies suggest to install a liquefaction plants near aLNG regasification plant to reduce the energy required during the pre-cooling process.
Political	As with other hydrogen (storage) related technologies, certification and regulation is unclear concerning handling liquid hydrogen.	N/A

Social	Proving to the public that working with large scale liquefaction plants is safe is a challenge as there is no large scale plant available for reference.	Liquefied H_2 is already being applied in various (small scale) plants around the world, making its acceptance to the public easier.
Environmental	Liquefaction is currently a very energy consuming process.	The process can be made 100% CO_2 neutral by using the feed green hydrogen as an energy source for the plant.

References:

- Madison, U. Cardella (2017) Final design of a cost-optimized 100 tpd H_2 liquefier. CEC 2017.
- K. Ohlig and L.Decker (2014) The Latest Developments and Outlook for Hydrogen Liquefaction Technology. Advances in Cryogenic Engineering.
- H. Rezaie, M. Ziabasharhagh, M. Mafi (2016) A review of hydrogen liquefaction, current situation and its future. International Conference on Engineering and Applied Sciences, Dubai.
- J. Eckroll (2017) Concepts for Large Scale Hydrogen Liquefaction Plants. Master of Energy and Environmental Engineering.
- U Cardella, L. Decker and H Klein,I OP (2017) Economically viable large-scale hydrogen liquefaction. Conf. Series: Materials Science and Engineering.
- K. Stolzenburg and R. Mubbala, 2013. Integrated Design for Demonstration of Efficient Liquefaction of Hydrogen (IDEALHY), Fuel Cells and Hydrogen Joint Undertaking (FCH JU).
- U Cardella, L. Decker and H Klein (2017) Roadmap to economically viable hydrogen liquefaction. International Journal of Hydrogen Energy.
- Liquefaction and Pipeline Costs (2007) Hydrogen Delivery Analysis Meeting.
- Yang, C., & Ogden, J. (2007). Determining the lowest-cost hydrogen delivery mode. International Journal of Hydrogen Energy, 32(2), 268-286

C3a: NH_3 - small scale

Data sheet prepared by/owner: Bob Weehuizen, Proton Ventures BV

Data sheet reviewed by: Jonathan Moncada & Andrea Ramirez, Delft University of Technology

Technology Description: At the moment the worldwide production of ammonia is app. 180 million ton/year. 85 to 90% of this production finds his way direct or indirect into the fertilizer market. Other applications are DeNox and as a chemical precursor. A second big application will be as an energy storage medium and as a fuel.

Most of the ammonia is produced in world scale plants with capacities of more than .5 million ton per year. Decentralized small scale production will grow because of the high transport/storage cost, availability of cheap feedstock and the fit with renewable energy. Renewable energy and the availability of electrolysers give production quantities between 1 and 20 MT/year of ammonia.

Ammonia is already more than 100 years mainly produced by the so called Haber-Bosch process. This process is optimized to a high level. The production of ammonia from hydrogen and nitrogen is an exothermic reaction.

Because there is a big difference between a small and big plant the KPIs of ammonia will be given for a production of 20.000 and 1 million MTon per year. This data sheet covers the small-scale conversion.

Key Performance Indicators (KPIs)

Technological		Economic				Environmental	
		Year	**Base year (2019 - 2034)**	**2030**	**2050**		
TRL (scaled to Nth of a kind)	9	Equipment Cost (M€)	1			Water consumption (m^3/kg NH_3)	0
Round trip efficiency (%)	75 (1)	CAPEX (M€)	13(4)			Water withdrawal (m^3/kg NH_3)	0
Capacity (TJ/y)	372 (2)	Annualized CAPEX (M€/y)	0.87(5)			Heat (MJ/kg NH_3)	18.6
Capacity (ktonne/y)	20	Annualized CAPEX (€/H_2)	0.25			Electricity (kWh/kg FA)	1.3
Capacity (ktonne H_2-eq/y)	4	Annualized CAPEX (€/kg H_2-eq)				GHG emissions (kg CO_2-eq/kg NH_3)	0
Product concentration, purity (wt.%)	>99.9	OPEX (M€/y)	3 (6)			Land footprint (m^2/Mkg NH_3) (7)	75
Volumetric energy density (GJ/m^3)	14.3 (3)	OPEX (€/kg H_2)	0.85				
Losses during storage (%)	0	OPEX (€/kg H_2-eq)					

Notes:

- (1) We define the roundtrip efficiency for the process to produce ammonia and crack it back to hydrogen. The production of the hydrogen is not taken into account. The ammonia synthesis is an exothermic reaction. The heat that is produced will be used to produce steam. Also important is at what pressure the hydrogen is available. In the process the pressure must be app. 250 bar. For the

20.000 ton/year unit we come to the conclusion that efficiency of the ammonia production is app 100% and for the cracking of the ammonia app. 75%. So totally this will be 75%.

- (2) The LHV of ammonia is 18,6 MJ/kg. With 20.000 ton/year this gives 372.000.000MJ/year or 372 TJ/year.
- (3) Density NH_3: .771 kg/l or .771 ton/m^3.
- LHV: 18.6 MJ/kg. This means 14,3 GJ/m3 NH_3.
- (4) 10 million for the ammonia production unit and 3 million for the cracking equipment.
- (5) Interest 3% and life time 20 years.
- (6) The cost price of the hydrogen is not included because the hydrogen is formed back after cracking. So only energy costs and other OPEX costs are included for example the power cost of producing ammonia (app. 1 million euro) and the heat cost of cracking the ammonia (app. 1.5 million euro) Maintenance costs are app 200.000 euro as well as the personnel costs. The total OPEX are app. 3 million euro per year.
- (7) Footprint 1500 m^2 voor 20.000 ton NH_3/year.

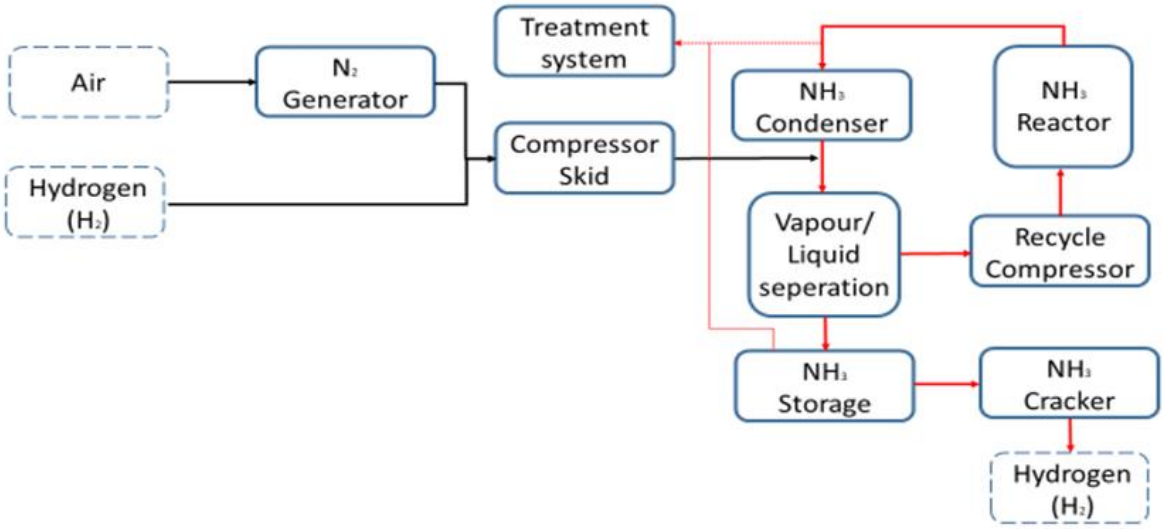
Quality Assessment

The following matrix shows the scores on quality assessment of data inputs and indicators grouped as total system.

Uncertainty for Data Inputs				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	4	4	4	3
Economic	4	4	4	3
Environmental	3	3	3	3

Uncertainty for Key Performance Indicator Outcomes				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	4	4	4	3
Economic	4	4	4	3
Environmental	3	3	3	3

Process flow diagram



References:

- None listed

C3b: NH_3 - large scale

Data sheet prepared by/owner: Emile Herben, Yara

Data sheet reviewed by: Jonathan Moncada & Andrea Ramirez, Delft University of Technology

Technology Description: At the moment the worldwide production of ammonia is app. 180 MTon/year. 85 to 90% of this production finds its way directly or indirectly into the fertilizer market. Other applications are DeNox and as a chemical precursor. A second big application will be as an energy storage medium and as a fuel.

Most of the ammonia is produced in world scale plants with capacities of more than 0.5 million ton per year. Decentralized small scale production will grow because of the high transport/storage cost, availability of cheap feedstock and the fit with renewable energy. Renewable energy and the availability of electrolysers give production quantities between 1 and 20 MT/year of ammonia.

Ammonia has mainly been produced for already more than 100 years via the so called Haber-Bosch process. This process is optimized to a high level. The production of ammonia from hydrogen and nitrogen is an exothermic reaction.

Because there is a big difference between a small and big plant the KPIs of ammonia is given for a production of 20.000 and 1 million MTon per year.

Key Performance Indicators (KPIs)

Technological		Economic				Environmental	
		Year	**Base year (2019 - 2034)**	**2030**	**2050**		
TRL (scaled to Nth of a kind)	9	Equipment Cost (M€)	275			Water consumption (m_3/GJ)	
Round trip efficiency (%)	0.83	CAPEX (M€)	650			Water withdrawal (m^3/GJ)	0
Capacity (TJ/y)	14880	Annualized CAPEX (M€/y)	54.5			Heat (MJ/kg NH_3)	0.1
Capacity (ktonne/y)	800	Annualized CAPEX (€/kg H_2)	0.39			Electricity (kWh/kg NH_3)	3.5
Capacity (ktonne H_2-eq/y)	141	Annualized CAPEX (€/kg H_2-eq)				GHG emissions (kg CO_2-eq/kg NH_3)	0
Product concentration, purity (wt.%)	99.9	OPEX (M€/y)	25			Land footprint (m_2/kg/yr NH_3)	0.00005
Volumetric energy density (GJ/m^3)	14.3	OPEX (€/kg H_2)	0.18				
Losses during storage (%)	0	OPEX (€/kg H_2-eq)					

Notes:

- We have considered here as inputs atmospheric nitrogen and hydrogen and electricity. As outputs only ammonia. In reality, the Haber-Bosch loop is highly heat integrated and a net exporter of energy. The electricity is mainly used for compression of syngas and refrigeration for the NH_3 condenser.
- The capex estimate is just for the Haber-Bosch part.
- The volumetric energy density is assuming NH_3 at room temp and atm pressure.

- The annualized capex assumes 40yr depreciation and 8% interest rate.
- The opex excludes the cost of hydrogen, in order to compare apples-to-apples with other conversion technologies.
- The electricity is assumed to be renewable.
- Although the equipment list is known, it is difficult to identify the individual capacity factors and assumptions to scale each individual equipment.
- The six-tenth rule of thumb is then used

Quality Assessment

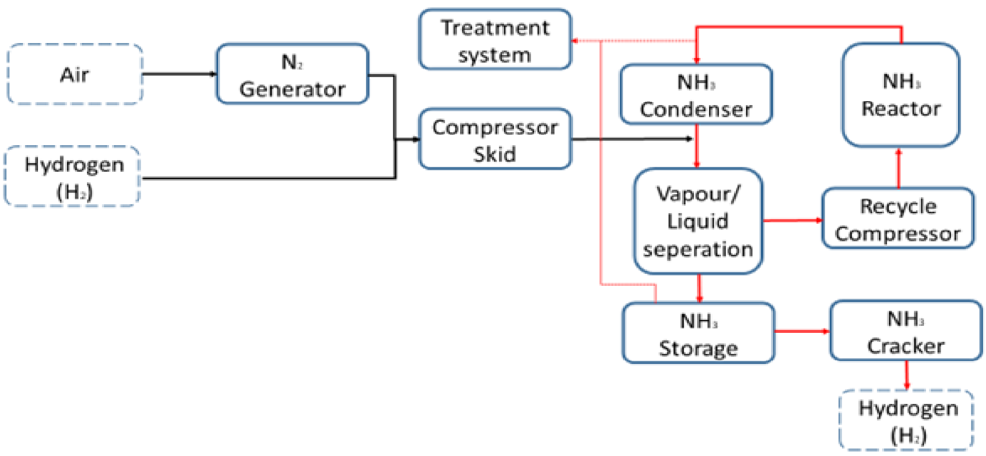
The following matrix shows the scores on quality assessment of data inputs and indicators grouped as total system.

Uncertainty for Data Inputs/KPIs				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	4	4	4	4
Economic	4	3	4	2
Environmental	4	4	4	4

Notes:

- The NH_3 process is very mature and there is a lot of data available. Economic data is restricted because that is often confidential, hence the lower score there.
- The uncertainties for KPIs are the same as for data inputs.

Process flow diagram



Risks and opportunities

	Risks	Opportunities
Technological	Very mature technology, but untested for use with intermittent hydrogen supply.	Mature technology, so this is ready for large scale commercial exploitation today.
Economic	Small scale production is more suited for local stranded supply of renewable hydrogen.	Large scale production brings economies of scale.
Political		There is still a lot of research looking into further improving the energy efficiency of the Haber Bosch process.
Social		
Environmental		

References:

- Yara internal project documentation
- Brown, Trevor (2018). Innovations in ammonia, Ammonia Energy Association, Retrieved from: https://www.4echile.cl/4echile/wp-content/uploads/2018/09/OK_P17_Block-4_Trevor-Brown_AMMONIA.pdf

C4: CH_3OH

Data sheet prepared by/owner: Marija Saric & Yvonne van Delft, ECN part of TNO

Data sheet reviewed by: Jonathan Moncada & Andrea Ramirez, Delft University of Technology

Technology Description: Methanol represents large market, and it is typically produced at the large scale from the syngas mixture (H_2, CO and CO_2). Methanol synthesis from captured CO2 is moving forward: Iceland (Carbon Recycling International, 2019) and Japan have different plants that combine CO_2 and renewable H_2. Carbon Recycling International (CRI) started the operation of the first commercial demonstration plant in Iceland, in 2011, whose aim is to improve plant economics for larger plants and to gain operation expertise. Its capacity is about 5 tMeOH/yr. Mitsui Chemicals Inc., in 2008, built a pilot plant to synthesize MeOH from CO_2 and H_2 in Osaka, with a capacity of around 100 tMeOH/yr. The installation uses CO_2 emitted from factories and H_2 obtained from water photolysis. The purpose of the produced MeOH is to produce olefins and aromatics (Mitsui Chemicals Inc., 2008) . The presence of these plants allow us to conclude a Technology Readiness Level (TRL) of 6–7 for MeOH from CO_2 (European Commission, 2014).

The stoichiometric reaction for MeOH synthesis from CO_2 and H_2 is:

$$3H_2 + CO2 \Leftrightarrow CH_3OH + H_2O$$

CO_2 and H_2 are fed into the plant in a 1:3 ratio and react under 50 to 100 bar pressure and at a temperature of 250 °C.

Key Performance Indicators (KPIs)

Technological		Economic				Environmental	
		Year	**Base year (2019 - 2034)**	**2030**	**2050**		
TRL (scaled to Nth of a kind)	6-7	Equipment Cost (M€)[1]	91 (Pérez-Forte et al. 2016, corrected for 2017)			Water consumption (m^3/GJ)	1.33
Round trip efficiency (%)	83.33%	CAPEX (M€)	203			Water withdrawal (m^3/GJ)	1.36
Capacity (TJ/y)	8756	Annualized CAPEX (M€/y)[2]	16			Heat (MJ/GJ)	79.42
Capacity (ktonne/y)	440 (ref. 4)	Annualized CAPEX (€/GJ)	1.85			Electricity (kWh/GJ)	8.49
Capacity (ktonne H_2-eq/y)	55	Annualized CAPEX (€/kg H_2-eq)	0.29			GHG emissions (kg CO_2-eq/GJ)	4.52
Product concentration, purity (wt.%)	99.9	OPEX (M€/y)[3]	302 (2.95 for utilities)			Land footprint (m^2/GJ)	
Volumetric energy density (GJ/m^3)	15.9	OPEX (€/GJ)	34.53				
Losses during storage (%)	N/A	OPEX (€/kg H_2-eq)	5.49				

Notes:

- [1] Note for H2 is available at 25 bara and CO_2 at 1 bara and they are compressed to 75 bara.
- [2] Assumed 20 years lifetime and 5% interest rate. Capex is in +/- 50% accuracy
- [3] Fixed operating costs from ref 4, assumed variable costs: electricity costs 34 €/MWh, water costs 0.03 €/t, H_2 costs =3.09 €/kgH_2, CO_2 costs =20 €/t CO_2. Use of H2 = 0.199 t/t MeOH, CO_2 = 1.46 t/tMeOH, Electricity = 0.169 MWh/t MeOH, water = 26.39 t/t MeOH. For more details check ref 4. Table 1 and Table 4.

CAPEX as function of capacity

	ktonne/y		M€		M€
Capacity 1	440 (Pérez-Fortes et al., 2016)	Equipment cost 1	91	CAPEX	203
Capacity 2	100 (Szima & Cormos, 2018)	Equipment cost 2	30	CAPEX	56
Capacity 3		Equipment cost 3		CAPEX	

Quality Assessment

The following matrix shows the scores on quality assessment of data inputs and indicators grouped as total system.

Uncertainty for Data Inputs				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	2	2	3	1
Economic	2	2	3	1
Environmental	2	2	3	1

Uncertainty for Key Performance Indicator Outcomes				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	2	2	3	1
Economic	2	2	3	1
Environmental	2	2	3	1

Notes:

- Calculated in flowsheeting model Aspen in detail for all proxy values
- Max. of 4 references available for CO_2 and H_2 feed
- Established methodology
- There is plant running no comparison between model and data from plant available

Process flow diagram

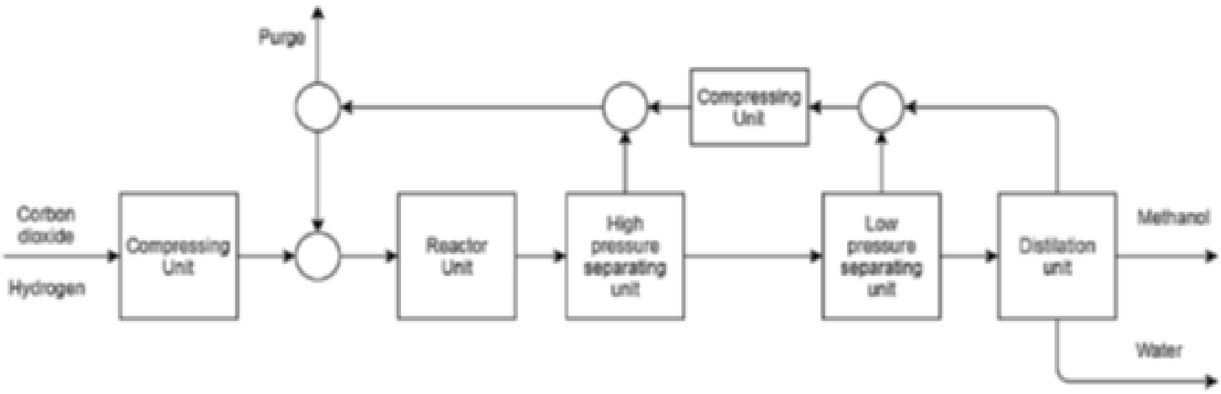


Figure 1. Methanol synthesis unit

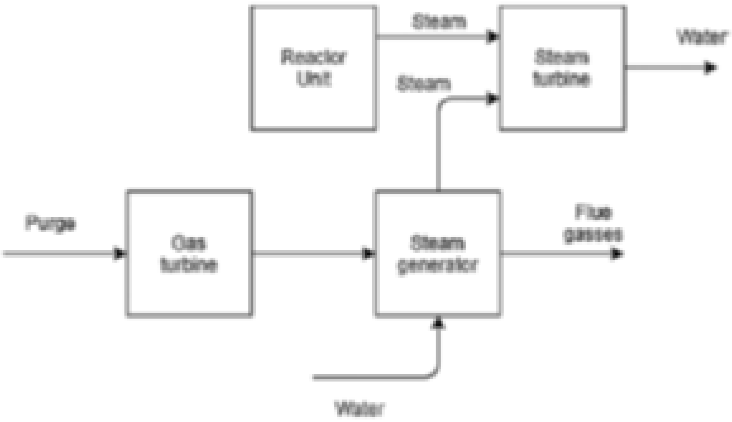


Figure 2. Energy recovery unit

Risks and opportunities

	Risks	Opportunities
Technological		Technology at high TRL level. Not major risks foreseen.
Economic	Cost of product highly dependent on the hydrogen cost.	Growing demand.
Political		Growing interest for CCU.
Social	N/A	N/A
Environmental	N/A	Reduction in total CO_2 emission due to CCU.

References:

- 1) Carbon Recycling International (2019). Products. Retrieved from: http://www.carbonrecycling.is/vulcanol/ , last visit 02.01.2019.
- 2) Mitsui Chemicals Inc. (2008) Mitsui Chemicals to establish a pilot facility to study a methanol synthesis process from CO2. Company webpage. Retrieved from: http://www.mitsuichem.com/release/2008/080825e.htm [last accessed January 2019].
- 3) European Commission. (2014). Horizon 2020 – work programme 2014–2015. General Annexes, European Commission (EC), Brussels. Retrieved from: http://ec.europa.eu/research/participants/data/ref/h2020/wp/2014_2015/annexes/h2020-wp1415-annex-g-trl_en.pdf [last accessed January 2019]

- 4) M. Pérez-Fortes,J. C. Schöneberger, A. Boulamanti, E. Tzimas (2016). Methanol synthesis using captured CO2 as raw material:Techno-economic and environmental assessment, Applied Energy 161 (2016) 718–732.
- 5) S.Szima, C-C.Cormos (2018). Improving methanol synthesis from carbon-free H2 and captured CO2: A techno-economic and environmental evaluation, Journal of CO2 Utilization 24 (2018) 555-563
- 6) D.Bellotti, M.Rivarolo, L.Magistri, A.F.Massardo (2017). Feasibility study of methanol production plant from hydrogen and captured carbon dioxide, Journal of CO2 Utilization 21 (2017) 132-138

C5: CH_4 (synthetic)

Data sheet prepared by/owner: Marija Saric & Yvonne van Delft, ECN part of TNO

Data sheet reviewed by: Jonathan Moncada & Andrea Ramirez, Delft University of Technology

Technology Description:

Synthetic natural gas is produced by CO_2hydrogenation via Sabatier reaction:

$$CO_2 + 4H_2 \leftrightarrow CH_4 + 2H_2O \quad \Delta H = -164.9 \text{ kJ/mol}$$

This reaction is highly exothermic and it is carried out at the pressures of typically 1 -100 bar. The reaction is carried out in the series of adiabatic reactors with intermediate cooling. Typical inlet temperature to the reactor is 250 -550 °C. The large scale methanation plants are commercialised. The example is a Great Plains Synfuels Plant by the Dakota Gasification Company began production in 1984 with a subsequent capacity of 1,900 MW SNG (ref. 1). Smaller units (several MW's) are not available off the shelf.

Key Performance Indicators (KPIs)

Technological		Economic				Environmental	
		Year	**Base year (2019 - 2034)**	**2030**	**2050**		
TRL (scaled to Nth of a kind)	8-9	Equipment Cost (M€)	4.68 (ref. 2-5)	Water consumption (m^3/GJ)	-	8-9	Equipment Cost (M€)
Round trip efficiency (%)	84% (ref. 2)	CAPEX (M€)	10.02	Water withdrawal (m^3/GJ)	1.3	84% (ref. 2)	CAPEX (M€)
Capacity (TJ/y)	459.3	Annualized CAPEX (M€/y)	0.8	Heat (MJ/GJ)	-	459.3	Annualized CAPEX (M€/y)
Capacity (ktonne/y)	9.23	Annualized CAPEX (€/GJ)	1.74	Electricity (kWh/GJ)	15.56	9.23	Annualized CAPEX (€/GJ)
Capacity (ktonne H_2-eq/y)	2.3	Annualized CAPEX (€/kg H_2-eq)	0.34	GHG emissions (kg CO_2-eq/GJ)	?	2.3	Annualized CAPEX (€/kg H_2-eq)
Product concentration, purity (wt.%)	97.9	OPEX (M€/y)	17.9 (2.43 utilities)	Land footprint (m^2/GJ)		97.9	OPEX (M€/y)
Volumetric energy density (GJ/m^3)	1.8 for CH_4 at 50 bar	OPEX (€/GJ)	39			1.8 for CH_4 at 50 bar	OPEX (€/GJ)
Losses during storage (%)	N.A.	OPEX (€/kg H_2-eq)	7.76			N.A.	OPEX (€/kg H_2-eq)

Notes:

- Assumed methanation operation at 70 bar.
- Assumed 8000 operating hours.
- 20 years lifetime, 5% interest rate.
- $H_2$and $CO_2$are compressed from atmospheric pressure to methanation pressure of 70 bar.
- Fixed operating costs from ref. 2. Variable costs: electricity costs 34 €/MWh, water costs 0.03 €/t, H_2 costs =3.09 €/kgH_2, CO_2 costs =20 €/t CO_2. Use of H_2 = 0.5 t/t CH_4, CO_2= 2.75 t/t CH_4.

CAPEX as function of capacity

	ktonne/y		M€		M€
Capacity 1	979 (ref. 6)	Equipment cost 1		CAPEX	315
Capacity 2	0.6 (ref. 2)	Equipment cost 2		CAPEX	1.2
Capacity 3		Equipment cost 3		CAPEX	

Notes:

- Information on CO/CO2 used for only CO2 feedstock. Influence on the reaction kinetics did not taken into account.

Quality Assessment

The following matrix shows the scores on quality assessment of data inputs and indicators grouped as total system.

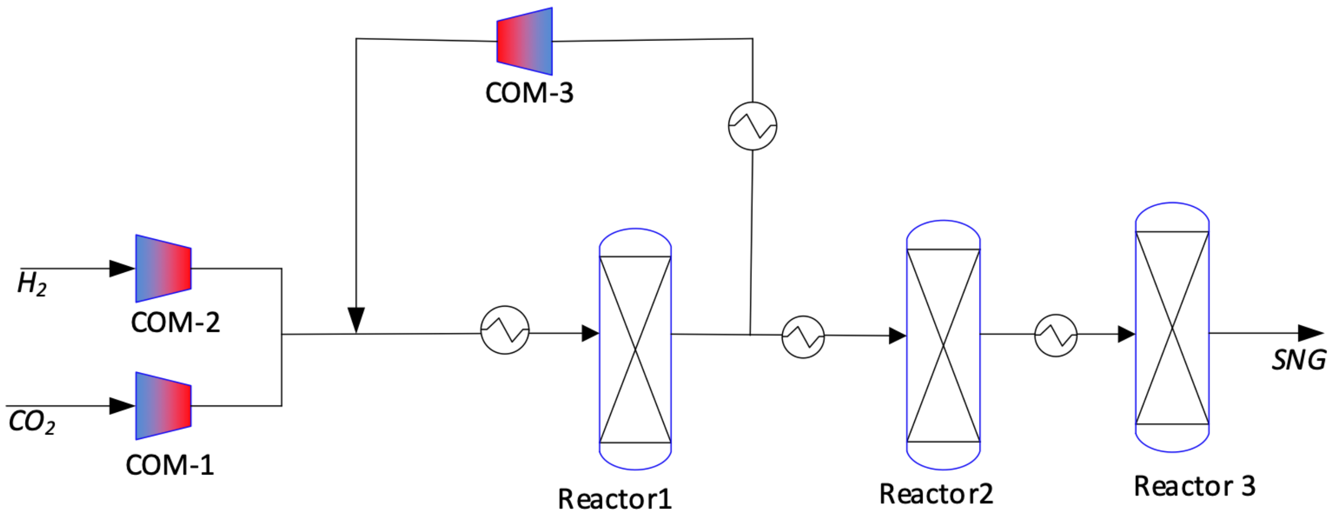
Uncertainty for Data Inputs				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	3	3	3	3
Economic	2	2	3	3
Environmental	1	1	1	1

Uncertainty for Key Performance Indicator Outcomes				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	3	3	3	3
Economic	2	2	3	3
Environmental	1	2	1	1

Notes:

- 5-6 references found
- Costs compared with plants in operation
- CO_2 emissions depend on application. Direct CO_2 emissions calculated from Aspen Plus simulation model
- Costs compared with plant in operation.

Process flow diagram



Risks and opportunities

	Risks	Opportunities
Technological		No major risks foreseen. Mature technology
Economic	Low current prices of NG	Infrastructure already exists
Political	N.A.	Interest for CCU
Social		Abandoning of using Natural Gas heating in households.
Environmental		Lower CO_2 emissions than CCU.

References:

- Great Plains Synfuels Plant (2019). Thriving in uncertainty. Retrieved from http://www.rmcmi.org/docs/default-source/default-document-library/mike-just--thriving-in-uncertain-times.pdf?sfvrsn=0
- DNV KEMA Energy & Sustainability (2013). Systems Analyses Power to Gas Deliverable 1: Technology Review
- Carbo, Smith, (2010). SNG production for GdF Suez, SNG feasibility case for 20 MWth commercial plant, ECN-X--10-032
- Leatherman (2008). The case for synthetic natural gas from coal. Presented at the 25th annual International Pittsburgh Coal Conference.
- Hansen (2009). Presentation from John Bøgild Hansen, Haldor Topsøe., IEA-meeting 13-15 Mei 2009 Karlsruhe
- Smit (2012). The Economy of Large Scale Biomass to Substitute Natural GaS (SNG), ECN-E--12-007

C6: LOHC (Hydrogenation)

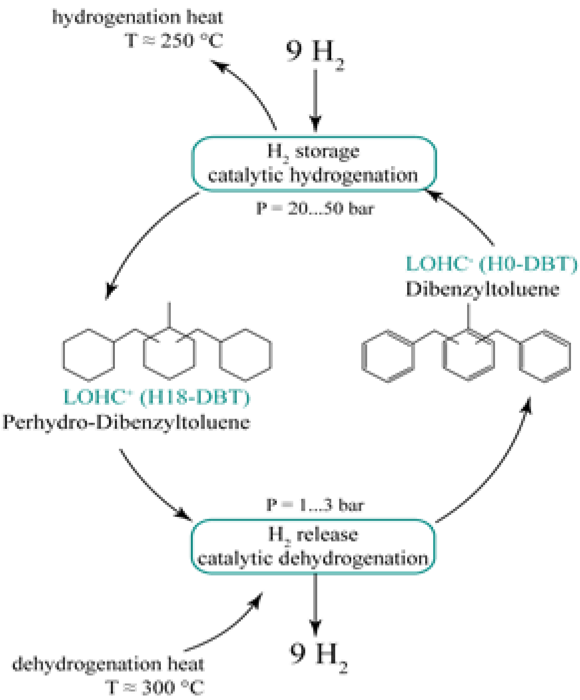
Data sheet prepared by/owner: Tim Lauret, Frames

Data sheet reviewed by: Jonathan Moncada & Andrea Ramirez, Delft University of Technology

Technology Description: The LOHC technology is based on the reversible catalytic hydrogenation and dehydrogenation of an organic carrier oil (in this case Dibenzyltoluene (DBT)).

The LOHC-technology is described by three steps:

1. In the hydrogen storage process, DBT is loaded with 9 molecules of hydrogen in a catalytic hydrogenation process, which results in a hydrogen storage density of 6,23 wt.% (57 kg /m³). This volumetric storage density is comparable to high pressure storage at >1,200 bar. The hydrogenation process runs at 25 to 50 bar and ~250 °C. Due to the exothermy of the reaction, 8 kWh_{th}/kg_{H2} of usable heat is released during the process.
2. During the storage/transport step the hydrogenated DBT can be stored and transported at ambient conditions in today's fossil fuel infrastructure. Due to the lack of high pressures and low temperatures the LOHC can be handled very conveniently.
3. The hydrogen release process is an endothermic reaction requiring 11 kWh_{th}/kg_{H2} of thermal energy input, at a temperature level of ~300 °C. After dehydrogenation, the unloaded DBT can be reused as hydrogen carrier. Due to its high temperature stability, DBT exhibits high cycle and long-term stability.



Key Performance Indicators (KPIs)

Technological		Economic				Environmental	
		Year	**Base year (2019 - 2034)**	**2030**	**2050**		
TRL (scaled to Nth of a kind)	7	Equipment Cost (M€)	2.4	1.65		Water consumption (m^3/GJ)	-
Round trip efficiency (%)	99%	CAPEX (M€)	4	2.2		Water withdrawal (m^3/GJ)	1.8
Capacity (TJ/y)	215.98	Annualized CAPEX (M€/y)	0.32	0.18		Heat (GJ/GJ)	-0.24
Capacity (ktonne/y)	31.6	Annualized CAPEX (M€/GJ)				Electricity (kWh/kg H_2-eq)	< 1
Capacity (ktonne H_2-eq/y)	1.8	Annualized CAPEX (M€/kg H_2-eq)	0.000000178317	0.0000000980743		GHG emissions (kg CO_2-eq/GJ)	
Product concentration, purity (wt.%)	99.999	OPEX (M€/y)	0.28	0.23		Land footprint (m^2)	50
Volumetric energy density (GJ/m^3)	6.8	OPEX (M€/GJ)					
Losses during storage (%)	0	OPEX (M€/kg H_2-eq)	0.000000155556	0.000000127778			

Notes:

- Capacity: StoragePLANT 5 tonnes per day of hydrogen storage.
- The storage of 1,8 kt/y of hydrogen leads to a loaded DBT amount of 31,6 ktonne/y.
- Density: 57kg H_2/m^3 LOHC.
- Annualized capex calculated for a period of 20 years and interest rate of 5%.
- OPEX is including utilities, service maintenance and labor costs, but excluding raw costs of hydrogen.
- Electricity price: 0,10€/kWh.

- Water withdrawal: Water for cooling purposes is not consumed, but circulated in a closed process steam cycle.
- Heat: Exothermic hydrogenation, which is producing 8 kWh/kg H_2-eq. This positive effect therefore leads to a negative value.

CAPEX as function of capacity

	ktonne/y		M€		M€
Capacity 1	1.8	Equipment cost 1	2.4	CAPEX	4
Capacity 2	4.32	Equipment cost 2	4.5	CAPEX	6
Capacity 3		Equipment cost 3		CAPEX	

Equipment	ktonne/y	Scaling factor
Reactor	1.8	0.6
Catalyst	1.8	0.99
Vessels, pumps, fittings, piping	1.8	0.3
Thermal heat unit	1.8	0.3

Notes:

- Hydrogenation
- Data based on known cost data of today (see Technology KPIs for target costs)

Quality Assessment

The following matrix shows the scores on quality assessment of data inputs and indicators grouped as total system.

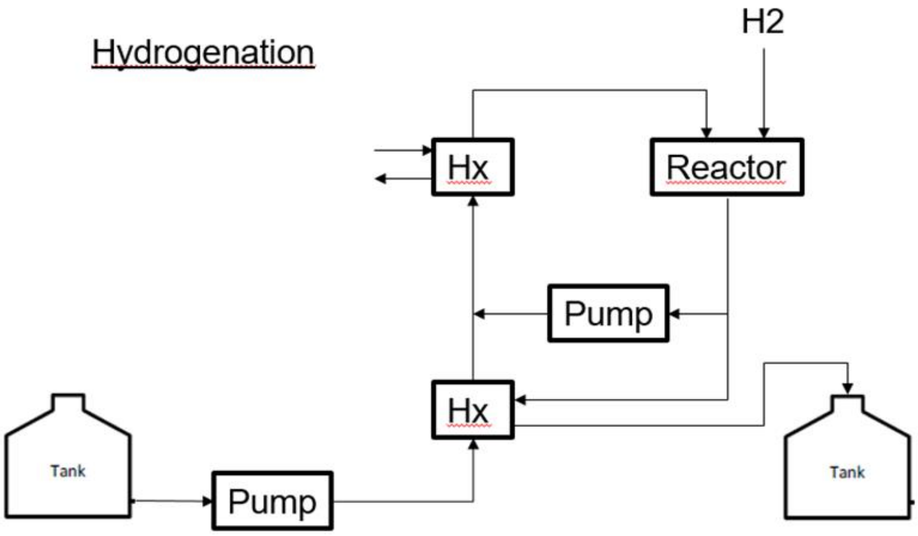
Uncertainty for Data Inputs				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	4	4	3	2
Economic	4	3	3	3
Environmental	4	4	3	2

Uncertainty for Key Performance Indicator Outcomes				
Areas	Proxy	Empirical basis	Methodological rigour	Validation process
Technical	4	4	3	2
Economic	4	4	2	2
Environmental	4	4	3	2

Notes:

- LOHC scores high in the indicator proxy because only directly measured values are used in technical and economic models.
- Empirical data is excellent for Technical and Environmental since values stem from focused experiments and direct measurements. Economic relies on historic data.
- Models use common approaches.
- Validation process of LOHC scores medium because there are not independent studies to compare with.

Process flow diagram



Notes:

- The main stream starts at the tank on the left with unloaded LOHC which is pumped through the reactor circuit to be loaded with H2 and stored as loaded
- LOHC in the tank on the right

Risks and opportunities

	Risks	Opportunities
Technological	The hydrogen released from the dehydrogenation unit might not comply with the required quality standards, preventing the use at a e.g. HRS Mitigation: Hydrogen released from DBT already has a purity of >99,9%, which is significantly higher than purity of other industrial raw hydrogen sources. Purification technology is well established in industrial settings and if needed, purification technology included in the system can therefore be extended to meet requirements. Dependence on external feedstocks: LOHC production is currently dependent on the supply of toluene. But LOHC faces only minor wear. Thus, toluene has only indirect influence.	The aspect of safety becomes even more relevant than today due to increasing volumes of hydrogen in a semi-public environment. The inherent safety of the LOHC technology provides an existing scalable solution considering these aspects and thus can offer a global infrastructure. Operational flexibility: The storage and release units can be ramped up and down in technical ranges. Just at the time of design the required range has to be defined. 50 - 120% are common. Compatibility with existing infrastructure: Liquid hydrocarbons are widely used and transported. Thus, the LOHC technology is well compatible. Scalability: The technology is scalable in dimensions of the chemical industry. Large scale is therefore favorable for the LOHC-process.

Economic	Economics of the LOHC-devices might not meet the targeted cost assumptions. Mitigation: Both processes, hydrogenation, as well as dehydrogenation are standard processes in the chemical industry with well established cost structures. Suppliers for equipment are available worldwide and will even increase in number with hydrogen becoming more relevant in other industry sectors. Current demand: LOHC technology has not yet seen a large scale market roll-out.	Faster roll-out of new market segments will open an opportunity for the LOHC technology, as more infrastructure for the transport and storage of hydrogen will be required. This will enhance numbering up and therefore cost down potentials. Additionally DBT is a well established thermal oil. Due to that, the channels of distributions are already well established. Current supply: Unloaded LOHC is well available in multi-10000t-scale. Suppliers are well available, but will number up with increasing demand.
Political	The source of Dibenzyltoluol is from crude oil. The political situation is unstable in some countries, that are hauling crude oil. Mitigation: Crude oil is used over a century without major breakdowns of the international oil industry. Furthermore DBT is cycled and not consumed, therefore the overall demand for DBT will be lower than for e.g. Diesel.	DBT is produced by companies all over the world. As a result, there will be no DBT-shortage, if there is a trade embargo by one country and hydrogen supply is always secured.
Social	As DBT is a hydrocarbon, a small risk exists that the public will see DBT as "not decarbonized". Mitigation: This risk can be mitigated through communication and explanation as the DBT is not consumed and therefore does not lead to carbon emissions. Sound, odor, and visual pollution: Storage - Comparable to current industrial complexes. Release - Comparable to current refueling stations. Public perception and acceptance: No major change in handling compared to current hydrocarbon infrastructure. This enhances the adaptability for hydrogen as an energy carrier, compared to CGH_2.	Using LOHC, hydrogen is handled like a fluid, not as a gas. As people are used to use fluids for mobile transport the acceptance of a hydrogen fueled mobility and for many other applications will be higher than with existing technologies like compressed hydrogen and liquified hydrogen.
Environmental	The source of Dibenzyltoluol is from crude oil. Mitigation: The thermal oil is not consumed during the hydrogenation and dehydrogenation process. Therefore it is possible to cycle the fluid between the	This energy consumption of the dehydrogenation is thermodynamically given, but the source of the thermal energy supply can be changed. The biggest impact on reducing CO_2-emissions is achieved, when thermal energy is provided by burning

	hydrogenation and dehydrogenation processes up to a 1,000 times with a subsequent regeneration step and then be re-used again.	biogas or by heating electrically using 100 % renewable power. If these two options are not realizable, in countries like Germany one can use natural gas to reduce the CO_2-footprint about 40 – 50 % in comparison to electrical heating with standard power supply. Toxic pollution/risk: LOHC is stored at ambient conditions. It is hardly flammable and not classified as a dangerous good. Recyclability: Steel, Catalyst (platin based materials - recyclability is state of the art in catalyst industry), DBT as LOHC (high stability with of over 500 cycles. Can additionally be redistilled after end of lifetime).

References:

- This technology was assessed based on 9 years of development work in academia and industry. During this time numerous lab plants were built and many industrial demonstration units were designed, built and brought into operation in different industries and countries. Data, models, correlations and patents are IP of Hydrogenious Technologies.

C7: $NaBH_4$

Data sheet prepared by/owner: Jonathan Moncada & Andrea Ramirez, Delft University of Technology

Data sheet reviewed by: Eddy van Oort, Frames

Technology Description:

The production of NaBH4 has been carried out commercially using the Brown-Schlesinger process. This process consists of 5 reactions steps. The first one is the reaction between hydrogen and sodium to yield sodium hydride (NaH) at 370 °C. Sodium hydride is an important intermediate for producing sodium borohydride ($NaBH_4$). The second step consists of reforming borax for producing boric acid at 90 °C, which is followed by the conversion of boric acid into trimethylborate (B(OCH3)3) with methanol at 50 °C. After recovering the excess methanol and separating trimethylborate from water, it reacts with sodium hydride to obtain sodium borohydride and sodium methoxide (CH3NaO). Sodium borohydride is extracted with diglyme, which is later separated and recycled. After this step, sodium borohydride is obtained at high purity (>99 wt%). Sodium methoxide is hydrolysed with water producing sodium hydroxide and methanol. Methanol is recovered in a distillation column and recycled to the trimethylborate production step. Sodium hydroxide is later recovered as a side product. Only 50% of the initial mass of hydrogen is delivered in the final product (NaBH4) as hydrogen is released embedded in other co-products.

Note that although in this sheet sodium is assumed to be bought, its production step is typically included in the Brown-Schlesinger process. This step consists of the electrochemical conversion of sodium chloride.

The technology was set to process a hydrogen input flow of 5 ktonne/y.

Key Performance Indicators (KPIs)

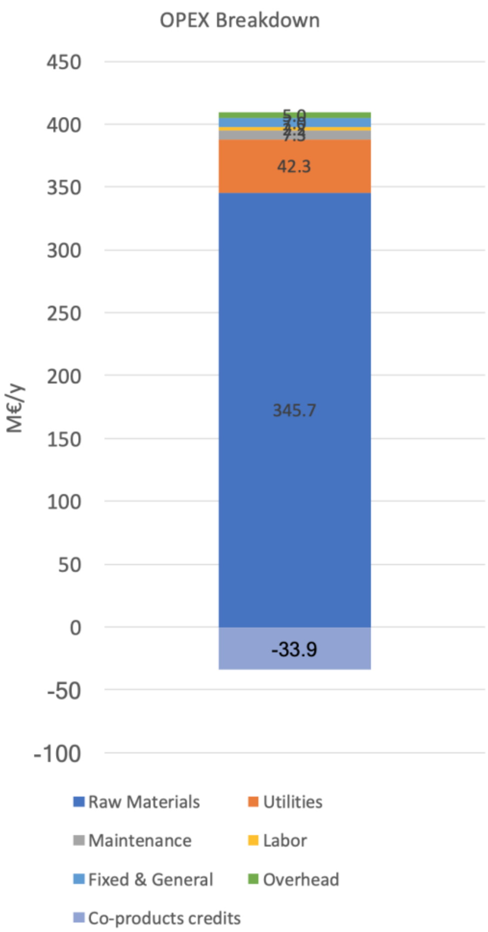
Technological		Economic				Environmental	
		Year	**Base year (2019 - 2034)**	**2030**	**2050**		
TRL (scaled to Nth of a kind)	9	Equipment Cost (M€)	29	N/A	N/A	Water consumption (m^3/kg $NaBH_4$)	Negligible
Round trip efficiency (%)	0.41	CAPEX (M€)	106	N/A	N/A	Water withdrawal (m^3/kg $NaBH_4$)	1
Capacity (TJ/y)	1418	Annualized CAPEX (M€/y)	8.5	N/A	N/A	Heat (MJ/kg $NaBH_4$)	37.3
Capacity (ktonne/y)	47	Annualized CAPEX (€/kg $NaBH_4$)	0.2	N/A	N/A	Electricity (kWh/kg $NaBH_4$)	0.019
Capacity (ktonne H_2-eq/y)	2.5	Annualized CAPEX (€/kg H_2-eq)	3.4	N/A	N/A	GHG emissions (kg CO_2-eq/kg $NaBH_4$)	2.5
Product concentration, purity (wt.%)	99	OPEX (M€/y)	376	N/A	N/A	Land footprint (m^2/kg $NaBH_4$)	N/A
Volumetric energy density (GJ/m^3)	32	OPEX (€/kg $NaBH_4$)	8.1	N/A	N/A		
Losses during storage (%)	-	OPEX (€/kg H_2-eq)	151	N/A	N/A		

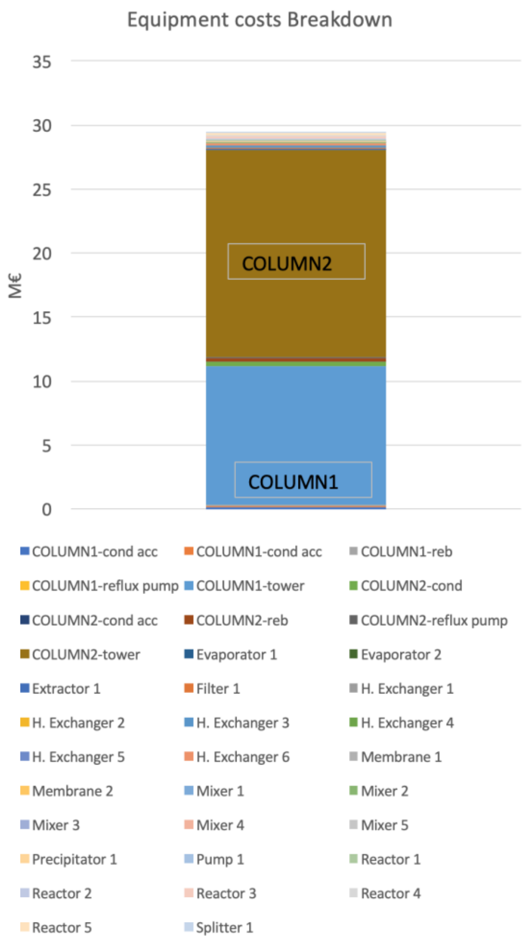
Notes:

- The technology was set to process a hydrogen input flow of 5 ktonne/y. Base year 2017. The capacity was assumed for this study as it was not possible to retrieve real $NaBH_4$ processing flows in industry. Note that the amount of $NaBH_4$ produced corresponds only to 50% of the hydrogen input.
- Due to low availability of primary data (available) for this technology, the process was modelled in Aspen Plus. Equipment costs were estimated in Aspen Economic Analyzer at the selected capacity. CAPEX was estimated using typical factors which can be found in the calculations tab.
- OPEX was estimated based on the mass and energy balances retrieved from a model developed in Aspen Plus, and using additional inputs such as prices. The environmental indicators were also estimated based on mass and energy balances. For clarification, additional data can be provided.
- Co-products revenues were assumed as credits to operational costs.
- The annualized CAPEX was calculated for a period of 20 years and interest rate of 5%.
- Costs for 2030 and 2050 are not available for this technology.
- LHV of $NaBH_4$ @99wt% is 30.4 MJ/kg. LHV of H_2 is 117.9 MJ/kg.

CAPEX as function of capacity

	ktonne/y		M€		M€
Capacity 1	23	Equipment cost 1	19	CAPEX	70
Capacity 2	47	Equipment cost 2	29	CAPEX	106
Capacity 3	70	Equipment cost 3	37	CAPEX	135





Equipment	Cost k€
COLUMN1-cond acc	151.9
COLUMN1-cond acc	50.2
COLUMN1-reb	93.3
COLUMN1-reflux pump	19.3
COLUMN1-tower	10884.8
COLUMN2-cond	289.9

Equipment	Cost k€
Membrane 1	20.3
Membrane 2	18.6
Mixer 1	18
Mixer 2	20.6
Mixer 3	18
Mixer 4	35.5

COLUMN2-cond acc	53.9	Mixer 5	25.5
COLUMN2-reb	270.6	Precipitator 1	16.2
COLUMN2-reflux pump	20.5	Pump 1	9.4
COLUMN2-tower	16195.9	Reactor 1	116.7
Evaporator 1	19.3	Reactor 2	117.9
Evaporator 2	30.7	Reactor 3	152.5
Extractor 1	41	Reactor 4	77.8
Filter 1	94.7	Reactor 5	152.5
H. Exchanger 1	11.2	Splitter 1	32.3
H. Exchanger 2	21.5	Total equipment cost at capacity 2	29398
H. Exchanger 3	137.6		
H. Exchanger 4	46		
H. Exchanger 5	7.9		
H. Exchanger 6	125.8		

Notes:

- Although the equipment list is known, it is difficult to identify the individual capacity factors and assumptions to scale each individual equipment. The six-tenth rule of thumb is then used.

Quality Assessment

The following matrix shows the scores on quality assessment of data inputs and indicators grouped as total system.

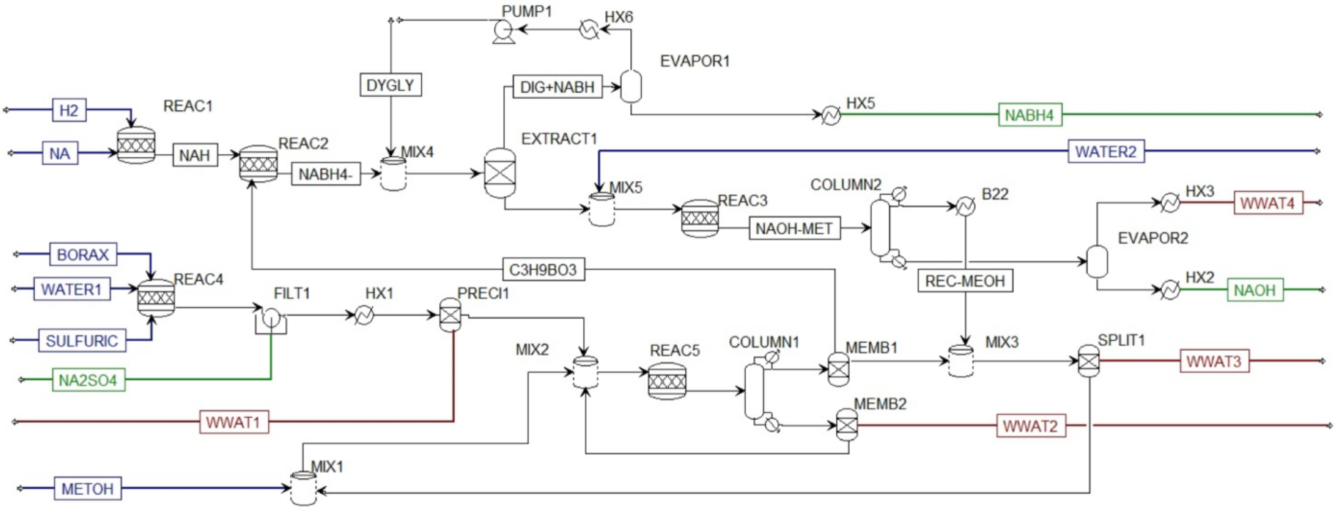
Uncertainty for Data Inputs				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	1	2	2	0
Economic	1	2	2	2
Environmental	1	2	2	1

Uncertainty for Key Performance Indicator Outcomes				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	2	2	3	0
Economic	2	2	2	0
Environmental	2	1	2	0

Notes:

- $NaBH_4$ score low in data inputs as even the technology is at TRL 9, there was very limited availability (to the knowledge of the authors) of data regarding the technology. Only couple of studies reporting the main conversion steps and reactions were available. This information was therefore used to model the process, but many intermediate steps such as recovery of solvents and separations units were designed by the authors based on imprecise descriptions provided in literature. Validation process for technical data inputs was not possible.
- Technical, economic and environmental data is based on data derived from a technical model. The model is mild resolution.
- Reliability on the environmental indicators is unknown. Emission factors are those from the current electricity mix in the Netherlands, and steam for industry. Emission factors do not take into account possible transition to renewables.
- Validation process was not possible.

Process flow diagram



Notes:

- Additional details on inputs, products and waste streams flow rates can be provided upon request.
- Equipment list:
    - REAC1: Reactor where sodium hydride is produced. Conditions 370 ºC , 1 bar
    - REAC2: Reactor where sodium borohydride is produced. Conditions 250 ºC, 1 bar
    - MIX4: Makeup tank for extraction of NaBH4. Solvent used diglyme.
    - EXTRACT1: Extraction column
    - EVAPOR1: Evaporator
    - HX6: Heat exchanger
    - PUMP1: Centrifugal pump
    - HX5: Heat exchanger
    - MIX5: Mixer
    - REAC3: Methanol recovery reaction. Conditions 50 ºC , 1 bar
    - COLUMN2: Distillation column for methanol recovery
    - EVAPOR2: Evaporator
    - HX3: Heat exchanger
    - HX2: Heat exchanger
    - REAC4: Boric acid production reaction. Conditions 90 ºC , 1 bar
    - FILT1: filter
    - HX1: Heat exchanger
    - PRECI1: Sedimentation tank
    - MIX1, MIX2: Mixers
    - REAC5: Trimethyl borate production reactor. Conditions 50 ºC , 1 bar
    - COLUMN1: Distillation column
    - MEMB1, MEMB2: Membrane units
    - MIX3: Mixer
    - SPLIT1: Molecular sieve
    - List of main streams

- Inputs
    - H2: Hydrogen
    - NA: Sodium
    - BORAX: Boraz
    - WATER1, WATER 2: Process water
    - SULFURIC: Sulfuric acid
    - METOH: Methanol
    - Products:
    - NABH4: Sodium borohydride
    - NAOH: Sodium hydroxide
    - NA2SO4: Sodium sulfate
    - Waste streams:
    - WWAT1, WWAT2, WWAT3, WWAT4, WWAT4: waste water streams

Risks and opportunities

	Risks	Opportunities
Technological	Technology designed to operate continuously. The number of reaction and separation steps make this technology highly inflexible and very complex. The need of distillation columns to recover methanol, and the need of evaporation to recover diglyme makes the downstream process complex and highly dependent on the continuous inputs of material. $NaBH_4$ is produced commercially, however, with small scale applications and large scale production for hydrogen storage (carrier) has not been carried out in practice. Large scale $NaBH_4$ production would require fine tuning and possibly development of infrastructure for its large scale supply.	The fact that $NaBH_4$ needs to be cracked back to H_2 opens to opportunity to include recycling loops for the regeneration of $NaBH_4$. However that would imply redesigning the system for an integrated recycling loop. Knowledge on $NaBH_4$ production from commercial plants can be used as a basis for NaBH4 as hydrogen carrier.
Economic	Giving the complexities of the technology the process is capital and energy intensive, thus having a large impact on the economic performance of the system. Feedstock costs are the major contributors to $NaBH_4$ costs as it requires sodium and borax as auxiliary raw materials.	Possibility to develop $NaBH_4$4 for fuel cell applications.
Political	N/A	N/A
Social	$NaBH_4$ needs to be properly handled as it can easily react with air and water. Public acceptance on $NaBH_4$ use needs to be monitored giving safety risks associated with its use.	The types of jobs is expected to be skilled workforce at factory level.

Environmental	Handling of $NaBH_4$ is a critical aspect in its production. $NaBH_4$ can easily react with water and air and release its hydrogen content, which can be a fire source or risk for explosion. Upstream inputs such as borax and sodium can be large contributors to environmental impacts as those are traditionally produced using fossil energy inputs. Decarbonization of upstream production processes might be required.	N/A

References:

- Liu, C. H., & Chen, B. H. (2015). The concept about the regeneration of spent borohydrides and used catalysts from green electricity. Materials, 8(6), 3456-3466.
- Wu, Y., Kelly, M. T., & Ortega, J. V. (2004). Review of chemical processes for the synthesis of sodium borohydride. Millennium Cell Inc.
- Gerhartz, W. (1988). Boron Compounds. Ullmann's encyclopedia of industrial chemistry. Wiley-Vch.
- Monteverde, M., & Magistri, L. (2012). Hydrogen from sodium borohydride and fossil source: An energetic and economical comparison. International Journal of Hydrogen Energy, 37(6), 5452-5460.
- Muir, S. S. (2013). Sodium borohydride production and utilisation for improved hydrogen storage.
- The technology was modeled in Aspen Plus to build mass and energy balances. Equipment costs were estimated in Aspen Economic Analyzer.

C8a: CHOOH (Formic Acid - electrochemical)

Data sheet prepared by/owner: Jonathan Moncada & Andrea Ramirez, Delft University of Technology

Data sheet reviewed by: Eddy van Oort, Frames

Technology Description:

This process corresponds to the electrochemical production of formic acid, starting from water and CO_2. The process was designed to exclusively use renewable energy as input. For this case, formic acid is produced at a concentration of 85wt%. The system considers the electrochemical reactor and downstream processing, which includes a distillation column and deionization columns as shown in the flow diagram sheet. The electrochemical reactor operates at 25 ºC, using a Sn cathode with Na_2SO_4 catholyte, and Pt anode with H_2SO_4 anolyte. The reactor operates at a pH of 2.5. Pressure on the anolyte compartment is 1.1 atm, while in the catholyte compartment 1 atm in order to allow mass transfer between the compartments. Concentration of formic acid at the reactor's outlet is 10 wt%.

The technology was scaled to deliver 12 ktonne of formic acid per year. As the technology is at early TRL level, the scaling explores what the costs would be today if performance would be that shown in the laboratory.

The CO_2 capture unit was not included in this data sheet, It is assumed CO_2 is available at gate from a main pipeline. Different CO_2 prices were considered for estimating OPEX.

Key Performance Indicators (KPIs)

Technological		Economic				Environmental	
		Year	**Base year (2019 - 2034)**	**2030**	**2050**		
TRL (scaled to Nth of a kind)	2	Equipment Cost (M€)	12	N/A	N/A	Water consumption (m^3/GJ)	0.0005
Round trip efficiency (%)	0.09	CAPEX (M€)	42	N/A	N/A	Water withdrawal (m^3/GJ)	0.72
Capacity (TJ/y)	46	Annualized CAPEX (M€/y)	3.4	N/A	N/A	Heat (MJ/GJ)	34.9
Capacity (ktonne/y)	12	Annualized CAPEX (€/GJ)	0.28	N/A	N/A	Electricity (kWh/GJ)	2.4

Capacity (ktonne H_2-eq/y)	0.54	Annualized CAPEX (€/kg H_2-eq)	6.2	N/A	N/A	GHG emissions (kg CO_2-eq/GJ)	4.1
Product concentration, purity (wt.%)	85	OPEX excluding CO_2 costs (M€/y)	21	N/A	N/A	Land footprint (m^2/GJ)	N/A
Volumetric energy density (GJ/m^3)	4.1	OPEX including CO_2 costs (M€/y)	21	N/A	N/A		
Losses during storage (%)	-	OPEX excluding CO_2 costs (€/tonne FA)	1713	N/A	N/A		
		OPEX including CO_2 costs (€/tonne FA)	1750	N/A	N/A		
		OPEX excluding CO_2 costs (€/kg H_2-eq)	37.8	N/A	N/A		

Notes:

- Annualized capex calculated for a period of 20 years and interest rate of 5%.
- Costs for 2030 and 2050 are not available for this technology.
- LHV of formic acid @85wt% is 3.8 MJ/kg LHV of H_2 is 117.9 MJ/kg.
- LHV of H_2 is 117.9 MJ/kg
- Details on mass and energy balances can be found in the calculations tab.
- Technology designed for using renewable electricity as input.
- Continuous operation is considered.

CAPEX as function of capacity

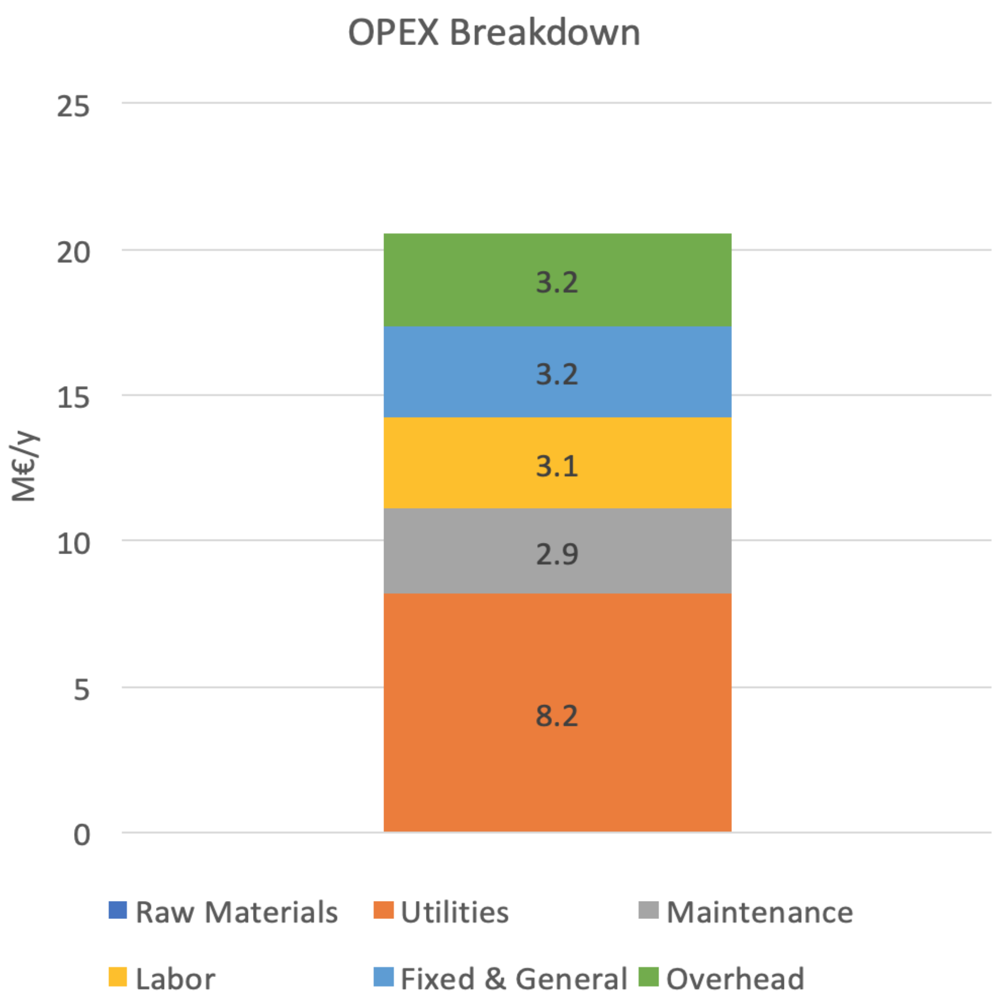
	ktonne/y		M€		M€
Capacity 1	8	Equipment cost 1	9	CAPEX	33
Capacity 2	12	Equipment cost 2	12	CAPEX	42
Capacity 3	20	Equipment cost 3	16	CAPEX	57

Equipment	ktonne/y	Scaling factor
C01-Distillation column		
E01-Heater		
E02-Cooler		
E03-Cooler		
K01-Turbine expander		
P01-Pump		
R01-Electrochemical reactor		
S01-Capacitive deionisation column		
S02-Capacitive deionisation column		

Notes

- Equipment costs at Capacity 2 were retrieved from Apeldoorn T, 2018. Equipment costs were calculated by combining different approaches.
- Some equipment was estimated using the Aspen Plus data bases, including typical equipment such as heat exchangers, pumps, columns.
- More specialized equipment such as electrolyzers were estimated using data from the literature and reported by Apeldoorn T.

- The reference used in this study does not provide a breakdown of equipment costs and only a total of 12 M€ for producing 12 ktonne/y of formic acid was reported. For confidential aspects detailed on equipment costs were not provided.
- Equipment list can also be provided.



Quality Assessment

The following matrix shows the scores on quality assessment of data inputs and indicators grouped as total system.

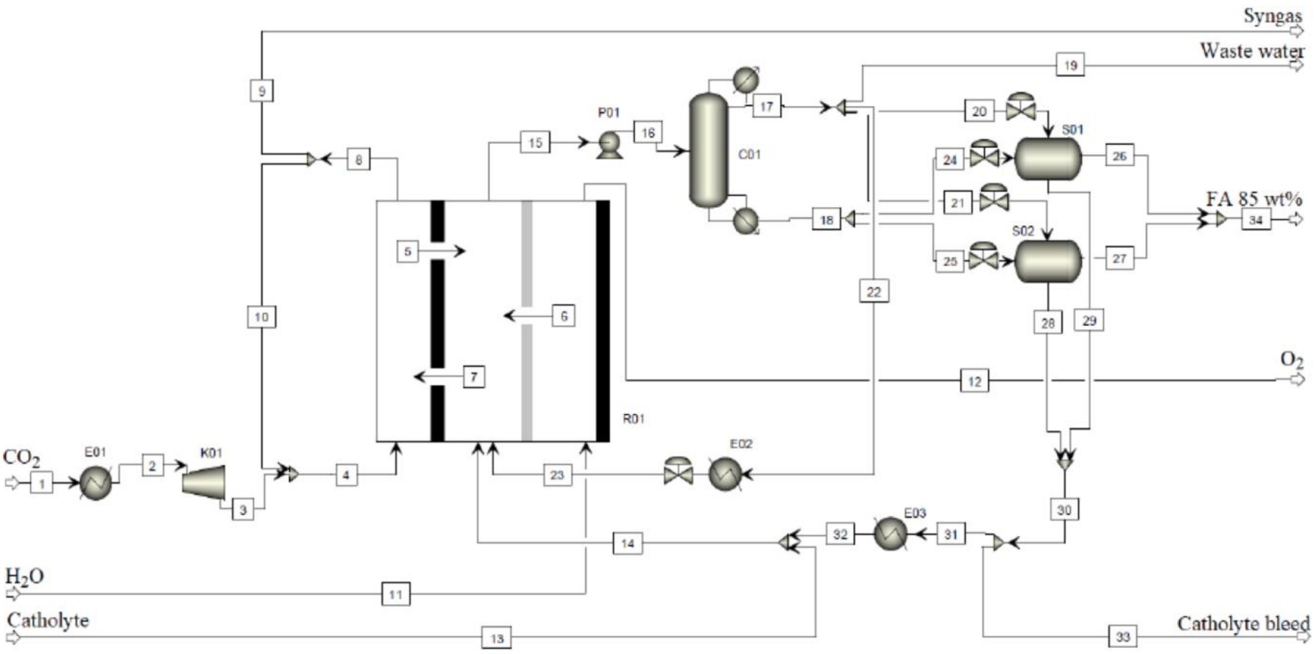
Uncertainty for Data Inputs				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	3	2	2	1
Economic	2	2	2	1
Environmental	2	2	2	1

Uncertainty for Key Performance Indicator Outcomes				
K01-Turbine expander	**K01-Turbine expander**	**K01-Turbine expander**	**K01-Turbine expander**	**K01-Turbine expander**
Technical	2	2	2	0
Economic	2	2	2	0
Environmental	2	2	2	0

Notes:

- Electrochemical formic acid production scored low in technical inputs as in most cases data from indirect measurements were selected to carry out the design. Although there is relevant literature on the technology, many process parameters still need to be validated, for instance whether a concentration of 10wt% of formic acid is achievable in practice. Input data was gathered through consultation with experts and literature review. The technology was modeled by the authors.
- Technical data from the technical assessment was used as input for the economic analysis (derived data). Formic acid score low, because the cost data was difficult to obtain and thus modeled, additionally literature supporting some of the assumptions is lacking.
- Environmental data inputs score low as it is unclear the sources mainly for electricity and steam, thus proxy values togethers with educated guesses were used to characterize impacts of upstream flow rates (e.g., steam, electricity).
- Validation process is difficult for outputs in the three dimensions.

Process flow diagram



Process equipment summary					
C01	Distillation column	E03	Cooler	R01	Electrochemical reactor
E01	Heater	K01	Turbine expander	S01	Capacitive deionisation column
E02	Cooler	P01	Pump	S02	Capacitive deionisation column

Notes:

- CO_2 input, 10.60 ktonne/y
- Water input, 22.86 ktonne/y
- Syngas output, 0.50 ktonne/y, but used internally for producing heat
- O_2 output, 3.94 ktonne/y
- Formic acid output 12 ktonne/y. For details on flow rates look into the calculations tab

Risks and opportunities

	Risks	Opportunities
Technological	Electrochemical conversion has not been developed at large scale. Currently the limiting factor on scaling up the technology is the electrochemical reactor due to its size footprint as well as issues regarding selectivity and efficiency. The process is water intensive and the concentration of products at the reactor outlet is rather low, which difficults the downstream processing and thereby affecting net energy requirements. The presence of a distillation unit makes it difficult to be adapted in case on intermittent supply of electricity. Intermittency can represent a challenge for scaling this technology further and assessments carried out by the authors have shown that scaling down would be needed if continuous electricity supply is not possible. CO_2 is assumed to be available at the gate of the factory .	The reaction process is carried out at mild conditions, which may facilitate operability. Optimization including heat integration strategies is still possible for this technology. Another opportunity for this technology is that producing hydrogen in an intermediate step is not required. Direct water conversion is possible. Electrochemically produced formic acid can be a drop-in to the already existing market
Economic	Large investment costs in electrochemical reactors have a large influence on the economic performance. As formic acid is highly diluted in water, the energy intensity in the downstream processing is large and thus the contribution of utilities in OPEX is significant. Integration of renewable heat might increase OPEX. The technology operates at low scales and there is still no evidence on scaling up though experts suggest that could be commercial after 2030.	On a supply chain perspective, avoiding the intermediate step on converting hydrogen, can result in lower system costs. use of renewable electricity (for instance potential use as energy storage) create further market possibilities to those considered nowadays.
Political	N/A	N/A
Social	N/A	The types of jobs is expected to be skilled workforce at the factory level. At this stage it is difficult to determine whether the technology would affect jobs across the supply chain. To understand that, a more detailed supply chain analysis would be required.

Environmental	Supply of heat is the major contributor to GHG emissions (from a gate to gate perspective). Water use needs to be closely monitored as there could be potential environmental trade-offs between different impact categories.	Avoidance of the hydrogen production step can contribute on decreasing total system GHG emissions, however, trade-offs need to be further identified. Formic acid is a corrosive chemical and safety measures are currently taken into consideration. However, it is currently produced and distributed, thus, a particular supply barrier is not identified at this stage.

References:

- Apeldoorn T. (2018) Process design and trade-off assessment of techno-economic and environmental system performance of a continuous process and a renewables load-following electrochemical production of formic acid from CO_2. Master Thesis Chemical Engineering.
- The process was modelled in Aspen Plus for estimating the mass and energy balances. Equipment costs of units such as heat exchangers, pumps, columns were estimated using Aspen Economic Analyzer and updated to 2017.
- Electrolyzers costs were directly retrieved from Apeldoorn, T.

C8b: CHOOH (Formic Acid - Thermochemical route)

Data sheet prepared by/owner: Jonathan Moncada & Andrea Ramirez, Delft University of Technology

Data sheet reviewed by: Eddy van Oort, Frames

Technology Description:

Direct production of formic acid from hydrogen and CO_2. The CO_2 capture unit is not considered within this data sheet. The reaction taking place is:

Formic acid is produced via direct hydrogenation of CO_2 in dimethyl sulphoxide (DMSO) using a homogeneous ruthenium catalyst:

H2 + CO_2 <-> HCOOH

Formic acid is produced at 60 °C, 100 bar and a H_2/CO_2 molar ratio of 1.

The downstream process includes a flash step to separate the unconverted gases, a filter to recover and recycle the catalyst and a final distillation step to separate the solvent DMSO and obtain FA at 99.9 wt% of purity. The overall CO_2 conversion is 93%.

This technology was scaled up to an Nth of a kind for producing 200 ktonne/y of formic acid.

Key Performance Indicators (KPIs)

Technological		Economic				Environmental	
		Year	**Base year (2019 - 2034)**	**2030**	**2050**		
TRL (scaled to Nth of a kind)	4-5	Equipment Cost (M€)	12	N/A	N/A	Water consumption (m^3/kg FA)	0
Round trip efficiency (%)	0.56	CAPEX (M€)	42	N/A	N/A	Water withdrawal (m^3/kg FA)	0.042
Capacity (TJ/y)	974	Annualized CAPEX (M€/y)	3.3	N/A	N/A	Heat (MJ/kg FA)	3.7
Capacity (ktonne/y)	200	Annualized CAPEX (€/kg FA)	0.017	N/A	N/A	Electricity (kWh/kg FA)	0.015
Capacity (ktonne H_2-eq/y)	4.4	Annualized CAPEX (€/kg H2-eq)	0.8	N/A	N/A	GHG emissions (kg CO_2-eq/kg FA)	0.3
Product concentration, purity (wt.%)	99	OPEX excluding CO_2 costs (M€/y)	47	N/A	N/A	Land footprint (m_2/kg FA)	N/A
Volumetric energy density (GJ/m^3)	5.8	OPEX including CO_2 costs (M€/y)	50-61	N/A	N/A		
Losses during storage (%)	-	OPEX excluding CO_2 costs (€/tonne FA)	236	N/A	N/A		
		OPEX including CO_2 costs (€/tonne FA)	250-305	N/A	N/A		
		OPEX excluding CO_2 costs (€/kg H_2-eq)	10.7	N/A	N/A		

Notes:

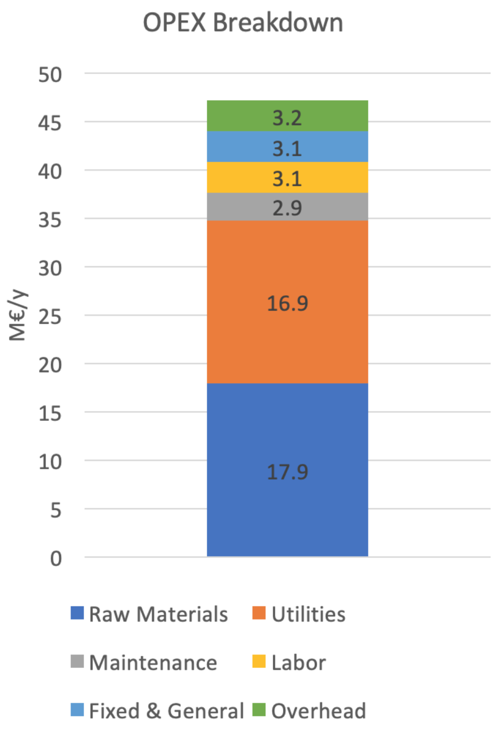
- Annualized capex calculated for a period of 20 years and interest rate of 5%
- Costs for 2030 and 2050 are not available for this technology.
- To produce 200 ktonne/y of FA, it is required 8.4 ktonne/y of H_2 and 206 ktonne/y of CO_2
- LHV of formic acid @99wt% is 4.87 MJ/kg
- LHV of H_2 is 117.87 MJ/kg
- Base year 2017.
- Details on mass and energy balances can be found in the calculations tab.
- The technology was scaled up to an Nth of a kind
- OPEX including CO_2 costs ranges as different prices for CO_2 inputs were considered. Please see Table with main inputs

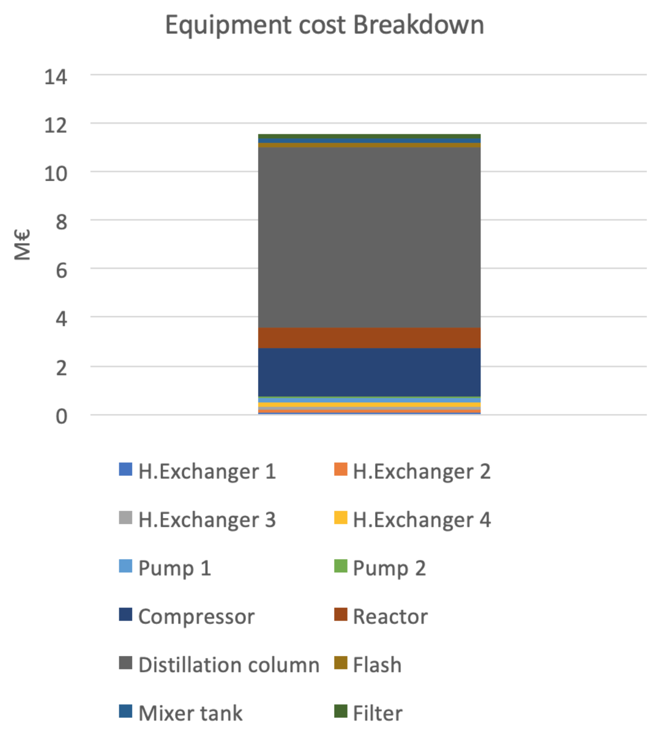
CAPEX as function of capacity

	ktonne/y		M€		M€
Capacity 1	100	Equipment cost 1	8	CAPEX	27
Capacity 2	200	Equipment cost 2	12	CAPEX	42
Capacity 3	500	Equipment cost 3	20	CAPEX	72

Equipment	ktonne/y	Scaling factor
H.Exchanger 1		67
H.Exchanger 2		147
H.Exchanger 3		74
H.Exchanger 4		221
Pump 1		165
P01-Pump		
R01-Electrochemical reactor		

S01-Capacitive deionisation column		
S02-Capacitive deionisation column		
Pump 2		83
Compressor		1968
Reactor		866
Distillation column		7418
Flash		165
Mixer tank		197
Filter		170
Total at capacity 2		11541





Notes:

- Although the equipment list is known, it was difficult to identify the individual capacity factors and assumptions to scale each individual equipment.
- The six-tenth rule of thumb is then used
- Equipment costs corresponds to those for producing 200 ktonne/y of formic acid (capacity 2)

Quality Assessment

The following matrix shows the scores on quality assessment of data inputs and indicators grouped as total system.

Uncertainty for Data Inputs				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	3	2	3	1
Economic	2	2	2	2
Environmental	2	1	2	2

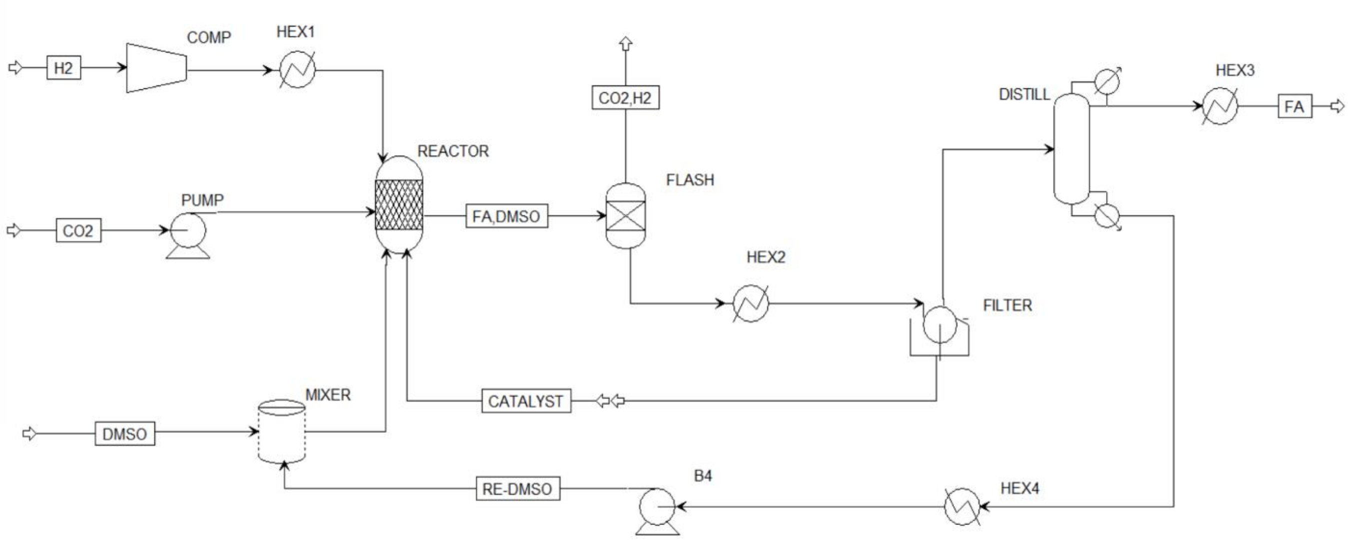
Uncertainty for Key Performance Indicator Outcomes				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	3	2	3	1
Economic	2	2	2	0
Environmental	2	2	1	0

Notes:

- Formic acid scores high in the indicator proxy because the input parameters to the technical models are the same as in the lab experiments for the same components and products. Validation process of FA production scores low because there are no independent studies to compare with. Input data is taken from scientific papers and patents published by one research group (Moret et al.).
- Technical data from the technical assessment has been used as input for the economic analysis (derived data). Formic acid scores low, because the cost data are difficult to obtain, and the assumptions for the cost in the literature are not explicitly reported.
- Environmental data inputs score low as it is unclear the sources mainly for electricity and steam, thus proxy values together with educated guesses were used to characterize impacts of upstream flow rates (e.g., steam, electricity).
- Validation process is difficult for outputs in the three dimensions.

* Technical, economic and environmental data is based on data derived from a technical model. The model is mild resolution.
* Reliability of the environmental KPÍs is unknown

Process flow diagram



Notes:

* CO_2 and H_2 after the flash are difficult to recycle to the reactor. The stream was assumed to be released to the environment.
* This stream has a flow rate of 16 ktonne/y.
* DMSO: Dimethyl sulfoxide 0.2 ktonne/y
* CO_2 flow rate is 206 ktonne/y at 98wt%.
* H_2 flow rate is 8.4 ktonne/y at 99.5 wt%

Risks and opportunities

	Risks	Opportunities
Technological	Process highly dependent on CO_2 input. The CO_2 source might significantly impact the overall performance of the system. Impurities in the CO_2 stream can affect the performance of the electrolyzer. The use of distillation makes the system very inflexible to possible fluctuations in raw materials supply due to fluctuating supply of electricity in case renewable sources are used (intermittency). The effect of material buffering (storage to guarantee continuous supply to conversion technologies) needs to be taken into account in case intermittency would affect the production capacity.	Formic acid can be easily integrated as a drop-in and use already available infrastructure used for formic acid.

	The technology is intended to be applied at large scale. Small scale production is difficult due to its inflexibility. In case small scale is desired, it would probably require redesigning the technology.	
Economic	Costs highly depend on upstream hydrogen costs. The system should also consider on a longer term, what the effect on producing utilities for the plant (e.g., steam) using renewable inputs, as those largely affect operational costs.	The market of formic acid is already developed, which facilitates incorporating renewable formic acid.
Political	Most technologies are still under development stages and innovation would need to be accelerated to be able to put in place policy making and incentive frameworks. Evidence on large scale potential is still unknown.	Possibility of developing a support framework for renewable chemicals.
Social	N/A	The types of jobs is expected to be skilled workforce at the factory level.
Environmental	Heat is the major contributor to gate-to-gate CO_2 emissions, introduction of renewable heat could play a major role for determining the renewability of the product.	Formic acid is a corrosive chemical and safety measures should be taken into consideration. However, it is currently produced and distributed, thus, a particular supply barrier is not identified at this stage

References:

- Moret et al. (2014). EDDiCCUT project, novel CO_2 capture and utilization technologies.
- The process was modelled in Aspen Plus for estimating the mass and energy balances. Equipment costs were estimated using Aspen Economic Analyzer and updated to 2017.

C9: DME-OME

Data sheet prepared by/owner: Marija Saric & Yvonne van Delft, ECN part of TNO

Data sheet reviewed by: Jonathan Moncada & Andrea Ramirez, Delft University of Technology

Technology Description:

DME is produced from syngas (CO and H_2) by direct and indirect synthesis route. The indirect route consists of two steps: firstly, methanol is produced from a synthesis gas and then the methanol stream is dehydrated producing DME. The direct method is one-step configuration, where methanol and DME production occurs simultaneously in a packed bed reactor with a bi-functional catalyst as Cu-ZnOAl$_2$O$_3$/HZSM-5 or physically mixed catalysts (Cu-ZnOAl$_2$O$_3$for methanol synthesis and Cu-ZnO-HZSM-5 for methanol dehydration). In terms of efficiency, direct DME synthesis process outperforms the indirect synthesis, yet the need for separation and recycling remains. The O-surplus of the feed ends up in CO_2, which means that about equal molar amounts of DME and $CO_2$are produced. Since the reaction is equilibrium limited, downstream separation produces recycle streams of syngas (CO and H_2), CO_2, and methanol. The reactions involved in the synthesis of DME are:

$$CO + 2H_2 = CH_3OH$$

$$CO_2 + H_2 = CO + H_2O$$

$$2CH_3OH = DME + H_2O$$

In industry DME is produced via direct root using CO as a C source. CO_2 has an unfavorable thermodynamics for production of DME. No plants with CO_2 feed are known.

Key Performance Indicators (KPIs)

Technological		Economic				Environmental	
		Year	**Base year (2019 - 2034)**	**2030**	**2050**		
TRL (scaled to Nth of a kind)	3-4	Equipment Cost (M€)	25			Water consumption (m^3/GJ)	-
Round trip efficiency (%)	91.5 (ref. 1)	CAPEX (M€)	50			Water withdrawal (m^3/GJ)	0.05
Capacity (TJ/y)	719	Annualized CAPEX (M€/y)	4			Heat (MJ/GJ)	-
Capacity (ktonne/y)	25	Annualized CAPEX (€/GJ)	5.56			Electricity (kWh/GJ)	10.35
Capacity (ktonne H_2-eq/y)	3.24	Annualized CAPEX (€/kg H_2-eq)	1.23			GHG emissions (kg CO_2-eq/GJ)	-
Product concentration, purity (wt.%)	>98.5%	OPEX (M€/y)	28.2 (0.26 is for utilities)			Land footprint (m^2/GJ)	
Volumetric energy density (GJ/m^3)	19.3	OPEX (€/GJ)	39.2				
Losses during storage (%)	-	OPEX (€/kg H_2-eq)	8.7				

Notes:

- 20 years lifetime and 5% interest rate.
- DME produced at 75 bar.
- H_2 used is 7500 t/a, CO2 = 1250 t/a, maintenance =4% CAPEX, labor costs are 0.24 M€/year. Assumed H_2 price is 3.28 €/kg and CO_2 = 20 €/t.

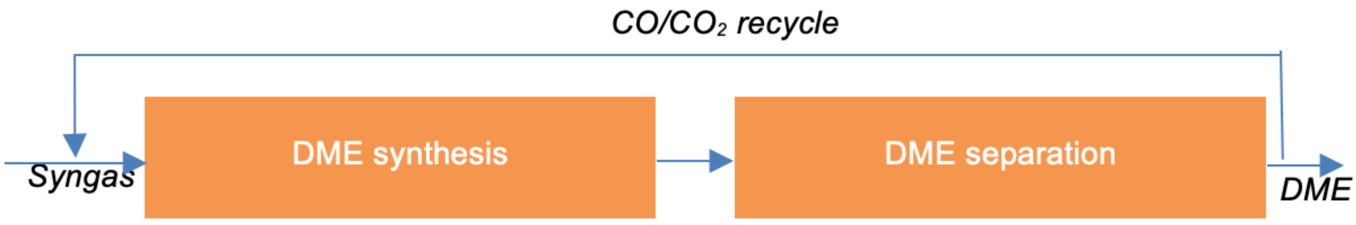
Quality Assessment

The following matrix shows the scores on quality assessment of data inputs and indicators grouped as total system.

Uncertainty for Data Inputs				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	1	1	1	1
Economic	1	1	1	1
Environmental	1	1	1	1

Uncertainty for Key Performance Indicator Outcomes				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	1	1	1	1
Economic	1	1	1	1
Environmental	1	1	1	1

Process flow diagram



Risks and opportunities

	Risks	Opportunities
Technological	Route via CO_2 on lower TRL level. Low conversion per pass due to low conversions.	Use of separation enhanced DME production.
Economic	High recycles may be required due to low conversion per pass.	DME selected as one of the most promising biofuels. No changes on ICE required.
Political		Increased interest in CCU
Social		
Environmental		Decrease of CO_2 emissions via CCU.

References:

- Tremel, Wasserscheid, Baldauf, Hammer, (2015). Techno-economic analysis for the synthesis of liquid and gaseous fuels based on hydrogen production via electrolysis. International Journal of Hydrogen energy 40, 11457 -11464

Transportation

T1a: Pipeline H_2 gas - High pressure backbone

Data sheet prepared by/owner: Albert van den Noort & Nicolien van der Sar, Gasunie

Data sheet reviewed by: Jonathan Moncada & Andrea Ramirez, Delft University of Technology

Technology Description: Using existing infrastructure, currently used for natural gas, hydrogen can be transported. This existing infrastructure will become available since the demand for natural gas is decreasing in the Netherlands. This infrastructure needs to be adapted (valves, metering, compression) in order to transport hydrogen. Due to the lower calorific value but higher velocities, the capacity of hydrogen pipelines is approximately 80% of the capacity of pipelines carrying H-cal natural gas and approximately 100% of the pipelines currently carrying Groningen-gas

Key Performance Indicators (KPIs)

Technological		**Economic**				**Environmental**	
		Year	**Base year (2019 - 2034)**	**2030**	**2050**		
TRL		Transportation costs (€/t .km)				Fuel type	
Capacity (GW)	15	Transportation costs (€/t H_2-eq.km)				Fuel consumption (L/t.km)	
Capacity (ktonne/y)		CAPEX (M€/1000km)	1700			Heat (MJ/t.km)	
Capacity (ktonne H_2-eq/y)						Electricity (kWh/t.km)	
Concentration of transported product (wt.%)						GHG emissions (kg CO_2-eq/t.km	

Notes:

- Using existing infrastructure wherever possible minimizes CAPEX.
- Connecting supply and demand of the five largest industrial areas has an average investment costs (partly existing, partly new infrastructure) of €1700 mln/1000 km with an average capacity of some 15 GW.

Quality Assessment

The following matrix shows the scores on quality assessment of data inputs and indicators grouped as total system.

Uncertainty for Data Inputs				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	2	1	1	1
Economic	2	1	1	1
Environmental				

Uncertainty for Key Performance Indicator Outcomes				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	2	1	1	1
Economic	2	1	1	1
Environmental				

Notes:

- Input based on internal Gasunie numbers; which is a proxy, not validated number. No data available for environment (removed numbers)
- Used same input for data input as for KPIs

Risks and opportunities

	Risks	Opportunities
Technological	Some pipeline material is not suitable for hydrogen transport. Might need to be replaced.	Existing infrastructure can be reused in principal, but need to check some materials (see risks).
Economic	Costs of adaptations of existing infrastructure is higher than expected.	As existing infrastructure can be reused, this is a very attractive opportunity for energy transport using hydrogen as a carrier.
Political	Permitting procedures might take a long time.	Infrastructure can be used in the same way as for natural gas.
Social	Public perception of renewable gasses like hydrogen (and tend more towards electricity, reducing the need for hydrogen and therefore the corresponding infrastructure).	Infrastructure can be used in the same way as for natural gas.
Environmental	Permitting process might take a long time.	Infrastructure can be used in the same way as for natural gas. No additional environmental risks, or need to build new infrastructure.

References:

- Gasunie

T1b: Pipeline H_2 gas - Regional grid

Data sheet prepared by/owner: Stedin/GasUnie

Data sheet reviewed by: Jonathan Moncada & Andrea Ramirez, Delft University of Technology

Technology Description:

The Netherlands the distribution natural gas grid is managed by 7 DSO's. In total the natural gas distribution grid in the Netherlands stretches 124,600 km of piping with approximately 7,190,000 customer connections.

For further description of the natural gas distribution grid we refer to figures of the Stedin grid, which represents approximately 30% of the Dutch total.

The distribution grid is characterized by several elements:

- Pressure regimes
- Piping materials
- In addition to piping material the natural gas distribution grid also consists of City Gate Stations (CGS) and District Stations (DS)
    - CGS receive natural gas at 40 bar from the transport grid and reduce the pressure to 8 bar into the distribution grid
    - DS further reduce the pressure within the distribution grid from 8 bar typically to 100 mbar
- Current estimates indicate that the Stedin grid (30% of Dutch total) operates of 65% of its max capacity. At peak moments (the whole month of Jan 2017) the grid transported 823 million m^3 of natural gas. Based on this figure the total peak transport capacity of the Dutch natural gas distribution grid is 823/0.65/0.3 = 4.2 billion m^3 of natural gas over a 1 month period.
- Furthermore the following materials are used in the distribution gas grid:
    - POM (polyoxymethylene) for coupling components
    - NBR (nitrile-butadiene rubber) and SBR (styrene-butadiene rubber are used as seals or connectors between components

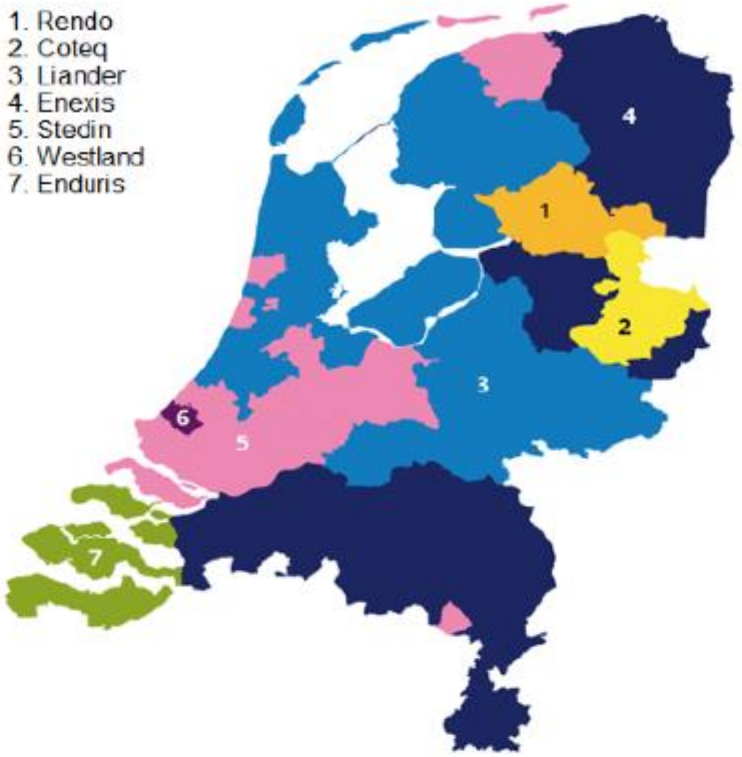
The following pressure levels can be identified in the Stedin distribution gas grid

High Pressure	Minimum Pressure
8 bar	1.5 bar
4 bar	0.8 bar
3 bar	0.6 bar
2 bar	0.4 bar
1 bar	0.2 bar
Low Pressure	
200 mbar	70 mbar

100 mbar	40 mbar
30 mbar	25.8 mbar

The following piping materials can be found in the Stedin distribution gas grid

material	km	%
Steel	3,301	14%
Cast Iron Gray	1,256	5%
Cast Iron Nodular	318	1%
Asbest Cement	545	2%
other	33	0%
PE	3,329	14%
PVC	1,212	5%
PVC/CPE	13,303	57%
total	**23,297**	**100%**


1. Rendo
2. Coteq
3. Liander
4. Enexis
5. Stedin
6. Westland
7. Enduris
1
2
3
4
5
6
7


PVC
PE
Steel

Key Performance Indicators (KPIs)

Technological		Economic				Environmental	
		Year	**Base year (2019 - 2034)**	**2030**	**2050**		
TRL	9	Transportation costs per volume (€/MWh/h)	7,726.66			Fuel type	
Peak Volume Demand (MWh/h)	89,560	Transportation costs per volume (€/MWh/year)	5.13			Fuel consumption (L/t.km)	
Annual Volume Demand (MWh)	135,000,000	Transportation costs capacity (€/MWh/year)	6,920			Heat (MJ/t.km)	
Peak Transport Capacity (MW)	100,000					Electricity (kWh/t.km)	
						GHG emissions (kg CO_2-eq/t.km	

Notes:

- The asset value of the Stedin natural gas distribution grid is approximately 1.9 billion euro (2018; incl. grid and customer connections; excl. metering.) The annual depreciation cost of the Stedin natural gas distribution grid is approximately 91 million euro (2018; incl. grid and customer connections; excl. metering.)
- The OPEX of the Stedin natural gas distribution grid is approximately 78 million euro (2015; incl. grid and customer connections; excl. metering.)
- The asset value of the Total Dutch natural gas distribution grid is approximately 8.15 billion (2018; incl. grid and customer connections; excl. metering).
- The annual depreciation cost of the Total Dutch natural gas distribution grid is approximately 377 million euro (2018; incl. grid and customer connections; excl. metering.)
- The OPEX of the Total Dutch natural gas distribution grid is approximately 315 million euro (2015; incl. grid and customer connections; excl. The total metering.)
- The total annual costs of the Dutch natural gas distribution grid is approximately 315 + 377 = 692 million euro (2018)
- Peak Volume Demand (MWh/h) 89.560 (source: Gasunie measurement March 1, 2018)
- Annual Volume Demand (MWh) 135.000.000 (source: Gasunie Netwerk Ontwikkelingsplan 2017)
- Peak Transport Capacity (MW) 100.000 (source: Gasunie Netwerk Ontwikkelingsplan 2017)

CAPEX as function of capacity

	ktonne/y		M€		M€
Capacity 1	100,000	Equipment cost 1		CAPEX	678
Capacity 2		Equipment cost 2		CAPEX	
Capacity 3		Equipment cost 3		CAPEX	

Notes:

- The CAPEX cost represent the additional investments that are needed to convert the part of the Dutch distribution gas network to hydrogen.
- These costs are based on the "Nationaal" scenario of the "Net van de Toekomst" study by Netbeheer Nederland
- In this scenario a demand of 203 PJ (56,388,889 MWh) H_2 is assumed to service approximately 3,3 million household equivalents (out of a total of 9 million)
- The additional OPEX in this scenario amounts to 422 million euro

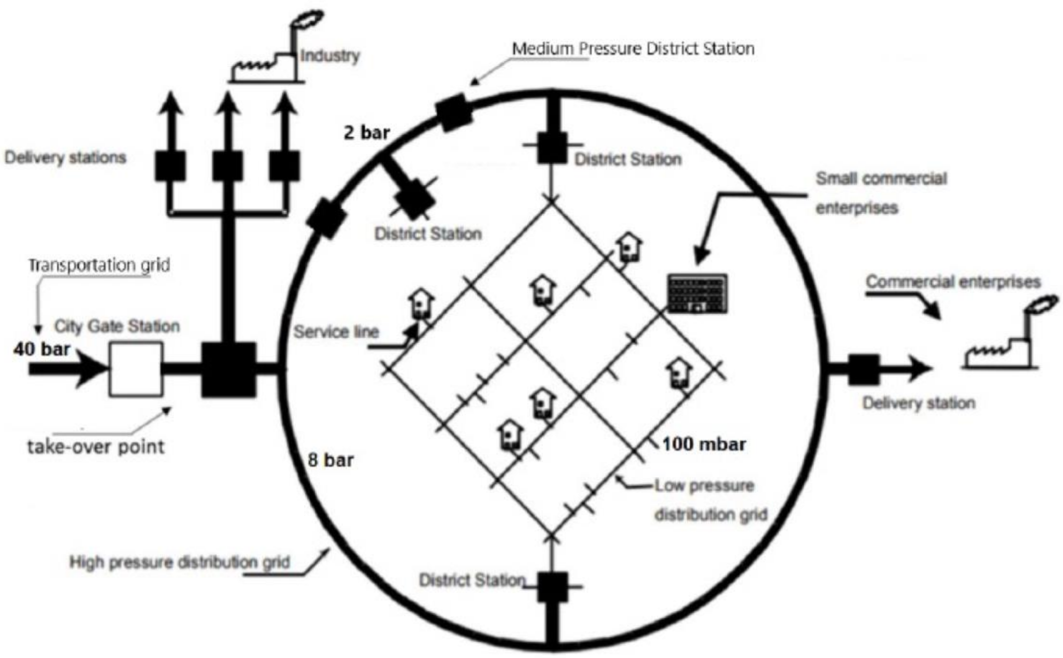
Quality Assessment

The following matrix shows the scores on quality assessment of data inputs and indicators grouped as total system.

Uncertainty for Data Inputs				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	3	3	4	3
Economic	4	4	4	4
Environmental				

Uncertainty for Key Performance Indicator Outcomes				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	3	3	4	3
Economic	4	4	4	4
Environmental				

Process flow diagram



Notes:

- Natural gas enters the distribution network at the City Gate Station (CGS) at 40 bar, where it is reduced to 8 bar. Areas with a large gas demand are supplied by several CGS to insure security of supply.
- In general the natural gas distribution network is considered a low pressure network. Within the distribution network high pressure is considered between 1 and 8 bar. Pressures of 100mbar and 30 mbar are regarded as low pressure within the distribution network.
- Distribution stations reduce the pressure from 8 bar to 100 mbar or 30 mbar. Delivery stations connect the high pressure parts of the distribution network (1-8 bar) directly to large customers.

Risks and opportunities

	Risks	Opportunities
Technological	The technological risks are assessed to be low because desk research indicates that most modern materials applied in the distribution natural gas grid are suitable for the transport of hydrogen gas. Older materials such as cast iron or asbestos cement pipelines need to be replaced by 2023.	The existing gas grid provides a great opportunity because it's proven to be a reliable and effective means of transport for gaseous energy carriers and can transport and store very large volumes of renewable energy in a cost effective way
Economic	The existing natural gas distribution grid represents a total economic book value of 8 billion that will quickly be depreciated in the next 10 to 20 years. This represents an economic risk to the DSO's currently owning and operating them, and to their shareholders. Because all DSO's are government owned this is also a potential loss of significant societal (capital) value.	The reconfiguration of roughly 1/3 of the natural gas distribution grid is estimated at a total cost of 700 million euros. This amount represents less than 10% of the current asset value of the natural gas distribution grid. Its also equivalent to the total replacement investments over a period of 5-6 years and is less than 1% of the total estimated costs of the Dutch energy transition between 2030 and 2050. For relatively common CAPEX the gas distribution grid can become a vital part of a low carbon system energy system
Political	The technical and economic potential of the current natural gas distribution grid for hydrogen transport is not fully recognized by national and local politicians. This lack of knowledge could result in a premature decisions to remove large parts of the current natural gas grid, thereby eliminating the possibility to re-use it for hydrogen transport.	The relatively low costs, limited amount of additional space required, and reduced public disturbance compared to removal of the distribution grid make reconfiguration for hydrogen transport an appealing option for a significant part of the Netherlands. Also the other alternatives to natural gas heating (district heating, direct electrification) are not economically or technically viable in significant areas in the built environment
Social	The perception that hydrogen is less safe when compared to natural gas or electricity is one that remains and needs to be addressed with focus. The reconfiguration of the distribution gas grid for hydrogen transport will not be effective if consumers don't accept hydrogen in their homes.	The use of hydrogen for residential heating (through the natural gas grid) requires less immediate physical changes to buildings, which corresponds to limited immediate and large investments by homeowners. These characteristics make residential heating using hydrogen potentially interesting and possibly preferred by consumers.

Environmental	The different characteristics of hydrogen transport (gas medium, pressure) can result in more medium losses in the vent of small leakage (which are often hard to detect) during transport compared to natural gas. The behavior of hydrogen when transported through underground plastic materials needs to be studied extensively	The natural gas grid can serve as a storage vessel for decentral hydrogen production through electrolysis linked to solar fields. The electricity production of solar arrays are usually high when heat (gas) demand is low. In the summer the grid can be filled (line packing) with hydrogen from solar fields.

References:

- Autoriteit Consument en Markt (2016). GAW sheet bij x-factorbesluiten RNB’s gas 2017-2021 (XLSM - 13.29 MB). Retrieved from https://www.acm.nl/nl/publicaties/publicatie/16355/GAW-sheet-bij-x-factorbesluiten-RNBs-gas-2017-2021
- Autoriteit Consument en Markt (2016). Kostenbestand behorende bij de x-factorberekeningen RNB’s gas 2017-2021 (XLSX - 278.4 KB). Retrieved from https://www.acm.nl/nl/publicaties/publicatie/16356/Kostenbestand-behorende-bij-de-x-factorberekeningen-RNBs-gas-2017-2021
- Autoriteit Consument en Markt (2016). Investeringenbestand bij x-factorbesluiten RNB’s Gas 2017-2021 (XLSX - 164.67 KB) Retrieved from https://www.acm.nl/nl/publicaties/publicatie/16357/Investeringenbestand-bij-x-factorbesluiten-RNBs-Gas-2017-2021
- Oprinsen, I (2018). The Transition from Natural Gas to 100% Hydrogen in an Existing Distribution Network, Case Study: Stad aan 't Haringvliet. TU Delft MSc thesis.
- KIWA (2018). Toekomstbestendige gasnetten. Retrieved from https://www.netbeheernederland.nl/_upload/Files/Toekomstbestendige_gasdistributienetten_133.pdf

T1c: Pipeline H_2 gas - Existing Hydrogen network

Data sheet prepared by/owner: Albert van den Noort & Nicolien van der Sar, Gasunie

Data sheet reviewed by: Jonathan Moncada & Andrea Ramirez, Delft University of Technology

Technology Description: According to the review of the roads2hy project (2007) and the overview on h2tools.org, in 2016 there were approximately 4500 km of pure hydrogen pipelines. The majority in the US (2608km) and Europe (1598 km). In the Netherlands there is 237km of pipeline, operated by Air Products and (the majority by) Air Liquide. The Air Liquide system has an operating pressure of 100 bar and pipelines with diameters ranging between 25-30 cm. It is connected to a larger system in Belgium and the North of France. Pipelines were built in the previous century and are made of steel.

Key Performance Indicators (KPIs)

Technological		**Economic**				**Environmental**	
		Year	**Base year (2019 - 2034)**	**2030**	**2050**		
TRL	9	Transportation costs (€/t .km)				Fuel type	
Capacity (TJ/y)		Transportation costs (€/t H_2-eq.km)				Fuel consumption (L/t.km)	
Capacity (ktonne/y)	191	CAPEX (M€/km)	0.703			Heat (MJ/t.km)	
Capacity (ktonne H_2-eq/y)		Annualized CAPEX (M€/y/km)	0.017575			Electricity (kWh/t.km)	
Concentration of transported product (wt.%)		OPEX (M€/km/y)	0.02812			GHG emissions (kg CO_2-eq/t.km	

Notes:

- 70-100 bar; O&M = 4% /yr; density=5.7 kg/m3; speed = 15 m/s; costs according to [2]; here assume diameter of 300 mm
- Pipeline costs depend on the location (rural/urban/metropolitan)
- Diameters up to 600 mm
- Depreciation period = 40 years (linear here)
- Other KPIs are unknown

Quality Assessment

The following matrix shows the scores on quality assessment of data inputs and indicators grouped as total system.

Uncertainty for Data Inputs				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	4	4	4	4
Economic	3	3	3	2
Environmental				

Uncertainty for Key Performance Indicator Outcomes				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	4	4	4	4
Economic	3	3	3	2
Environmental				

Notes:

- Technical data available; high TRL; economic data somewhat limited (but should be available for pipeline operators)
- Used same indication for data input as for KPIs

Risks and opportunities

	Risks	Opportunities
Technological	Highly flammable gas when released. Appropriate risk mitigating actions needed.	Proven technology.
Economic	TRL	9
Political	Capacity (TJ/y)	
Social	Capacity (ktonne/y)	191
Environmental	Capacity (ktonne H_2-eq/y)	

References:

- Roads2HyCom. (2017). European Hydrogen Infrastructure Atlas, July 2007
- Robinius, M., Linßen, J., Grube, T., Reuß, M., Stenzel, P., Syranidis, K., Kuckertz, P. & Stolten, D. (2018). Comparative Analysis of Infrastructures: Hydrogen Fueling and Electric Charging of Vehicles. Retrieved from: Stoltenhttps://www.ieafuelcell.com/documents/Comparative%20Analysis%20of%20Infrastructures-Hydrogen%20Fueling%20and%20Electric%20Charging%20of%20Vehicles.pdf

T2: Pipeline liquids general

Data sheet prepared by/owner: Albert van den Noort & Nicolien van der Sar, Gasunie

Data sheet reviewed by: Jonathan Moncada & Andrea Ramirez, Delft University of Technology

Technology Description: Long distance transport of ammonia is typically done by using pipelines since it is the most economical transport method. A 4,830 km carbon steel pipeline network is already used in the United States to transport ammonia from port and production facilities to agricultural areas for use as a fertilizer. There are currently storage facilities and terminals located along the pipeline to support operations, as an example, there are more than 800 retail ammonia retail locations in Iowa alone (Bartels, 2008).

Converting hydrogen to other liquid carriers could include:

1. Liquid hydrogen (cooling to -253°C): not realistic

2. Methanol

3. OME (polyoxymethylene dimethyl ethers): DME as fuel. Produced from syngas via methanol.

4. Liquid organic hydrogen carriers

5. Formic acid

These carriers are (as far as we know) not yet used in large scale transport systems using pipelines. Liquid hydrogen, LOHC and methanol are considered in tank transport (truck/ship). For ammonia, normal iron pipelines are used; transport is at relatively low pressures (up to 35bar) where ammonia is liquid and can be pumped.

Key Performance Indicators (KPIs)

Technological		Economic				Environmental	
		Year	**Base year (2019 - 2034)**	**2030**	**2050**		
TRL (scaled to Nth of a kind)	9	Transport costs ($/kg H_2-eq)	0.194			Electricity (kJ/kg ammonia)	185
Roundtrip efficiency (%)	99.2						
Capacity (ktonne/y)	3149.50032						
Losses during transport (%)	0.08						

Notes:

- Ammonia is currently transported by using pipelines, and therefore commercial tariffs for transporting ammonia are presently available from the pipeline operators. The commercial price to transport ammonia between Donaldsonville, Louisiana and Marshalltown, Iowa via pipeline, a distance of approximately 1,610 km, is 31.22 $/short ton or 0.0344 $/kg-$NH_3$ (NuStar Energy, 2019). Adjusting this cost to hydrogen gives a cost of 0.194 $/kg-$H_2$ for existing pipelines. If a new pipeline is installed, the cost may increase, but overall the cost is about one-third of the lowest estimate for hydrogen pipeline transportation cost.
- Bartels (2008) gives example calculations using: 99,87 kg/s (liquid at 2.2 m/s) and an efficiency of 99.2%: equals 3149 ktonne/year
- Total energy input in kJ/kg = 185 (work = 18 MW); assumed to be electricity costs for running the pumps. GHG emissions/land footprint and heat are unknown

Quality Assessment

The following matrix shows the scores on quality assessment of data inputs and indicators grouped as total system.

Uncertainty for Data Inputs				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	3	2	3	3
Economic	3	3	3	3
Environmental				

Uncertainty for Key Performance Indicator Outcomes				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	3	2	3	3
Economic	3	3	3	3
Environmental				

Notes:

- Limited data on environmental impacts; mature technology with more than 1 example (prices); capacities from model; method and proxy are 3.

Risks and opportunities

	Risks	Opportunities
Technological	Fluid pipelines are proven technology	Transport large quantities of energy, through relative small pipelines because of the fluid state of ammonia
Economic	Conversion losses; for LOHC -> two pipelines needed (because the carrier should be returned)	Low transport costs per GW
Political	Safety perception of NH_3 pipelines, NH_3 is a toxic and corrosive molecule	
Social	Safety perception of NH_3 pipelines, as NH_3 is a toxic and corrosive molecule	
Environmental	Safety perception of NH_3 pipelines, as NH_3 is a toxic and corrosive molecule	

References:

- Bartels, Jeffrey Ralph, "A feasibility study of implementing an Ammonia Economy" (2008). Graduate Theses and Dissertations. 11132.
- NuStar Energy. (2019). Tariff Documents. Retrieved from: http://nustarenergy.com/TariffDocuments

T3: Road cryogenic truck for liquefied & slurry H_2 (onshore)

Data sheet prepared by/owner: Tim Lauret, Frames in collaboration with Rolande

Data sheet reviewed by: Jonathan Moncada & Andrea Ramirez, Delft University of Technology

Technology Description: Transport of liquefied hydrogen in stainless steel semi trailer driving an average of 100,000 km per year and 100 km per trip.

To calculate operational costs in this data sheet, an average cruising speed of 60 km/h was assumed (based on literature) and 25% extra time of that spent on road for loading and unloading. Fuel efficiency was assumed as 27 KG diesel/100 km which is a typical value received from a LNG tank station operator in The Netherlands. Maximum truck weight was set to 40 tonnes with typical liquefied hydrogen payload of 4 ton. Diesel was assumed as fuel.

Key Performance Indicators (KPIs)

Technological		**Economic**				**Environmental**	
		Year	**Base year (2019 - 2034)**	**2030**	**2050**		
TRL	9	Transportation costs (€/t .km)	0.16	N/A	N/A	Fuel type	Diesel
Capacity (TJ/truck.y)	480	Transportation costs (€/t H_2-eq.km)	312.87	N/A	N/A	Fuel consumption (L/t Met.km)	0.014
Capacity (ktonne/truck.y)	4					Heat (MJ/t Met.km)	-
Capacity (ktonne H_2-eq/truck.y)	4					Electricity (kWh/t Met.km)	-
Concentration of transported product (wt.%)	1					GHG emissions (kg CO_2-eq/t Met.km	0.006

Notes:

- This system assumes an average transport distance of 100,000 km per year and single trips of 100 km each. Return trip was not considered.
- OPEX was estimated using typical cost structure for road transport including the categories: fuel, maintenance and repair, labor, insurance and tires.
- The annualized CAPEX was calculated for a period of 6 years and interest rate of 5%.

Quality Assessment

The following matrix shows the scores on quality assessment of data inputs and indicators grouped as total system.

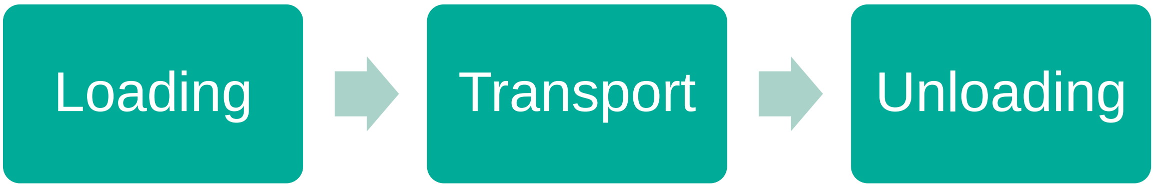
Uncertainty for Data Inputs				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	3	3	3	3
Economic	3	3	3	2
Environmental	3	3	3	2

Uncertainty for Key Performance Indicator Outcomes				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	3	3	3	3
Economic	3	2	3	2
Environmental	3	2	3	2

Notes:

- Transport scored high for all input parameters as information on trucks is widely available in the public domain and technical specifications of stainless steel tankers are easily accessible. Validation process for data inputs however scores low as there could be different region dependant inputs such as fuel consumption, truck costs, cruise speed etc, which can differ from truck to truck in the Netherlands. Environmental inputs in this case depends on emissions factor for diesel, which has been widely studied during the last decades.
- Scores on technical outputs are well understood as payload for trucks are available in the public domain and EC legislation, thus evaluating the amount of product is easily achievable.
- Scores on economic outputs are relatively high as the system is well understood and checked with LNG truck operator. Only trailer cost is changed for liquefied hydrogen. Fuel is a major contributor to costs, and its consumption can drastically differ from aspects such as road type, driver's behavior, geography, etc.
- Environmental outputs are dependent on fuel consumption levels which is uncertain for each case. Average data was used, and validation of emissions was not directly possible to be carried out. However, the approach is considered as best available practice.

Process flow diagram



Notes:

- Road transport of hydrogen using a stainless steel semi-trailer which in average drives 100,000 km per year
- Transport only one way. Return trip not considered in calculations.

Risks and opportunities

	Risks	Opportunities
Technological	A technological risk that was identified for this system is the change on car fleet when new types of fuels penetrate the system. Transport is still highly dependent on fossil sources	Liquefied hydrogen is already done for a small amount of production locations worldwide and is in complexity very close to transport of LNG, which is an already mature technology. The tube trailers do not become obsolete when the truck fleet needs to change due to the need to implement alternative fuel types
Economic	Personal salaries is one of the major contributors to transport costs.	Maturity of road transport of chemicals can benefit hydrogen economy from fast learning curves.
Political	Transitioning to renewable car fleet is still a major political challenge.	In order to meet environmental targets, replacing current car fleet would require policies and incentives for smooth transition.
Social	Perception of road transport as inefficient and pollutant medium.	Noise of trucks can be up to 90 db, however, it does not show any (reported) risk. Transport is labor intensive as the number of hours on the road can be large.
Environmental	System still fully dependent on fossil fuels.	As renewable energy is aimed to be introduced to the current system, replacing fossil sources for transport would have a large long term GHG emissions reduction.

References:

- International Energy Agency (IEA) (2017). The Future of Trucks.
- Rolande, LNG refueling station operator
- Uk Department for Transport (2010) Truck Specification for Best Operational Efficiency. Retrieved from: https://ukerc.rl.ac.uk/pdf/Truck_Best_Operational_Efficiency.pdf
- Yang, C., & Ogden, J. (2007). Determining the lowest-cost hydrogen delivery mode. *International Journal of Hydrogen Energy*, *32*(2), 268-286.
- Wang, J. & Rakha, H. (2017). Fuel consumption model for heavy duty diesel trucks: Model development and testing. Transportation Research Part D 55 127–141

T4: Road Gas H_2 - compressed gas tanks (tube trailers)

Data sheet prepared by/owner: Tim Lauret, Frames

Data sheet reviewed by: Jonathan Moncada & Andrea Ramirez, Delft University of Technology

Technology Description: Transport of compressed Hydrogen in tube trailers pressurized to 500 bar, driving an average of 100,000 km per year and 100 km per trip. To calculate operational costs in this factsheet, an average cruising speed of 40 km/h was assumed (based on literature). Loading and unloading were calculated based on compression needs. Fuel efficiency was assumed as 30 L / 100 km, which is a typical value for large-scale trucks in the Netherlands. Maximum truck weight was set to 45 tonnes. For this system, the largest trailer capacity available (26 Cubic meters, @ 500 bar g = 1,100 kg per container trailer) is considered. Trailer and cabin weight are assumed to be roughly 30 tonnes. Estimated capacity transported per truck per trip equals to 1.1 tonne of Hydrogen, driving 100,000 km/y, trips of 100 km each. Diesel is assumed as the fuel and costs are estimated over a one-way trip.

Key Performance Indicators (KPIs)

Technological		Economic				Environmental	
		Year	**Base year (2019 - 2034)**	**2030**	**2050**		
TRL	8	Transportation costs (€/t CGH_2 .km)	3.34	N/A	N/A	Fuel type	Diesel
Capacity (TJ/truck.y)	157	Transportation costs (€/t H2-eq.km)				Fuel consumption (L/t CGH_2.km)	0.27
Capacity (ktonne/truck.y)	1.1					Heat (MJ/t CGH_2.km)	-
Capacity (ktonne H_2-eq/truck.y)	1.1					Electricity (kWh/t CGH_2.km)	1.45
Concentration of transported product (wt.%)	99					GHG emissions (kg CO_2-eq/t CGH2.km	1.13

Notes:

- This system assumes an average transport distance of 100,000 km per year and single trips of 100 km each. Return trip was not considered.
- OPEX was estimated using typical cost structure for road transport including the categories: fuel, maintenance and repair, labor, insurance and tire.Electricity for compression was accounted for.
- The annualized CAPEX was calculated for a period of 6 years and interest rate of 5% for truck.
- Compression and decompression capital costs were estimated approx. to 1.5 M€ with a lifetime of 20 years.

Quality Assessment

The following matrix shows the scores on quality assessment of data inputs and indicators grouped as total system.

Uncertainty for Data Inputs				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	3	3	3	2
Economic	3	3	3	2
Environmental	3	3	3	3

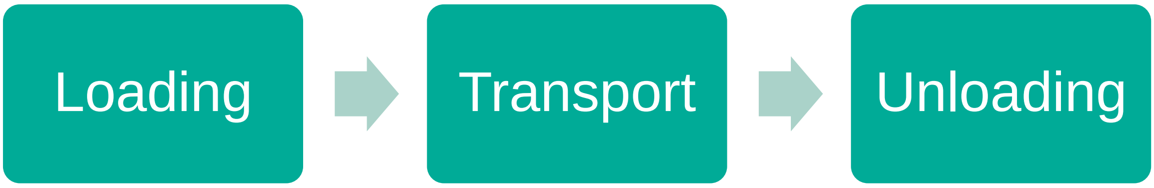
Uncertainty for Key Performance Indicator Outcomes				
Areas	Proxy	Empirical basis	Methodological rigour	Validation process
Technical	3	3	3	3
Economic	3	2	3	2
Environmental	3	2	3	1

Notes:

- Transport scored high for all input parameters as information on trucks is widely available in the public domain and technical specifications of stainless steel tankers are easily accessible. Validation process for data inputs however scores low as there could be different region dependant

inputs such as fuel consumption, truck costs, cruise speed etc, which can differ from truck to truck in the Netherlands. Environmental inputs in this case depends on emissions factor for diesel, which has been widely studied during the last decades.
- Scores on technical outputs are well understood as payload for trucks are available in the public domain and EC legislation, thus evaluating the amount of product is easily achievable.
- Scores on economic outputs are relatively high as the system is well understood and checked with LNG truck operator. Only trailer cost is changed for compressed gaseous hydrogen. Fuel is a major contributor to costs, and its consumption can drastically differ from aspects such as road type, driver's behavior, geography, etc.
- Environmental outputs are dependent on fuel consumption levels which is uncertain for each case. Average data was used, and validation of emissions was not directly possible to be carried out. However, the approach is considered as best available practice

Process flow diagram



Risks and opportunities

	Risks	Opportunities
Technological	A technological risk that was identified for this system is the change on car fleet when new types of fuels penetrate the system. Transport is still highly dependent on fossil sources. Safety in loading and unloading might represent a technology risk.	Transport of compressed CNG in tube trailers is an already mature technology. The tube trailers do not become obsolete when the truck fleet needs to change due to the need to implement alternative fuel types.
Economic	Compression costs are significant in loading tube trailers. Personal salaries is one of the major contributors to transport costs.	Maturity of road transport of chemicals can benefit hydrogen economy from fast learning curves.
Political	Transitioning to renewable car fleet is still a major political challenge.	In order to meet environmental targets, replacing current car fleet would require policies and incentives for smooth transition.

Social	Perception of road transport as inefficient and pollutant medium. Risk of explosion due to high pressure. Safety can change the perception of the technology.	Noise of trucks can be up to 90 db, however, it does not show any (reported) risk. Transport is labor intensive as the number of hours on the road can be large.
Environmental	System still fully dependent on fossil fuels. The major contributor to emissions is in this case electricity needed for compression. Transition to renewable electricity from the grid is not possible to be captured with current numbers.	As renewable energy is aimed to be introduced to the current system, replacing fossil sources for transport would have a large long term GHG emissions reduction.

References:

- International Energy Agency (IEA) (2017). The Future of Trucks.
- NKCF tube trailer specification for CNG transport.
- Shell Hydrogen Study, Energy of the Future? Sustainable Mobility Through Fuel Cells and H2
- Uk Department for Transport (2010) Truck Specification for Best Operational Efficiency. Retrieved from: https://ukerc.rl.ac.uk/pdf/Truck_Best_Operational_Efficiency.pdf
- Wang, J. & Rakha, H. (2017). Fuel consumption model for heavy duty diesel trucks: Model development and testing. Transportation Research Part D 55 127–141
- World Bank Group Energy & Extractives (2015). Comparison of Mini-Micro LNG and CNG for commercialization of small volumes of associated gas. Public report. October 2015.

Hydrohub

T5a: Road Gas CH_4 (syn) - ISO container compressed gas tube trailers

Data sheet prepared by/owner: Jonathan Moncada & Andrea Ramirez, Delft University of Technology

Data sheet reviewed by: Eddy van Oort, Frames

Technology Description: Transport of Synthetic compressed methane in tube trailer pressurized to 250 bar, driving an average of 100,000 km per year and 100 km per trip.

To calculate operational costs in this datasheet, an average cruising speed of 40 km/h was assumed (based on literature). Loading and unloading were calculated based on compression needs. Fuel efficiency was assumed as 30 L/100 km, which is a typical value for large scale trucks in the Netherlands. Maximum truck weight was set to 45 tonnes, following the European Commission regulations.

For this system, the trailer capacity is 24640 water liters. Trailer and cabin weight were assumed to be roughly 26 tonnes. The estimated capacity transported per truck per trip is 4.1 tonne of CH4. On an annual basis, a truck is able to transport 4.1 ktonne of synthetic methane (driving 100,000 km/y and trips of 100 km each). Diesel was assumed as fuel. Costs were estimated for a one-way trip.

Key Performance Indicators (KPIs)

Technological		Economic				Environmental	
		Year	Base year (2019 - 2034)	2030	2050		
TRL	9	Transportation costs (€/t CH_4.km)	0.93			Fuel type	Diesel
Capacity (TJ/truck.y)	218	Transportation costs (€/t H_2-eq.km)	3.70			Fuel consumption (L/t CH_4.km)	0.07
Capacity (ktonne/truck.y)	4					Heat (MJ/t CH_4.km)	-
Capacity (ktonne H_2-eq/truck.y)	1					Electricity (kWh/t CH_4.km)	1.45
Concentration of transported product (wt.%)	99					GHG emissions (kg CO_2-eq/t CH_4.km	1.05

Notes:

- This system assumes an average transport distance of 100,000 km per year and single trips of 100 km each. Return trip was not considered.
- OPEX was estimated using typical cost structure for road transport including the following categories: fuel, maintenance and repair, labor, insurance and tire. Electricity for compression was included in the calculation.
- The annualized CAPEX was calculated for a period of 6 years and interest rate of 5% for truck.
- Compression and decompression capital costs were estimated approx. to 1.5 M€ with a lifetime of 20 years. Capital costs estimated in Aspen Economic Analyzer.

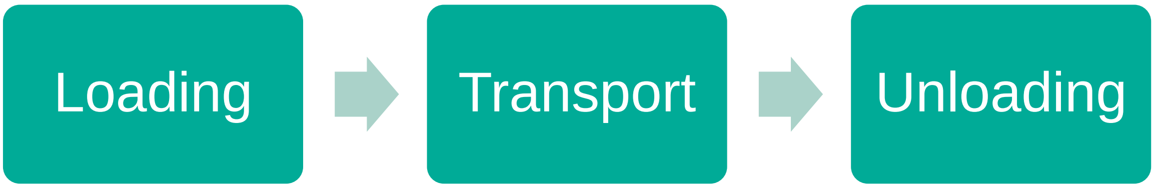
Quality Assessment

The following matrix shows the scores on quality assessment of data inputs and indicators grouped as total system.

Uncertainty for Data Inputs				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	3	3	3	2
Economic	3	3	3	2
Environmental	3	3	3	3

Uncertainty for Key Performance Indicator Outcomes				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	3	3	3	3
Economic	3	2	3	2
Environmental	3	2	3	1

Process flow diagram



Risks and opportunities

	Risks	Opportunities
Technological	Safety in loading and unloading might represent a technology risk. A technological risk that was identified for this system is the change on car fleet when new types of fuels penetrate the system. The risk on heavy road transport is that a transition to a renewable fleet is still very immature. Transport is still highly dependent on fossil sources. Safety in loading and unloading might represent a technology risk.	Transport of compressed CNG in tube trailers is an already mature technology which can facilitate their deployment.
Economic	Costs can significantly increase by changes in the fleet, and fuel type. Compression costs are significant in loading tube trailers. Personal salaries is one of the major contributors to transport costs.	Maturity of road transport of chemicals can benefit hydrogen economy due to rapid learning curves.
Political	Transitioning to a fully renewable car fleet is still a major political challenge.	In order to meet environmental targets, replacing the current car fleet would require significant policies and incentives for a smooth transition.
Social	There is perception of road transport as inefficient and pollutant medium. Risk of explosion due to high pressure. Concerns on safety can change the perception of the technology.	Noise of trucks can be up to 90 db, however, it does not show any (reported) risk. Transport is labor intensive as the number of hours on the road can be large.
Environmental	System still fully dependent on fossil fuels. The major contributor to emissions is in this case electricity needed for compression, as for this data sheet electricity from the grid in 2017 was assumed.	As renewable energy is aimed to be introduced to the current system, replacing current fuels with low carbon fuels for transport would have a large long term GHG emissions reduction.

References:

- ENK (n.d) ENK Catalogue. NKCF tube trailer specification for CNG transport. Retrieved from: http://nkcf.com/en/data/file/sub6_4_E/3672952421_TBWdpyxF_6ce07f3253ba604049bdfd97f0d0869f61b168b3.pdf
- International Energy Agency (IEA) (2017). The Future of Trucks. Retrieved from : https://www.iea.org/publications/freepublications/publication/TheFutureofTrucksImplicationsforEnergyandtheEnvironment.pdf
- Uk Department for Transport (2010) Truck Specification for Best Operational Efficiency. Retrieved from: https://ukerc.rl.ac.uk/pdf/Truck_Best_Operational_Efficiency.pdf
- Wang, J. & Rakha, H. (2017). Fuel consumption model for heavy duty diesel trucks: Model development and testing. Transportation Research Part D 55 127–141
- World Bank Group Energy & Extractives (2015). Comparison of Mini-Micro LNG and CNG for commercialization of small volumes of associated gas. Public report. October 2015.

T5b: Road Gas CH_4(syn): Compressed gas in cylinder modules

Data sheet prepared by/owner: Jonathan Moncada & Andrea Ramirez, Delft University of Technology

Data sheet reviewed by: Eddy van Oort, Frames

Technology Description: Transport of Synthetic compressed methane in tube trailer modules (galileo) pressurized to 250 bar, driving an average of 100,000 km per year and 100 km per trip.

To calculate operational costs in this datasheet, an average cruising speed of 40 km/h was assumed (based on literature). Loading and unloading were calculated based on compression needs. Fuel efficiency was assumed as 30 L/100 km, which is a typical value for large scale trucks in the Netherlands. Maximum truck weight was set at 40 tonnes, following the European Commission regulations.

For this system, trucks containing 4 modules were assumed, which summed up to 23,400 L of hydraulic capacity. Trailer and cabin weight were assumed to be roughly 26 tonnes. One truck can transport 3.9 tonnes of methane per trip. On an annual basis, a truck is able to transport 3.9 ktonne of CH_4 (driving 100,000 km/y and trips of 100 km each). Diesel was assumed as fuel. Costs were estimated as one way trip.

Key Performance Indicators (KPIs)

Technological		**Economic**				**Environmental**	
		Year	**Base year (2019 - 2034)**	**2030**	**2050**		
TRL	9	Transportation costs (€/t CH_4.km)	0.97	N/A	N/A	Fuel type	Diesel
Capacity (TJ/truck.y)	207	Transportation costs (€/t H_2-eq.km)	3.87	N/A	N/A	Fuel consumption (L/t CH_4.km)	0.08
Capacity (ktonne/truck.y)	4					Heat (MJ/t CH_4.km)	-
Capacity (ktonne H_2-eq/truck.y)	1					Electricity (kWh/t CH_4.km)	1.45
Concentration of transported product (wt.%)	99					GHG emissions (kg CO_2-eq/t CH_4.km	1.05

Notes:

- This system assumes an average transport distance of 100,000 km per year and single trips of 100 km each. The return trip was not considered.
- OPEX was estimated using typical cost structure for road transport including the following categories: fuel, maintenance and repair, labor, insurance and tire. Electricity for compression was accounted for.
- The annualized CAPEX was calculated for a period of 6 years and an interest rate of 5% per truck.
- Compression and decompression capital costs were estimated approx. to 1.5 M€ with a lifetime of 20 years. Capital costs for compression were estimated in Aspen Economic Analyzer

Quality Assessment

The following matrix shows the scores on quality assessment of data inputs and indicators grouped as total system.

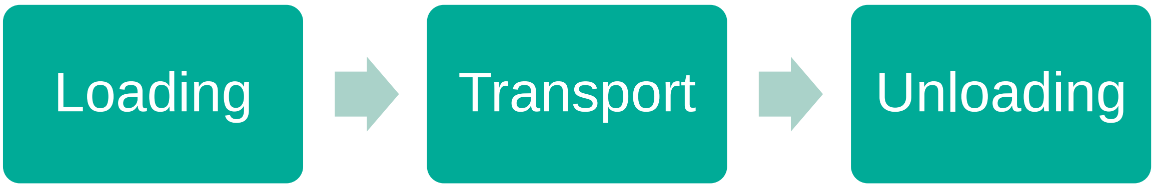
Uncertainty for Data Inputs				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	3	3	3	2
Economic	3	3	3	2
Environmental	3	3	3	3

Uncertainty for Key Performance Indicator Outcomes				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	3	3	3	3
Economic	3	2	3	2
Environmental	3	2	3	1

Notes:

- Transport scored high for all input parameters as information on trucks is widely available in the public domain and technical specifications of compressed cylinder modules are easily accessible. Validation process for data inputs, however, scores low as there could be different region dependant inputs such as fuel consumption, truck costs, cruise speed etc, which can differ from truck to truck in the Netherlands. Environmental inputs in this case depends on the emissions factor for diesel, which has been widely studied during the last decades.
- Scores on technical outputs are well understood as payload for trucks are available in the public domain and EC legislation, thus evaluating the amount of product is easily achievable.
- Scores on economic outputs are relatively high as the system is well understood, however, it is still model derived data to breakdown costs elements such as fuel consumption were estimated as an average for the heavy duty fleet in the Netherlands. Fuel is a major contributor to costs, and its consumption can drastically differ due to factors such as road type, driver's behavior, geography, etc. Direct validation was not possible for the Dutch case, however, costs are in the typical range for trucks.
- Environmental outputs are dependent on fuel consumption levels which are uncertain for each case. Average data was used, and validation of emissions was not possible. However, the approach is considered as best available practice

Process flow diagram



Notes:

- Road transport of methane in compressed cylinder modules pressurized to 250 bar, which in average drives 100,000 km per year
- Transport only one way. Return trip not considered in calculations

Risks and opportunities

	Risks	Opportunities
Technological	A technological risk that was identified for this system is the change on car fleet when new types of fuels penetrate the system. The risk on heavy road transport is that a transition to a renewable fleet is still very immature. Transport is still highly dependent on fossil sources. Safety in loading and unloading might represent a technology risk.	Transport of compressed CNG in tube trailers is an already mature technology which could facility the deployment in the short term

Economic	Costs can significantly increase by changing the fleet, and fuel type. Compression costs are significant in loading tube trailers. Personal salaries is one of the major contributors to transport costs.	Maturity of road transport of chemicals can benefit a hydrogen economy due to fast learning curves.
Political	Transitioning to a renewable car fleet is still a major political challenge.	In order to meet environmental targets, replacing the current car fleet will require significant policies and incentives for a smooth transition
Social	There is social perception of road transport as inefficient and pollutant medium. Risk of explosion due to high pressure. Safety concerns can change the perception of the technology.	Noise of trucks can be up to 90 db, however, it does not show any (reported) risk. Transport is labor intensive as the number of hours on the road can be large.
Environmental	The transport system is still fully dependent on fossil fuels. The major contributor to emissions is in this case electricity needed for compression.	As renewable energy is aimed to be introduced to the current system, replacing fossil fuels for transport would have a positive impact in large long term GHG emissions reduction.

References:

- Galileo technologies (n.d.) Microbox-Bio™ Biomethane gas upgrading and compression package & Virtual Pipeline™. Retrieved from: http://blank.ecomondo.com/upload/Allegati_com_aziende/RIC16/0010830_513.pdf
- International Energy Agency (IEA) (2017). The Future of Trucks. Retrieved from : https://www.iea.org/publications/freepublications/publication/TheFutureofTrucksImplicationsforEnergyandtheEnvironment.pdf
- Uk Department for Transport (2010) Truck Specification for Best Operational Efficiency. Retrieved from: https://ukerc.rl.ac.uk/pdf/Truck_Best_Operational_Efficiency.pdf
- Wang, J. & Rakha, H. (2017). Fuel consumption model for heavy duty diesel trucks: Model development and testing. Transportation Research Part D 55 127–141
- World Bank Group Energy & Extractives (2015). Comparison of Mini-Micro LNG and CNG for commercialization of small volumes of associated gas. Public report. October 2015.

T5c: Road Gas LNG

Data sheet prepared by/owner: Tim Lauret, Frames in collaboration with Rolande

Data sheet reviewed by: Jonathan Moncada & Andrea Ramirez, Delft University of Technology

Technology Description: Transport of LNG in stainless steel semi trailer driving an average of 100,000 km per year and 100 km per trip.

To calculate operational costs in this data sheet, an average cruising speed of 60 km/h was assumed (based on literature) and 25% extra time of that spent on road for loading and unloading LNG. Fuel efficiency was assumed as 24 KGLNG/100 km which is a typical value received from a LNG tank station operator in The Netherlands. Maximum truck weight was set to 40 tonnes with typical LNG payload of 19 ton. Diesel was assumed as the fuel.

Key Performance Indicators (KPIs)

Technological		**Economic**				**Environmental**	
		Year	**Base year (2019 - 2034)**	**2030**	**2050**		
TRL	9	Transportation costs (€/t Met.km)	0.11	N/A	N/A	Fuel type	Diesel
Capacity (TJ/truck/y)	923	Transportation costs (€/t H_2-eq.km)	38.37	N/A	N/A	Fuel consumption (L/t Met.km)	0.014
Capacity (ktonne/truck/y)	19					Heat (MJ/t Met.km)	-
Capacity (ktonne H_2-eq/truck/y)	19					Electricity (kWh/t Met.km)	-
Concentration of transported product (wt.%)	100%					GHG emissions (kg CO_2-eq/t Met.km	0.006

Notes:

- This system assumes an average transport distance of 100000 km per year and single trips of 100 km each. Return trip was not considered.
- OPEX was estimated using typical cost structure for road transport including the categories: fuel, maintenance and repair, labor, insurance and tires
- The annualized CAPEX was calculated for a period of 6 years and interest rate of 5%.
- Capacity and Transportation costs in H_2-eq not given as cracking back to Hydrogen is not considered an economically feasible route.

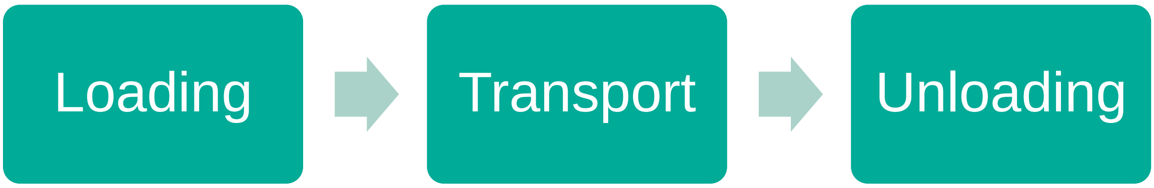
Quality Assessment

The following matrix shows the scores on quality assessment of data inputs and indicators grouped as total system.

Uncertainty for Data Inputs				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	3	3	3	2
Economic	3	3	3	2
Environmental	3	3	3	3

Uncertainty for Key Performance Indicator Outcomes				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	3	3	3	3
Economic	3	2	3	2
Environmental	3	2	3	2

Process flow diagram



Risks and opportunities

	Risks	Opportunities
Technological	A technological risk that was identified for this system is the change on car fleet when new types of fuels penetrate the system. Transport is still highly dependent on fossil sources	Transport of LNG is an already mature technology. The trailers do not become obsolete when the truck fleet needs to change due to the implementation of alternative fuels.
Economic	Personal salaries is one of the major contributors to transport costs.	Maturity of road transport of chemicals can benefit hydrogen economy from fast learning curves.
Political	Transitioning to renewable car fleet is still a major political challenge.	In order to meet environmental targets, replacing current car fleet would require policies and incentives for a smooth transition.
Social	Perception of road transport as inefficient and pollutant medium.	Noise of trucks can be up to 90 db, however, it does not show any (reported) risk. Transport is labor intensive as the number of hours on the road can be large.
Environmental	System still fully dependent on fossil fuels.	As renewable energy is aimed to be introduced to the current system, replacing fossil sources for transport would have a large long term GHG emissions reduction.

References:

- International Energy Agency (IEA) (2017). The Future of Trucks.
- Rolande, LNG refueling station operator
- Wang, J. & Rakha, H. (2017). Fuel consumption model for heavy duty diesel trucks: Model development and testing. Transportation Research Part D 55 127–141

T6: Road Gas DME: ISO containers/fuel tankers

Data sheet prepared by/owner: Jonathan Moncada & Andrea Ramirez, Delft University of Technology

Data sheet reviewed by: Eddy van Oort, Frames

Technology Description: Transport of Liquified DME in 40 ft ISO container pressurized to 10 bar and ambient temperature, driving an average of 100,000 km per year and 100 km per trip.

To calculate operational costs in this datasheet, an average cruising speed of 60 km/h was assumed (based on literature). Loading and unloading were calculated based on pumping needs. Fuel efficiency was assumed as 30 L/100 km, which is a typical value for large scale trucks in the Netherlands. Maximum truck weight was set to 45 tonnes, following the European Commission regulations.

For this system, the trailer capacity is estimated at 43,500 liters. Trailer and cabin weight were assumed to be roughly 19 tonnes. The estimated capacity transported per truck per trip was 26 tonne of DME. On an annual basis, a truck is able to transport 26 ktonne of DME (driving 100,000 km/y and trips of 100 km each). The ISO container was modeled as an LPG container but adapted to the DME case.

Diesel was assumed as fuel. Costs were estimated as one way trip.

Key Performance Indicators (KPIs)

Technological		Economic				Environmental	
		Year	**Base year (2019 - 2034)**	**2030**	**2050**		
TRL (scaled to Nth of a kind)	9	Transportation costs (€/t DME.km)	0.1	N/A	N/A	Fuel type	Diesel
Capacity (TJ/truck.y)	754	Transportation costs (€/t H_2-eq.km)	0.75	N/A	N/A	Fuel consumption (L/t DME.km)	0.01
Capacity (ktonne/truck.y)	26					Heat (MJ/t DME.km)	-
Capacity (ktonne H_2-eq/truck.y)	3.4					Electricity (kWh/t DME.km)	0.16
Concentration of transported product (wt.%)	99					GHG emissions (kg CO_2-eq/t DME.km)	0.11

Notes:

- This system assumes an average transport distance of 100,000 km per year and single trips of 100 km each. Return trip was not considered.
- OPEX was estimated using a typical cost structure for road transport including the categories: fuel, maintenance and repair, labor, insurance and tires. Electricity for compression was accounted for.
- The annualized CAPEX was calculated for a period of 6 years and an interest rate of 5% per truck.
- Capital costs of pumping for loading and unloading were estimated approx. to 250,000 € with a lifetime of 20 years.
- 1.35€/L diesel price; 60,000€/y assumed salary based on average Dutch personnel costs; 90,000€ Volvo FH16 cabin, conservative approach overestimated to account for extra components; 32,000€ average ISO container costs

Quality Assessment

The following matrix shows the scores on quality assessment of data inputs and indicators grouped as total system.

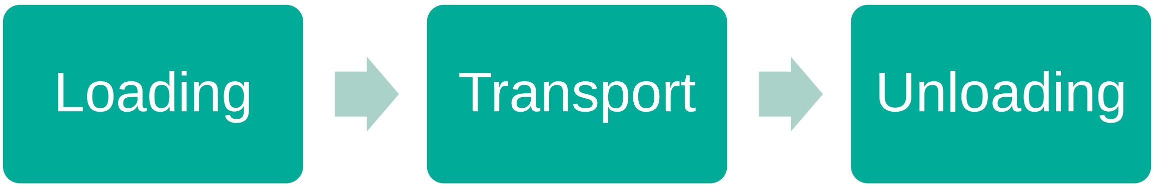
Uncertainty for Data Inputs				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	2	2	2	2
Economic	3	3	3	2
Environmental	3	3	3	3

Uncertainty for Key Performance Indicator Outcomes				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	3	3	3	3
Economic	3	2	3	2
Environmental	3	2	3	1

Notes:

- Transport scored low for all input technical parameters as most information on ISO containers trucks is widely available in the public domain for LPG but not necessarily available for DME. Validation process for data inputs however scores low as there could be different region dependant inputs such as fuel consumption, truck costs, cruise speed etc, which can differ from truck to truck in the Netherlands. Environmental inputs in this case depend on the emissions factor for diesel, which has been widely studied during the last decades.
- Scores on technical outputs are well understood as payload for trucks are available in the public domain and EC legislation, thus evaluating the amount of product is easily achievable.
- Scores on economic outputs are relatively high as the system is well understood, however, it is still model derived data to breakdown costs elements such as fuel consumption estimated as an average for the heavy duty fleet in the Netherlands. Fuel is a major contributor to costs, and its consumption can drastically differ from aspects such as road type, driver's behavior, geography, etc. Direct validation was not possible for the Dutch case, however, costs are in the typical range for trucks.
- Environmental outputs are dependent on fuel consumption levels which is uncertain for each case. Average data was used, and validation of emissions was not directly possible to be carried out. However, the approach is considered as best available practice.

Process flow diagram



Notes

- Road transport of liquid DME using LPG ISO container , which in average drives 100000 km per year
- Transport only one way. Return trip not considered in calculations
- Loading and unloading include pumping and cooling operations

Risks and opportunities

	Risks	Opportunities
Technological	Loading and unloading require special safety measures. However that is a common practice today.	DME transport is known, and could become very important as some studies indicate that cars and trucks are expected to run on DME in the future.
Economic	Pumping/cooling costs are significant in loading/unloading DME in ISO containers. Personal salaries is one of the major contributors to transport costs.	Maturity of road transport of DME can benefit hydrogen economy from fast learning curves.
Political	N/A	DME is moving forward as a potential fuel. Trucks running on DME can be found in Japan and China.
Social	Risk of explosion due to high pressure. Safety can change the perception of the technology.	Noise of trucks can be up to 90 db, however, it does not show any (reported) risk. Transport is labor intensive as the number of hours on the road are large.
Environmental	The major contributor to emissions is in this case the electricity needed for cooling and pressurization.	Noise of trucks can be up to 90 db, however, it does not show any (reported) risk. Transport is labor intensive as the number of hours on the road are large.

References:

- Department of transport UK (2010) Truck Specification for Best Operational Efficiency. Freight best practice. Retrieved from https://ukerc.rl.ac.uk/pdf/Truck_Best_Operational_Efficiency.pdf
- Wang, J., & Rakha, H. A. (2017). Fuel consumption model for heavy duty diesel trucks: Model development and testing. Transportation Research Part D: Transport and Environment, 55, 127-141.
- Teter, J., Cazzola, P., Gul, T., Mulholland, E., Le Feuvre, P., Bennett, S., ... & Scheffer, S. (2017). The future of trucks: implications for energy and the environment. https://www.iea.org/publications/freepublications/publication/TheFutureofTrucksImplicationsforEnergyandtheEnvironment.pdf
- Müller & Hübsch (2000) Dimethyl ether. Ullmann's Encyclopedia of Industrial Chemistry.
- ELGAS (2019) LPG transport. Retrieved from https://www.elgas.com.au/blog/1715-how-lpg-propane-is-transported-ships-trucks-rail-pipelines

T7: Road Fuel truck liquid NH_3 (onshore)

Data sheet prepared by/owner: OCI Nitrogen in Collaboration with Jonathan Moncada & Andrea Ramirez Delft University of Technology

Data sheet reviewed by: Eddy van Oort, Frames

Technology Description:

Transport of Ammonia in dedicated trailers or T10-type tank containers of maximum 20 tonnes. The same vessels typically also can be used to carry LPG. These trucks transport cargo in a liquid form, under pressure on local routes, typically in a radius below 200 km. In many countries truck transport is under strict regulations due to the hazardous nature of ammonia. This data sheet was assessed assuming that the truck drives an average of 100,000 km per year and 100 km per trip.

To calculate operational costs in this datasheet, an average cruising speed of 60 km/h was assumed (based on literature). Loading and unloading were calculated based on pumping needs. Fuel efficiency was assumed as 40 L/100 km, which is a typical value for large scale trucks in the Netherlands. Maximum truck weight was set to 20 tonnes, following the European Commission regulations.

For this system, the trailer capacity is estimated at 16,400 liters. Trailer and cabin weight were assumed to be roughly 9 tonnes. The estimated capacity transported per truck per trip was 20 tonnes of Ammonia. On an annual basis, a truck is able to transport 10 ktonnes of Ammonia (driving 100,000 km/y and trips of 100 km each).

Diesel was assumed as fuel. Costs were estimated as one way trip.

Key Performance Indicators (KPIs)

Technological		Economic				Environmental	
		Year	**Base year (2019 - 2034)**	**2030**	**2050**		
TRL (scaled to Nth of a kind)	9	Transportation costs (€/t $NaBH_4$.km)	0.2	N/A	N/A	Fuel type	Diesel
Capacity (TJ/truck.y)	186	Transportation costs (€/t H_2-eq.km)	1.11	N/A	N/A	Fuel consumption (L/t NH_3.km)	0.04
Capacity (ktonne/truck.y)	10					Heat (MJ/t NH_3.km)	-
Capacity (ktonne H_2-eq/truck.y)	1.8					Electricity (kWh/t NH_3.km)	0.07
Concentration of transported product (wt.%)	99					GHG emissions (kg CO_2-eq/t NH_3.km)	0.07

Notes:

- This system assumes an average transport distance of 100,000 km per year and single trips of 100 km each. Return trip was not considered.
- OPEX was estimated using a typical cost structure for road transport including the categories: fuel, maintenance and repair, labor, insurance and tires. Electricity for compression was accounted for.
- The annualized CAPEX was calculated for a period of 6 years and an interest rate of 5% per truck.
- Capital costs of pumping for loading and unloading were estimated approx. to 450,000 € with a lifetime of 20 years. Estimation using Aspen Plus.
- All-in costs for a 100km round trip is about 40-50€/ton.
- 1.35€/L diesel price; 60,000€/y assumed salary based on average Dutch personnel costs; 90,000€ Volvo FH16 cabin, conservative approach overestimated to account for extra components; 25,000€ T-10 trailer type costs

Quality Assessment

The following matrix shows the scores on quality assessment of data inputs and indicators grouped as total system.

Uncertainty for Data Inputs				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	3	3	3	2
Economic	3	3	3	2
Environmental	3	3	3	3

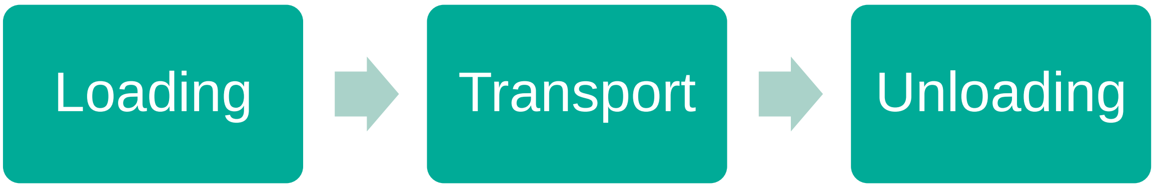
Uncertainty for Key Performance Indicator Outcomes				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	3	3	3	3
Economic	3	2	3	2
Environmental	3	2	3	1

Notes:

- Transport scored high for all input technical parameters as most information on T-10 trucks is widely available in the public domain for LPG and NH_3. Validation process for data inputs however scores low as there could be different region dependant inputs such as fuel consumption, truck costs, cruise speed etc, which can differ from truck to truck in the Netherlands. Environmental inputs in this case depend on the emissions factor for diesel, which has been widely studied during the last decades.
- Scores on technical outputs are well understood as payload for trucks are available in the public domain and EC legislation, thus evaluating the amount of product is easily achievable.
- Scores on economic outputs are relatively high as the system is well understood, however, it is still model derived data to breakdown costs elements such as fuel consumption estimated as an average for the heavy duty fleet in the Netherlands. Fuel is a major contributor to costs, and its consumption can drastically differ from aspects such as road type, driver's behavior, geography,

etc. Direct validation was not possible for the Dutch case, however, costs are in the typical range for trucks.
- Environmental outputs are dependent on fuel consumption levels which is uncertain for each case. Average data was used, and validation of emissions was not directly possible to be carried out. However, the approach is considered as best available practice.

Process flow diagram



Risks and opportunities

	Risks	Opportunities
Technological	Loading and unloading require special safety measures. However that is a common practice today.	NH_3 transport is known, and could become very important as some studies indicate that NH_3 can have a very important contribution in the energy market.
Economic	Pumping/cooling costs are significant in loading/unloading NH_3 in T-type container. Personal salaries is one of the major contributors to transport costs. Low volumes and high costs compared to train/barge/pipeline/etc	Maturity of road transport of NH_3 can benefit hydrogen economy from fast learning curves.
Political	Political acceptance of NH_3-truck transport can be an issue. In some countries it is considered an unacceptable risk.	NH_3 is moving forward as a potential fuel and energy carrier. NH_3 can be used as tanker fuel.
Social	Risk of explosion due to high pressure. Safety can change the perception of the technology.	Noise of trucks can be up to 90 db, however, it does not show any (reported) risk. Transport is labor intensive as the number of hours on the road are large.
Environmental	The major contributor to emissions is in this case the electricity needed for cooling and pressurization.	As renewable energy is aimed to be introduced to the current system, large long term GHG emissions reductions could be expected if electricity is zero carbon.

References:

- Department of transport UK (2010) Truck Specification for Best Operational Efficiency. Freight best practice. Retrieved from https://ukerc.rl.ac.uk/pdf/Truck_Best_Operational_Efficiency.pdf
- Wang, J., & Rakha, H. A. (2017). Fuel consumption model for heavy duty diesel trucks: Model development and testing. Transportation Research Part D: Transport and Environment, 55, 127-141.
- Teter, J., Cazzola, P., Gul, T., Mulholland, E., Le Feuvre, P., Bennett, S., ... & Scheffer, S. (2017). The future of trucks: implications for energy and the environment. https://www.iea.org/publications/freepublications/publication/TheFutureofTrucksImplicationsforEnergyandtheEnvironment.pdf
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- Direct communication with partners from OCI.

T8a: Road Fuel truck liquid Methanol

Data sheet prepared by/owner: Jonathan Moncada & Andrea Ramirez, Delft University of Technology

Data sheet reviewed by: Eddy van Oort, Frames

Technology Description:

Transport of methanol in stainless steel semi trailer driving an average of 100,000 km per year and 100 km per trip.

To calculate operational costs in this datasheet, an average cruising speed of 60 km/h was assumed (based on literature) and 25% extra time of that was assumed to be spent for loading and unloading methanol. Fuel efficiency was assumed as 30 L/100 km, which is a typical value for large scale trucks in the Netherlands. Maximum truck weight was set to 40 tonnes, following the European Commission regulations.

For this system, the trailer capacity is 26,000 liters for transporting methanol at 99wt%. Trailer and cabin weight were assumed to be roughly 15 tonnes, leaving 25 tonne of maximum capacity for methanol transport per trip. On an annual basis, a truck is able to transport 20 ktonne of methanol (driving 100,000 km/y and trips of 100 km each).

Diesel was assumed as fuel. The analysis presented here only considers one way trips.

Key Performance Indicators (KPIs)

Technological		Economic				Environmental	
		Year	Base year (2019 - 2034)	2030	2050		
TRL (scaled to Nth of a kind)	9	Transportation costs (€/t Met.km)	0.065	N/A	N/A	Fuel type	Diesel
Capacity (TJ/truck.y)	410	Transportation costs (€/t H_2-eq.km)	0.5	N/A	N/A	Fuel consumption (L/t Met.km)	0.015
Capacity (ktonne/truck.y)	21					Heat (MJ/t Met.km)	-
Capacity (ktonne H_2-eq/truck.y)	2.6					Electricity (kWh/t Met.km)	-
Concentration of transported product (wt.%)	99					GHG emissions (kg CO_2-eq/t Met.km)	0.006

Notes:

- This system assumes an average transport distance of 100,000 km per year and single trips of 100 km each. Return trip was not considered.
- OPEX was estimated using typical cost structure for road transport including the categories: fuel, maintenance and repair, labor, insurance and tires
- The annualized CAPEX was calculated for a period of 6 years and interest rate of 5%.
- 1.35€/L diesel price; 60,000€/y assumed salary based on average Dutch personnel costs; 70,000€ Volvo FH16 cabin, conservative approach overestimated to account for extra components; 30,000€ average steel semi trailer costs.

Quality Assessment

The following matrix shows the scores on quality assessment of data inputs and indicators grouped as total system.

Uncertainty for Data Inputs				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	3	3	3	2
Economic	3	3	3	2
Environmental	3	3	3	3

Uncertainty for Key Performance Indicator Outcomes				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	3	3	3	3
Economic	3	2	3	2
Environmental	3	2	3	1

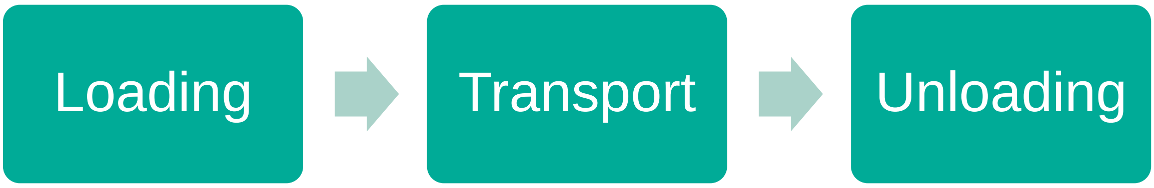
Notes:

- Transport scored high for all input parameters as information on trucks is widely available in the public domain and technical specifications of stainless steel tankers are easily accessible. Validation process for data inputs however scores low as there could be different region dependant inputs such as fuel consumption, truck costs, cruise speed etc, which can differ from truck to truck in the Netherlands. Environmental inputs in this case depends on emissions factor for diesel, which has been widely studied during the last decades.
- Scores on technical outputs are well understood as payload for trucks are available in the public domain and EC legislation, thus evaluating the amount of product is easily achievable.
- Scores on economic outputs are relatively high as the system is well understood, however, it is still model derived data to breakdown costs elements such as fuel consumption estimated as an average for the heavy duty fleet in the Netherlands and not specifically particular to the Methanol case. Fuel is a major contributor to costs, and its consumption can drastically differ from aspects

such as road type, driver's behavior, geography, etc. Direct validation was not possible for the Dutch case, however, costs are in the typical range for trucks.

- Environmental outputs are dependent on fuel consumption levels which is uncertain for each case. Average data was used, and validation of emissions was not possible to be carried out. However, the approach is considered as best available practice.

Process flow diagram



Notes:

- Road transport of methanol using a stainless steel semi-trailer which in average drives 100,000 km per year
- Transport only one way. Return trip not considered in calculations

Risks and opportunities

	Risks	Opportunities
Technological	Safety in loading and unloading might represent a technology risk. A technological risk that was identified for this system is the change on car fleet when new types of fuels penetrate the system. The risk on heavy road transport is that a transition to a renewable fleet is still very immature. Transport is still highly dependent on fossil sources and car fleets using alternative fuels still need further development.	Transport of chemicals is an already mature technology and thus the identification of bottlenecks and hotspots are very well known. Handling of hazardous substances is an already existing practice.
Economic	Costs can significantly increase by changes on the fleet, and fuel type. Personal salaries is one of the major contributors to transport costs.	Maturity of road transport of chemicals can benefit the hydrogen economy from fast learning curves.
Political	Transitioning to renewable car fleet is still a major political challenge.	In order to meet environmental targets, replacing the current car fleet would require policies and incentives for smooth transition.

Social	Perception of road transport as inefficient and pollutant medium.	Noise of trucks can be up to 90 db, however, it does not show any (reported) risk. Transport is labor intensive as the number of hours on the road can be large.
Environmental	Heavy duty transport is fully dependent on fossil fuels, which still represents a major risk to meet GHG emissions reduction as the transport sector is one of the major contributors to global emissions.	As renewable energy is aimed to be introduced to the current system, replacing fossil sources for transport would have a large long term GHG emissions reduction.

References:

- Department of transport UK (2010) Truck Specification for Best Operational Efficiency. Freight best practice. Retrieved from https://ukerc.rl.ac.uk/pdf/Truck_Best_Operational_Efficiency.pdf
- Wang, J., & Rakha, H. A. (2017). Fuel consumption model for heavy duty diesel trucks: Model development and testing. Transportation Research Part D: Transport and Environment, 55, 127-141.
- Teter, J., Cazzola, P., Gul, T., Mulholland, E., Le Feuvre, P., Bennett, S., ... & Scheffer, S. (2017). The future of trucks: implications for energy and the environment. https://www.iea.org/publications/freepublications/publication/TheFutureofTrucksImplicationsforEnergyandtheEnvironment.pdf

T8b: Road Fuel truck liquid LOHC (onshore)

Data sheet prepared by/owner: Jonathan Moncada & Andrea Ramirez, Delft University of Technology

Data sheet reviewed by: Eddy van Oort, Frames

Technology Description:

Transport of Dibenzyltoluene (DBT) in stainless steel semi trailer driving an average of 100,000 km per year and 100 km per trip.

To calculate operational costs in this datasheet, an average cruising speed of 60 km/h was assumed (based on literature) and 35% extra time of that was assumed to be spent for loading and unloading DBT. Fuel efficiency was assumed as 30 L/100 km, which is a typical value for large scale trucks in the Netherlands. Maximum truck weight was set to 40 tonnes, following the European Commission regulations.

For this system, the trailer capacity is 26,000 liters for transporting DBT at 99wt%. Trailer and cabin weight were assumed to be roughly 15 tonnes, leaving 25 tonne of maximum capacity for DBT transport per trip. On an annual basis, a truck is able to transport 25 ktonne of DBT (driving 100,000 km/y and trips of 100 km each).

Diesel was assumed as fuel. The analysis presented here only considers one way trips.

Key Performance Indicators (KPIs)

Technological		Economic				Environmental	
		Year	**Base year (2019 - 2034)**	**2030**	**2050**		
TRL (scaled to Nth of a kind)	9	Transportation costs (€/t DBT.km)	0.053	N/A	N/A	Fuel type	Diesel
Capacity (TJ/truck.y)	498	Transportation costs (€/t H_2-eq.km)	0.7	N/A	N/A	Fuel consumption (L/t DBT.km)	0.012
Capacity (ktonne/truck.y)	25					Heat (MJ/t DBT.km)	-
Capacity (ktonne H_2-eq/truck.y)	1.9					Electricity (kWh/t DBT.km)	-
Concentration of transported product (wt.%)	99					GHG emissions (kg CO_2-eq/t DBT.km)	0.005

Notes:

- This system assumes an average transport distance of 100000 km per year and single trips of 100 km each. Return trip was not considered.
- OPEX was estimated using typical cost structure for road transport including the categories: fuel, maintenance and repair, labor, insurance and tires
- The annualized CAPEX was calculated for a period of 6 years and interest rate of 5%.
- 1.35€/L diesel price; 60,000€/y assumed salary based on average Dutch personnel costs; 70,000€ Volvo FH16 cabin, conservative approach overestimated to account for extra components; 30,000€ average steel semi-trailer costs.

Quality Assessment

The following matrix shows the scores on quality assessment of data inputs and indicators grouped as total system.

Uncertainty for Data Inputs				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	3	3	3	2
Economic	3	3	3	2
Environmental	3	3	3	3

Uncertainty for Key Performance Indicator Outcomes				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	3	3	3	3
Economic	3	2	3	2
Environmental	3	2	3	1

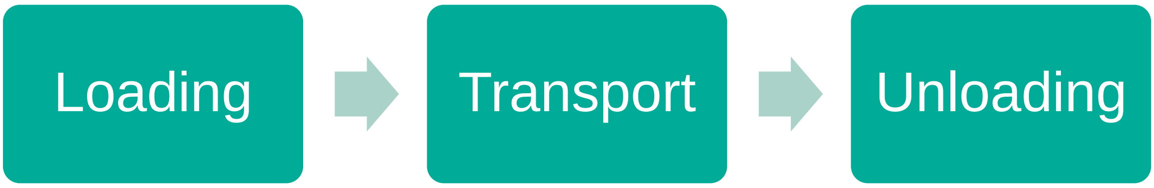
Notes:

- Transport scored high for all input parameters as information on trucks is widely available in the public domain and technical specifications of stainless steel tankers are easily accessible. Validation process for data inputs however scores low as there could be different region dependant inputs such as fuel consumption, truck costs, cruise speed etc, which can differ from truck to truck in the Netherlands. Environmental inputs in this case depends on emissions factor for diesel, which has been widely studied during the last decades.
- Scores on technical outputs are well understood as payload for trucks are available in the public domain and EC legislation, thus evaluating the amount of product is easily achievable.
- Scores on economic outputs are relatively high as the system is well understood, however, it is still model derived data to breakdown costs elements such as fuel consumption estimated as an average for the heavy duty fleet in the Netherlands and not specifically particular to the DBT case. Fuel is a major contributor to costs, and its consumption can drastically differ from aspects such as

road type, driver's behavior, geography, etc. Direct validation was not possible for the Dutch case, however, costs are in the typical range for trucks.

- Environmental outputs are dependent on fuel consumption levels which is uncertain for each case. Average data was used, and validation of emissions was not possible to be carried out. However, the approach is considered as best available practice.

Process flow diagram



Notes:

- Road transport of DBT using a stainless steel semi-trailer which in average drives 100,000 km per year
- Transport only one way. Return trip not considered in calculations

Risks and opportunities

	Risks	Opportunities
Technological	Safety in loading and unloading might represent a technology risk. A technological risk that was identified for this system is the change on car fleet when new types of fuels penetrate the system. The risk on heavy road transport is that a transition to a renewable fleet is still very immature. Transport is still highly dependent on fossil sources and car fleets using alternative fuels still need further development.	Transport of chemicals is an already mature technology and thus the identification of bottlenecks and hotspots are very well known. Handling of hazardous substances is an already existing practice.
Economic	Costs can significantly increase by changes on the fleet, and fuel type. Personal salaries is one of the major contributors to transport costs.	Maturity of road transport of chemicals can benefit the hydrogen economy from fast learning curves.
Political	Transitioning to renewable car fleet is still a major political challenge.	In order to meet environmental targets, replacing the current car fleet would require policies and incentives for smooth transition.

Social	Perception of road transport as inefficient and pollutant medium.	Noise of trucks can be up to 90 db, however, it does not show any (reported) risk. Transport is labor intensive as the number of hours on the road can be large.
Environmental	Heavy duty transport is fully dependent on fossil fuels, which still represents a major risk to meet GHG emissions reduction as the transport sector is one of the major contributors to global emissions.	As renewable energy is aimed to be introduced to the current system, replacing fossil sources for transport would have a large long term GHG emissions reduction.

References:

- Department of transport UK (2010) Truck Specification for Best Operational Efficiency. Freight best practice. Retrieved from https://ukerc.rl.ac.uk/pdf/Truck_Best_Operational_Efficiency.pdf
- Wang, J., & Rakha, H. A. (2017). Fuel consumption model for heavy duty diesel trucks: Model development and testing. Transportation Research Part D: Transport and Environment, 55, 127-141.
- Teter, J., Cazzola, P., Gul, T., Mulholland, E., Le Feuvre, P., Bennett, S., ... & Scheffer, S. (2017). The future of trucks: implications for energy and the environment. https://www.iea.org/publications/freepublications/publication/TheFutureofTrucksImplicationsforEnergyandtheEnvironment.pdf

T9: Road Fuel truck liquid Formic acid (onshore)

Data sheet prepared by/owner: Jonathan Moncada & Andrea Ramirez, Delft University of Technology

Data sheet reviewed by: Eddy van Oort, Frames

Technology Description: Transport of formic acid in stainless steel semi trailer driving an average of 100,000 km per year and 100 km per trip.

To calculate operational costs in this datasheet, an average cruising speed of 60 km/h was assumed (based on literature) and 25% extra time of that spent on road for loading and unloading the acid. Fuel efficiency was assumed as 30 L/100 km, which is a typical value for large scale trucks in the Netherlands. Maximum truck weight was set to 40 tonnes, following the European Commission regulations.

For this system, the trailer capacity is 26000 liters for transporting formic acid at 99wt%. Trailer and cabin weight were assumed to be roughly 15 tonnes, leaving 25 tonnes of maximum Formic acid transport capacity per trip. On an annual basis, a truck is able to transport 25 ktonne of formic acid (driving 100,000 km/y and trips of 100 km each).

Diesel was assumed as fuel. Calculations were done for one way trip. Return trips were not estimated in costs.

Key Performance Indicators (KPIs)

Technological		**Economic**				**Environmental**	
		Year	**Base year (2019 - 2034)**	**2030**	**2050**		
TRL	9	Transportation costs (€/t FA.km)	0.053	N/A	N/A	Fuel type	Diesel
Capacity (TJ/truck.y)	122	Transportation costs (€/t H_2-eq.km)	1.2	N/A	N/A	Fuel consumption (L/t FA.km)	0.012
Capacity (ktonne/truck.y)	25					Heat (MJ/t FA.km)	-
Capacity (ktonne H_2-eq/truck.y)	1.1					Electricity (kWh/t FA.km)	-
Concentration of transported product (wt.%)	99					GHG emissions (kg CO_2-eq/t FA.km	0.005

Notes:

- This system assumes an average transport distance of 100,000 km per year and single trips of 100 km each. Return trip was not considered.
- OPEX was estimated using typical cost structure for road transport including the categories: fuel, maintenance and repair, labor, insurance and tires.
- The annualized CAPEX was calculated for a period of 6 years and interest rate of 5%.

Quality Assessment

The following matrix shows the scores on quality assessment of data inputs and indicators grouped as total system.

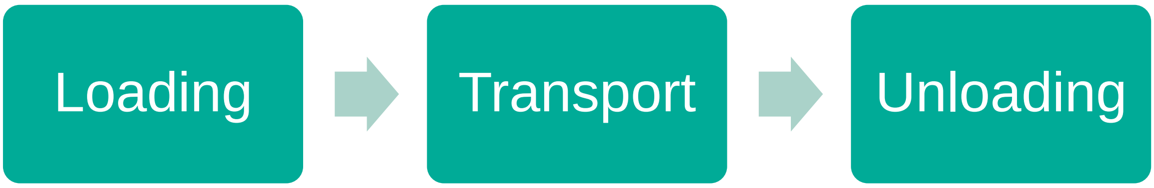
Uncertainty for Data Inputs				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	3	3	3	2
Economic	3	3	3	2
Environmental	3	3	3	3

Uncertainty for Key Performance Indicator Outcomes				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	3	3	3	3
Economic	3	2	3	2
Environmental	3	2	3	1

Notes:

- Transport scored high for all input parameters as information on trucks is widely available in the public domain and technical specifications of stainless steel tankers are easily accessible. Validation process for data inputs however scores low as there could be different region dependant inputs such as fuel consumption, truck costs, cruise speed etc., which can differ from truck to truck in the Netherlands. Environmental inputs in this case depends on emissions factor for diesel, which has been widely studied during the last decades.
- Scores on technical outputs are well understood as payload for trucks are available in the public domain and EC legislation, thus evaluating the amount of product is easily achievable.
- Scores on economic outputs are relatively high as the system is well understood, however, it is still model derived data to breakdown costs elements such as fuel consumption estimated as an average for the heavy duty fleet in the Netherlands and not specifically particular to the formic acid case. Fuel is a major contributor to costs, and its consumption can drastically differ from aspects such as road type, driver's behavior, geography, etc. Direct validation was not possible for the Dutch case, however, costs are in the typical range for trucks.
- Environmental outputs are dependent on fuel consumption levels which is uncertain for each case. Average data was used, and validation of emissions was not directly possible to be carried out. However, the approach is considered as best available practice.

Process flow diagram



Risks and opportunities

	Risks	Opportunities
Technological	Safety in loading and unloading might represent a technology risk. A technological risk that was identified for this system is the change on car fleet when new types of fuels penetrate the system. The risk on heavy road transport is that a transition to a renewable fleet is still very immature. Transport is still highly dependent on fossil sources and car fleets using alternative fuels still need further development.	Transport of chemicals is an already mature technology and thus the identification of bottlenecks and hotspots are very well known. Handling of hazardous substances is an already existing practice.
Economic	Costs can significantly increase by changing the fleet, and fuel type. Personal salaries is one of the major contributors to transport costs.	Maturity of road transport of chemicals can benefit the hydrogen economy from fast learning curves.
Political	Transitioning to renewable car fleet is still a major political challenge.	In order to meet environmental targets, replacing current car fleet would require significant policies and incentives for smooth transition
Social	Perception of road transport as inefficient and pollutant medium.	Noise of trucks can be up to 90 db, however, it does not show any (reported) risk. Transport is labor intensive as the number of hours on the road can be large.
Environmental	Heavy duty transport is fully dependent on fossil fuels, which still represents a major risk to meet GHG emissions reduction as the transport sector is one of the major contributors to global emissions.	As renewable energy is aimed to be introduced to the current system, replacing fossil sources for transport would have a large long term GHG emissions reduction.

References:

- International Energy Agency (IEA) (2017). The Future of Trucks. Retrieved from : https://www.iea.org/publications/freepublications/publication/TheFutureofTrucksImplicationsforEnergyandtheEnvironment.pdf
- Uk Department for Transport (2010) Truck Specification for Best Operational Efficiency. Retrieved from: https://ukerc.rl.ac.uk/pdf/Truck_Best_Operational_Efficiency.pdf
- Wang, J. & Rakha, H. (2017). Fuel consumption model for heavy duty diesel trucks: Model development and testing. Transportation Research Part D 55 127–141

T10: Road Truck bulk metal hydrides ($NaBH_4$)

Data sheet prepared by/owner: Jonathan Moncada & Andrea Ramirez, Delft University of Technology

Data sheet reviewed by: Eddy van Oort, Frames

Technology Description:

Transport of $NaBH_4$ in 40 ft high cube container in road trucks. Container packed with EUR Pallets containing 2x 50 kg NaBH4 drums each. Trucks driving an average of 100,000 km per year and 100 km per trip.

To calculate operational costs in this data sheet, an average cruising speed of 60 km/h was assumed (based on literature) and 25% extra time of that spent on road for loading and unloading the container. Fuel efficiency was assumed as 30 L/100 km, which is a typical value for large scale trucks in the Netherlands. Maximum truck weight was set to 40 tonnes, following the European Commission regulations.

For this system, considering arrangements of pallets in the container, the maximum possible net transport weight of NaBH4 is 6 tonne per trip. Trailer and cabin weight were assumed to be roughly 15 tonnes . On an annual basis, a truck is able to transport 6 ktonne of $NaBH_4$ (driving 100,000 km/y and trips of 100 km each).

Diesel was assumed as fuel. The analysis presented here only considers one way trips.

Key Performance Indicators (KPIs)

Technological		Economic				Environmental	
		Year	**Base year (2019 - 2034)**	**2030**	**2050**		
TRL (scaled to Nth of a kind)	9	Transportation costs (€/t $NaBH_4$.km)	0.21	N/A	N/A	Fuel type	Diesel
Capacity (TJ/ship.y)	182	Transportation costs (€/t H_2-eq.km)	2	N/A	N/A	Fuel consumption (t/t $NaBH_4$.km)	0.05
Capacity (ktonne/ship.y)	6					Heat (MJ/t Met.km)	-
Capacity (ktonne H_2-eq/ship.y)	0.6					Electricity (kWh/t Met.km)	-
Concentration of transported product (wt.%)	99					GHG emissions (kg CO_2-eq/t NaBH4.km)	0.02

Notes:

- This system assumes an average transport distance of 100000 km per year and single trips of 100 km each. Return trip was not considered.
- OPEX was estimated using typical cost structure for road transport including the categories: fuel, maintenance and repair, labor, insurance and tires
- The annualized CAPEX was calculated for a period of 6 years and interest rate of 5%.
- 1.35€/L diesel price; 60,000€/y assumed salary based on average Dutch personnel costs; 70,000€ Volvo FH16 cabin, conservative approach overestimated to account for extra components; 7,000€ average high cube 40ft container costs.

Quality Assessment

The following matrix shows the scores on quality assessment of data inputs and indicators grouped as total system.

Uncertainty for Data Inputs

Areas	Proxy	Empirical basis	Methodological rigour	Validation process
Technical	3	3	3	2
Economic	3	3	3	2
Environmental	3	3	3	3

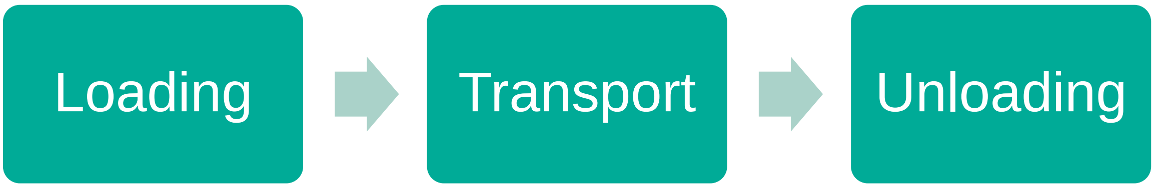
Uncertainty for Key Performance Indicator Outcomes

Areas	Proxy	Empirical basis	Methodological rigour	Validation process
Technical	3	3	3	2
Economic	3	2	3	2
Environmental	3	2	3	1

Notes:

- Transport scored high for all input parameters as information on trucks is widely available in the public domain and technical specifications of high cube containers are easily accessible. Data on drums weight, EUR pallets and pallets arrangements is easily accessible in the public domain. Validation process for data inputs however scores low as there could be different region dependant inputs such as fuel consumption, truck costs, cruise speed etc, which can differ from truck to truck in the Netherlands. Environmental inputs in this case depends on emissions factor for diesel, which has been widely studied during the last decades.
- Scores on technical outputs are well understood as payload for trucks are available in the public domain and EC legislation, thus evaluating the amount of product is easily achievable.
- Scores on economic outputs are relatively high as the system is well understood, however, it is still model derived data to breakdown costs elements such as fuel consumption estimated as an average for the heavy duty fleet in the Netherlands and not specifically particular to the NaBH4 case. Fuel is a major contributor to costs, and its consumption can drastically differ from aspects such as road type, driver's behavior, geography, etc. Direct validation was not possible for the Netherlands case, however, costs are in the typical range for trucks.
- Environmental outputs are dependent on fuel consumption levels which is uncertain for each case. Average data was used, and validation of emissions was not directly possible to be carried out. However, the approach is considered as best available practice

Process flow diagram



Notes:

- Road transport of NaBH4 using a high cube 40 ft container which in average drives 100,000 km per year
- Transport only one way. Return trip not considered in calculations

Risks and opportunities

	Risks	Opportunities
Technological	A technological risk that was identified for this system is that transport in EUR pallets with 2 iron steel drums containing 50kg of $NaBH_4$ each would limit the transport capacity of $NaBH_4$ if this is done in bulk.	Transport using EUR pallets of non bulky material is already mature
Economic	Costs can significantly increase by changing the fleet, and fuel type. Also the non-bulk	Transport in drums, EUR pallets and high cube containers is an already existing practice for non-bulky dry

	transport of $NaBH_4$ can affect transport costs for large scale applications. Personal salaries is one of the major contributors to transport costs.	materials. For hydrogen economy this can benefit from fast learning curves.
Political	Transitioning to a renewable car fleet is still a major political challenge.	In order to meet environmental targets, replacing current car fleet would require policies and incentives for smooth transition
Social	Perception of road transport as inefficient and pollutant medium.	Noise of trucks can be up to 90 db, however, it does not show any (reported) risk. Transport is labor intensive as the number of hours on the road can be large.
Environmental	System still fully dependent on fossil fuels, and given the limited transport of $NaBH_4$ in EUR pallets within high cube containers, specific environmental impacts related to transport tend to be higher in comparison to those for other chemicals.	As renewable energy is aimed to be introduced to the current system, replacing fossil sources for transport would have a large long term GHG emissions reduction.

References:

- Department of transport UK (2010) Truck Specification for Best Operational Efficiency. Freight best practice. Retrieved from https://ukerc.rl.ac.uk/pdf/Truck_Best_Operational_Efficiency.pdf
- Wang, J., & Rakha, H. A. (2017). Fuel consumption model for heavy duty diesel trucks: Model development and testing. Transportation Research Part D: Transport and Environment, 55, 127-141.
- Teter, J., Cazzola, P., Gul, T., Mulholland, E., Le Feuvre, P., Bennett, S., ... & Scheffer, S. (2017). The future of trucks: implications for energy and the environment. https://www.iea.org/publications/freepublications/publication/TheFutureofTrucksImplicationsforEnergyandtheEnvironment.pdf
- EPAL Pallets (2019) EPAL 1 Euro Pallet pallets. Retrieved from https://www.epal-pallets.org/eu-en/load-carriers/epal-euro-pallet/
- Seaplus (2009) Ocean container information. Retrieved from http://seaplus.com/container.html

T11: Shipping - $NaBH_4$

Data sheet prepared by/owner: Jonathan Moncada & Andrea Ramirez, Delft University of Technology

Data sheet reviewed by: Eddy van Oort, Frames

Technology Description:

Transport of $NaBH_4$ in 40 ft high cube containers in Panamax container ship with 5000 TEU capacity. The net weight of $NaBH_4$ that can be transported per trip is 15 ktonne (considering restriction in weight for panamax ships (52,000 DWT) and weight by drums and containers). It was assumed that the ship would exclusively transport $NaBH_4$ containers.

Shipping was modelled by considering an operation of 350 days/year, average fuel consumption of 166 tonnes of heavy fuel oil per day and assuming 7 days of loading and unloading. These inputs were gathered from literature and align with typical operation figures of container ships.

Single trips were assumed to cover a distance of 8,000 km. Speed was assumed as 25 knots. On an annual basis, a container ship is able to transport 370 ktonne of $NaBH_4$.

The analysis presented here only considers one way trips.

Key Performance Indicators (KPIs)

Technological		Economic				Environmental	
		Year	**Base year (2019 - 2034)**	**2030**	**2050**		
TRL (scaled to Nth of a kind)	9	Transportation costs (€/t $NaBH_4$.km)	0.00033	N/A	N/A	Fuel type	Heavy fuel oil
Capacity (TJ/ship.y)	11240	Transportation costs (€/t H_2-eq.km)	0.003	N/A	N/A	Fuel consumption (t/t $NaBH_4$.km)	0.0000004
Capacity (ktonne/ship.y)	370					Heat (MJ/t $NaBH_4$.km)	-
Capacity (ktonne H_2-eq/ship.y)	39.4					Electricity (kWh/t $NaBH_4$.km)	-
Concentration of transported product (wt.%)	99					GHG emissions (kg CO_2-eq/t $NaBH_4$.km)	0.001

Notes:

- This system assumes an average transport distance of 8000 km per single trip and 25 trips per year. Return trip was not considered.
- OPEX was estimated using typical cost structure for shipping including the categories: fuel, maintenance and insurance, manning and port charges. Main data inputs can be found below. In case the reader requires further understanding, further information can be provided on the calculations.
- The annualized CAPEX was calculated for a period of 15 years and interest rate of 5%.
- 400€/t average for heavy fuel oil from Ship & Bunker News; 69M€ vessel capital cost, estimations based on correlations presented by the United States Merchant Marine Academy, Economies of Scale in Container Ship Costs; 1,4M€/y for manning, from The Geography of Transport Systems; 2M€/y port charges, from The Geography of Transport Systems.

Quality Assessment

The following matrix shows the scores on quality assessment of data inputs and indicators grouped as total system.

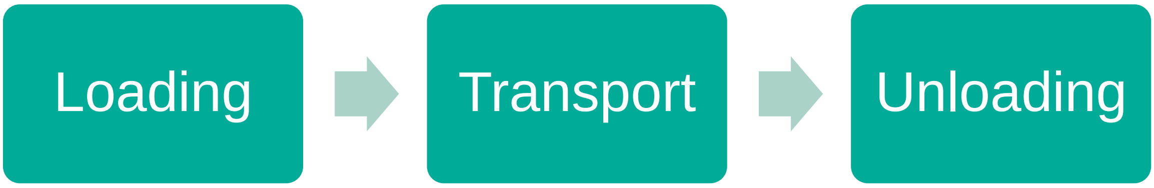
Uncertainty for Data Inputs				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	3	3	3	2
Economic	2	2	3	2
Environmental	3	3	3	3

Uncertainty for Key Performance Indicator Outcomes				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	3	3	3	2
Economic	2	2	3	2
Environmental	3	2	3	1

Notes:

- Transport scored high for technical input parameters as information on container ships is widely available in the public domain and technical specifications of Panamax containers can be found in the open literature. Economic data inputs are however largely proxy values which can significantly vary from ship to ship such as the case of capital investment.. Environmental inputs in this case depends on emissions factor for heavy fuel oil, which has been widely studied during the last decades.
- Scores on technical outputs are well understood as maximum tonnage of Panamax carriers are known, thus evaluating the amount of product is easily achievable.
- Scores on economic outputs score low relatively high as the system is well understood, however, it is still model derived data to breakdown costs elements such as fuel consumption and number of trips per year under the assumptions of loading and unloading considered in this data sheet.
- Environmental outputs are dependent on fuel consumption levels which is uncertain for each case. Average data was used, and validation of emissions was not directly possible to be carried out. However, the approach is considered as best available practice

Process flow diagram



Notes:

- Transport of NaBH4 using Panamax container ship
- Transport only one way. Return trip not considered in calculations

Risks and opportunities

	Risks	Opportunities
Technological	A technological risk that was identified for this system is that transport in EUR pallets with 2 iron steel drums containing 50kg of $NaBH_4$ each would limit the transport capacity of $NaBH_4$. The shipping capacity is low compared to bulk transport.	Transport using EUR pallets of non bulky material is already mature as well as Panamax ships for containers transport.
Economic	The non-bulk transport of $NaBH_4$ can affect transport costs for large scale applications.	Panamax container ships have been operating for several decades, thus handling and mobilizing containers is an already known technique which can benefit on the long term learning of transporting non-bulk $NaBH_4$

Political	Shipping is still a major GHG contributor. Transitioning to renewable bunker fuels is still challenging giving the limited knowledge on the topic.	In order to meet environmental targets bunker fuel decarbonization would be required. This opens the panorama for new research lines and new policy making directions.
Social	N/A	N/A
Environmental	System still fully dependent on fossil fuels, and given the limited transport of $NaBH_4$ in EUR pallets within high cube containers, specific environmental impacts related to transport tend to be higher in comparison to those for other chemicals.	As renewable energy is aimed to be introduced to the current system, replacing fossil sources for transport would have a large long term GHG emissions reduction.

References:

- Murray (2015) Economies of Scale in Container Ship Costs. United States Merchant Marine Academy.
- Ship & Bunker news (2019) Heavy fuel oil prices. Retrieved from https://shipandbunker.com/prices/emea/nwe/nl-rtm-rotterdam
- Jean-Paul Rodrigue (2017). The Geography of Transport Systems. The spatial organization of transportation and mobility. New York: Routledge, 440 pages. ISBN 978-1138669574. Available at: https://transportgeography.org
- Velman et al. (2011) Economies of size of large containerships based on internal and external costs. International Journal of Decision Sciences, Risk and Management, 2011 Vol.3 No.3/4, pp.384 - 400
- EPAL Pallets (2019) EPAL 1 Euro Pallet pallets. Retrieved from https://www.epal-pallets.org/eu-en/load-carriers/epal-euro-pallet/
- Seaplus (2009) Ocean container information. Retrieved from http://seaplus.com/container.html

T12: Shipping cryogenic tanker for liquefied H_2 (offshore)

Data sheet prepared by/owner: Data provided by Vopak

Data sheet reviewed by: Data sheet reviewed but comments not applied.

Technology Description:

Described here are the calculations behind a hydrogen vessel designed for the Euro-Quebec project, the ship was never realised. Later a new ship was proposed by Kawasaki for which a pilot vessel should be in operation in the coming years.

This datasheet does not include traveled distance as this is claimed to be unknown by the authors. Thus costs expressed per t.km of hydrogen are not included in this datasheet. Loading and unloading not included.

In case technical aspects to convert data into energy equivalence, and hydrogen equivalence other data sheets including this calculations can be used as reference.

Key Performance Indicators (KPIs)

Technological		**Economic**				**Environmental**	
		Year	**Base year (2019 - 2034)**	**2030**	**2050**		
TRL (scaled to Nth of a kind)	See notes	Equipment cost (M€)				Water consumption (m^3/GJ)	
Roundtrip efficiency (%)		CAPEX (M€)	146			Water withdrawal (m^3/GJ)	
Capacity (TJ/y)		Annualized CAPEX (M€/y)				Heat (GJ/GJ)	
Capacity (tonnes)	1050	Annualized CAPEX (M€/GJ)				Electricity (kWh/GJ)	
Capacity (ktonne H_2-eq/y)		Annualized CAPEX (M€/kg H_2-eq)				GHG emissions (kg CO_2-eq/GJ)	
Concentration of transported product (wt.%)		O&M (€/day)	11500			Land footprint (m^2/GJ)	
Volumetric energy density (GJ/m^3)		OPEX (M€/GJ)				Fuel consumption (tonnes per day)	65
Losses during storage (%)		O&M per day (€/kg H_2-eq)	0.01			Boil off losses (%/day)	0.3

Notes:

- Expected larger scale Kawasaki Carrier
- 10840 tonnes per ship.
- 481 mln euro.

- In the project a ship similar to LNG will be build with tanks specific for LH_2. It will be a combination of different (existing) technologies.

Quality Assessment

The following matrix shows the scores on quality assessment of data inputs and indicators grouped as total system.

Uncertainty for Data Inputs				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	3	2	2	3
Economic	1	1	1	1
Environmental	1	1	1	1

Uncertainty for Key Performance Indicator Outcomes				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	-	-	-	-
Economic	-	-	-	-
Environmental	-	-	-	-

Process flow diagram

Risks and opportunities

	Risks	Opportunities
Technological	Technology still under development.	-
Economic	Expensive as specialized storage are needed that still need to be developed.	If technology becomes more mature cost reductions can be expected.
Political	-	-
Social	-	-
Environmental	Slightly acidic reagent.	-

References:

- Teichmann D, Arlt W, Wasserscheid P. (2012). Liquid Organic Hydrogen Carriers as an efficient vector for the transport and storage of renewable energy. Int J Hydrogen Energy. 37(23):18118-18132 doi:10.1016/J.IJHYDENE.2012.08.066
- Kamiya S. Nishimura M, Harada E,. (2015). Study on Introduction of CO2 Free Energy to Japan with Liquid Hydrogen, Physics Procedia 67. 11 – 19 doi: 10.1016/j.phpro.2015.06.004

T13: Shipping liquid NH_3 (offshore)

Data sheet prepared by/owner: Emile Herben, Yara in collaboration with Gasunie

Data sheet reviewed by: Jonathan Moncada & Andrea Ramirez, Delft University of Technology

Technology Description: Ammonia is carried in specialist vessels of anywhere between 15,000-84,000 cubic metres. The same vessels typically also can be used to carry LPG. These vessels transport cargo in a liquid form, under pressure or in a refrigerated state on global routes such as the Middle East to South East Asia and the Far East.

Key Performance Indicators (KPIs)

Technological		**Economic**				**Environmental**	
		Year	**Base year (2019 - 2034)**	**2030**	**2050**		
TRL	9	Transportation costs (€/t .km)				Fuel type	
Capacity (TJ/y)		Transportation costs (€/t H_2-eq.km)				Fuel consumption (L/t.km)	
Capacity (ktonne/y)	20,000	CAPEX (M€)	71 [3]			Heat (MJ/t.km)	
Capacity (ktonne H_2-eq/ship/y)		OPEX (M€/y)	24,5k$/day [2]			Electricity (kWh/t.km)	
Concentration of transported product (wt.%)		OPEX (M€/kg H_2-eq)	41 $/mt [1]			GHG emissions (kg CO_2-eq/t.km	

Notes:

- Shipping charter rates, as a proxy for OPEX, are highly volatile.
- For shipping or transport in general, it doesn't make a whole lot of sense to talk about OPEX expressed per year. Charter rates are often expressed per day of charter or per metric ton.
- The capacity refers to the current global annual ammonia trading.
- OPEX is based on an 84000 m^3 ship
- Ammonia is typically shipped over distances of several thousand kilometers. HFO is the typical shipping fuel. Typical CO_2 emissions are 5.9 gram/tonne.km
- KPI Sources:
    - [1] 46.2K mt Gulf to and from Japan, Nov 2018, Clarksons Shipping Intelligence

- [(2)] 84k m^3 vessel, Nov 2018, Clarksons Shipping Intelligence
- [(3)] 82k m^3 vessel, Dec 2018, Clarksons Shipping Intelligence

Quality Assessment

The following matrix shows the scores on quality assessment of data inputs and indicators grouped as total system.

Uncertainty for Data Inputs/KPIs				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	3	3	3	3
Economic	3	3	3	3
Environmental	3	3	3	3

Risks and opportunities

	Risks	Opportunities
Technological		Mature technology, can be used at low-risk today.
Economic		Ammonia is one of the most economical ways to transport large amounts of hydrogen over a long distance.
Political		
Social		
Environmental		If shipping fuel can switch to a greener alternative (such as ammonia!), then ammonia transport by ship can become completely green.

References:

- Clarksons Shipping Intelligence (Nov 2018)
- Clarksons Shipping Intelligence (Dec 2018)

T14a: Shipping liquid Methanol, LOHC (offshore)

Data sheet prepared by/owner: Data provided by Vopak

Data sheet reviewed by: Data sheet reviewed but comments not applied.

Technology Description:

Modelled on: Eg Cajun Sun, Manchac Sun

Ship type: Chemical tanker

Ship size: MDR2

IMO/IMDG Class: III

Hull: Double

Noteworthy: Could technically be transported in VLCC

This datasheet does not include traveled distance as this is claimed to be unknown by the authors. Thus costs expressed per t.km of hydrogen are not included in this datasheet. Loading and unloading not included.

In case technical aspects to convert data into energy equivalence, and hydrogen equivalence other data sheets including this calculations can be used as reference.

Key Performance Indicators (KPI)

Technological		Economic				Environmental	
		Year	**Base year (2019 - 2034)**	**2030**	**2050**		
TRL		Equipment cost (M€)				Water consumption (m^3/GJ)	
Round trip efficiency (%)		CAPEX (M€)	44			Water withdrawal (m^3/GJ)	
Capacity (TJ/y)		Annualized CAPEX (M€/y)				Heat (GJ/GJ)	
Capacity (cbm)	52560	Annualized CAPEX (M€/GJ)				Electricity (kWh/GJ)	
Capacity (ktonne H_2-eq/y)		Annualized CAPEX (M€/kg H_2-eq)				GHG emissions (kg CO_2-eq/GJ)	
Product concentration, purity (wt.%)		OPEX (€/day)	7837			Land footprint (m^2/GJ)	
Volumetric energy density (GJ/m^3)		OPEX (M€/GJ)					
Losses during storage (%)		OPEX (M€/kg H_2-eq)					

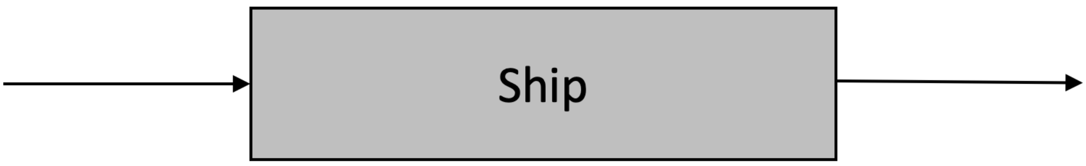
Quality Assessment

The following matrix shows the scores on quality assessment of data inputs and indicators grouped as total system.

Uncertainty for Data Inputs				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	4	3	4	3
Economic	3	3	4	3
Environmental				

Uncertainty for Key Performance Indicator Outcomes				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	4	3	4	3
Economic	3	3	4	3
Environmental				

Process flow diagram



Risks and opportunities

	Risks	Opportunities
Technological	Flammable product, precautions needed.	Currently used in chemical tankers. When market demand increases larger ships can be developed decreasing the costs.
Economic	-	Currently used in chemical tankers. When market demand increases larger ships can be developed decreasing the costs.
Political	-	Currently used in chemical tankers. When market demand increases larger ships can be developed decreasing the costs.
Social	-	Currently used in chemical tankers. When market demand increases larger ships can be developed decreasing the costs.
Environmental	No environmental contaminants, highly biodegradable.	Currently used in chemical tankers. When market demand increases larger ships can be developed decreasing the costs.

References:

- Numbers from model Kalavastra, checked internally within Vopak

T14b: Shipping DBT

Data sheet prepared by/owner: Data provided by Vopak

Data sheet reviewed by: Data sheet reviewed but comments not applied.

Technology Description:

Modelled on: Like MeOH

Ship type: Chemical tanker

Ship size: MDR2

IMO/IMDG Class: III

Hull: Double

Noteworthy: Could technically be transported in VLCC

This datasheet does not include traveled distance as this is claimed to be unknown by the authors. Thus costs expressed per t.km of hydrogen are not included in this datasheet. Loading and unloading not included.

In case technical aspects to convert data into energy equivalence, and hydrogen equivalence other data sheets including this calculations can be used as reference.

Key Performance Indicators (KPIs)

Technological		Economic				Environmental	
		Year	**Base year (2019 - 2034)**	**2030**	**2050**		
TRL		Equipment cost (M€)				Water consumption (m^3/GJ)	
Roundtrip efficiency (%)		CAPEX (M€)	44			Water withdrawal (m^3/GJ)	
Capacity (TJ/y)		Annualized CAPEX (M€/y)				Heat (GJ/GJ)	
Capacity (cbm)	52560	Annualized CAPEX (M€/GJ)				Electricity (kWh/GJ)	
Capacity (ktonne H_2-eq/y)		Annualized CAPEX (M€/kg H_2-eq)				GHG emissions (kg CO_2-eq/GJ)	
Product concentration, purity (wt.%)		OPEX (€/day)	7837			Land footprint (m^2/GJ)	
Volumetric energy density (GJ/m^3)		OPEX (M€/GJ)					
Losses during storage (%)		OPEX (M€/kg H_2-eq)					

Notes:

- Could technically be transported in VLCC.

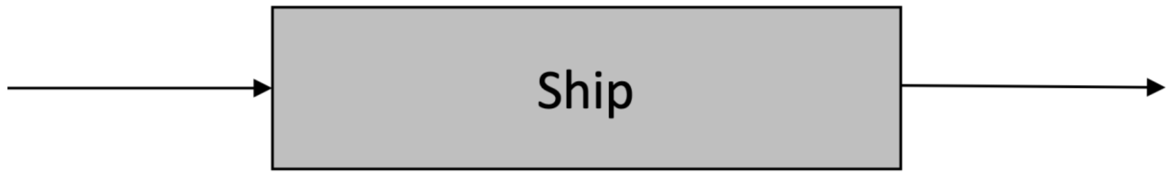
Quality Assessment

The following matrix shows the scores on quality assessment of data inputs and indicators grouped as total system.

Uncertainty for Data Inputs				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	4	3	4	3
Economic	3	3	4	3
Environmental				

Uncertainty for Key Performance Indicator Outcomes				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	4	3	4	3
Economic	3	3	4	3
Environmental				

Process flow diagram



Risks and opportunities

	Risks	Opportunities
Technological	-	Technology already used on large scale.
Economic	-	Technology already used on large scale.
Political	-	Technology already used on large scale.
Social	-	Technology already used on large scale.
Environmental	Could have long lasting effects on aquatic life, toxic when swallowed.	Technology already used on large scale.

References:

- Numbers from model Kalavastra, checked internally within Vopak.

T15: Shipping liquid formic acid (offshore)

Data sheet prepared by/owner: Data provided by Vopak

Data sheet reviewed by: Data sheet reviewed but comments not applied.

Technology Description:

Modelled on: Odfjell (unnamed)

Ship type: Chemical tanker

Ship size: Handysize

IMO/IMDG Class: II

Hull: ?

Noteworthy: Stainless steel tanks

This datasheet does not include traveled distance as this is claimed to be unknown by the authors. Thus costs expressed per t.km of hydrogen are not included in this datasheet. Loading and unloading not included.

In case technical aspects to convert data into energy equivalence, and hydrogen equivalence other data sheets including this calculations can be used as reference.

Key Performance Indicators (KPIs)

Technological		Economic				Environmental	
		Year	**Base year (2019 - 2034)**	**2030**	**2050**		
TRL		Equipment cost (M€)				Water consumption (m^3/GJ)	
Roundtrip efficiency (%)		CAPEX (M€)	60			Water withdrawal (m^3/GJ)	
Capacity (TJ/y)		Annualized CAPEX (M€/y)				Heat (GJ/GJ)	
Capacity (cbm)	54600	Annualized CAPEX (M€/GJ)				Electricity (kWh/GJ)	
Capacity (ktonne H_2-eq/y)		Annualized CAPEX (M€/kg H_2-eq)				GHG emissions (kg CO_2-eq/GJ)	
Product concentration, purity (wt.%)		OPEX (€/day)				Land footprint (m^2/GJ)	
Volumetric energy density (GJ/m^3)		OPEX (M€/GJ)					
Losses during storage (%)		OPEX (M€/kg H_2-eq)					

Notes:

- Stainless steel tankers needed

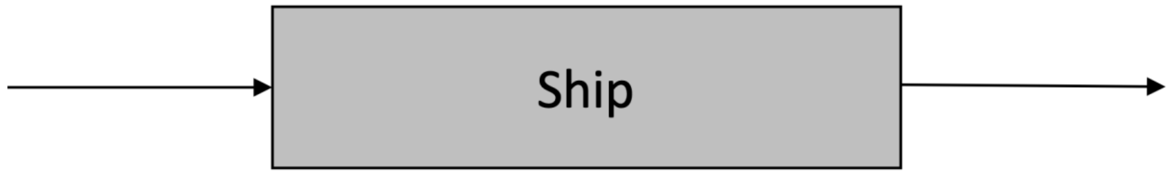
Quality Assessment

The following matrix shows the scores on quality assessment of data inputs and indicators grouped as total system.

Uncertainty for Data Inputs				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	4	3	4	3
Economic	3	3	4	3
Environmental				

Uncertainty for Key Performance Indicator Outcomes				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	-	-	-	-
Economic	-	-	-	-
Environmental	-	-	-	-

Process flow diagram



Risks and opportunities

	Risks	Opportunities
Technological	Stainless steel tanks needed due to acidity, highly corrosive.	Currently used in chemical tankers. When market demand increases larger ships can be developed decreasing the costs.
Economic	-	Currently used in chemical tankers. When market demand increases larger ships can be developed decreasing the costs.
Political	-	Currently used in chemical tankers. When market demand increases larger ships can be developed decreasing the costs.
Social	-	Currently used in chemical tankers. When market demand increases larger ships can be developed decreasing the costs.
Environmental	No environmental contaminants, highly biodegradable	Currently used in chemical tankers. When market demand increases larger ships can be developed decreasing the costs.

References:

- MarineLink (2019). Odffjell to Build Record Size Stainless Steel Chem Tankers. Retrieved from https://www.marinelink.com/news/stainless-odffjell417669
- Vopak internal information

T16: Shipping DME

Data sheet prepared by/owner: Jonathan Moncada & Andrea Ramirez, Delft University of Technology

Data sheet reviewed by: Eddy van Oort, Frames

Technology Description:

Transport of DME in modern refrigerated carrier of 84,000 m^3 capacity. The net weight of DME that can be transported per trip is 51 ktonne (considering restriction boil off losses of 0.15% per day, and "heel" left at the end of each trip of 4%).

Shipping was modelled by considering an operation of 350 days/year, average fuel consumption of 48 tonnes of heavy fuel oil per day and assuming 3 days of loading and unloading (port days). These inputs were gathered from literature which are typical for LPG carriers. DME shipping was modelled as LPG but using DME properties.

Single trips were assumed to cover a distance of 8,000 km. Speed was assumed as 19 knots. On an annual basis, a container ship is able to transport 1,459 ktonne of DME.

The analysis presented here only considers one way trips.

Key Performance Indicators (KPIs)

Technological		Economic				Environmental	
		Year	**Base year (2019 - 2034)**	**2030**	**2050**		
TRL (scaled to Nth of a kind)	9	Transportation costs (€/t DME.km)	0.000064	N/A	N/A	Fuel type	Heavy fuel oil
Capacity (TJ/ship.y)	72955	Transportation costs (€/t H_2-eq.km)	0.0005	N/A	N/A	Fuel consumption (t/t DME.km)	0.000000039
Capacity (ktonne/ship.y)	1459					Heat (MJ/t DME.km)	-
Capacity (ktonne H_2-eq/ship.y)	191.5					Electricity (kWh/t DME.km)	-
Concentration of transported product (wt.%)	99					GHG emissions (kg CO_2-eq/t DME.km)	0.0001

Notes:

- This system assumes an average transport distance of 8000 km per single trip and 28 trips per year. Return trip was not considered.
- OPEX was estimated using typical cost structure for shipping including the categories: fuel, maintenance and insurance, manning and port charges. Main data inputs can be found below. In case the reader requires further understanding, please visit the calculations tab.
- CAPEX is calculated based on typical LPG charter rates for 2017.
- Fuel consumption was considered as 48 tonnes of HFO per day. No information on boil-off losses available for this ship. Thus a rate of 0.15% per day was assumed as analogous to the LNG carrier case.
- 400€/t average for heavy fuel oil from Ship & Bunker News; 20,000€/day charter costs, from Rogers (2017); 0.5M€/y for manning, from The Geography of Transport Systems; 100,000€/day port charges, from Rogers (2017).

Quality Assessment

The following matrix shows the scores on quality assessment of data inputs and indicators grouped as total system.

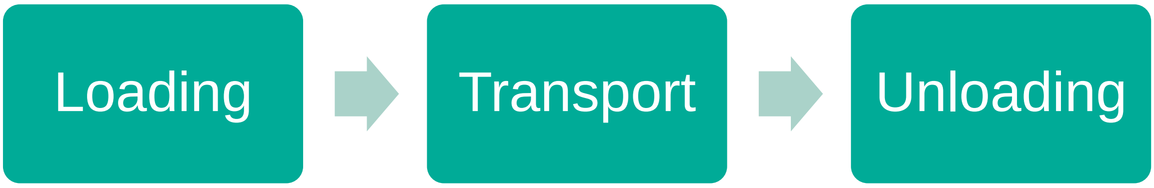
Uncertainty for Data Inputs				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	3	3	3	2
Economic	2	2	3	2
Environmental	3	3	3	3

Uncertainty for Key Performance Indicator Outcomes				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	3	3	3	2
Economic	2	2	3	2
Environmental	3	2	3	1

Notes:

- Transport scored high for technical input parameters as information on LPG carriers is widely available in the public domain and technical specifications can be found in the open literature. Economic data inputs are however largely proxy values which can significantly vary from ship to ship such as the case of charter rates. Environmental inputs in this case depends on emissions factor for heavy fuel oil, which has been widely studied during the last decades.
- Scores on technical outputs are well understood as maximum capacities of LPG carriers are known, thus evaluating the amount of product is easily achievable.
- Scores on economic outputs score low relatively high as although the system is well understood, however, it is still model derived data to breakdown costs elements such as fuel consumption and number of trips per year under the assumptions of loading and unloading and port stay
- Environmental outputs are dependent on fuel consumption levels which is uncertain for each case. Average data was used, and validation of emissions was not directly possible to be carried out. However, the approach is considered as best available practice

Process flow diagram



Notes:

- Transport of DME using a modern refrigerated LPG
- Transport only one way. Return trip not considered in calculations

Risks and opportunities

	Risks	Opportunities
Technological	N/A	The system is very well known and has been widely used to transport LPG and could easily adapt to the DME case. Hydrogen economy could benefit from the learning of this supply chain.
Economic	Charter rates highly fluctuate over time and might highly influence overall transport costs.	LPG carriers have been widely used for transporting liquified gases. DME transport could economically benefit from the bulk transport capacity of these carriers.
Political	Shipping is still a major GHG contributor. Transitioning to renewable bunker fuels is still challenging giving the limited knowledge on the topic.	In order to meet environmental targets bunker fuel decarbonization would be required. This opens the panorama for new research lines and new policy making directions
Social	N/A	N/A
Environmental	System still fully dependent on fossil fuels, and given the long distances travelled to transfer those commodities, emissions related to transport of renewable goods might represent a key challenge on achieving carbon neutrality.	As renewable energy is aimed to be introduced to the current system, replacing fossil sources for transport would have a large long term GHG emissions reduction.

References:

- Ship & Bunker news (2019) Heavy fuel oil prices. Retrieved from https://shipandbunker.com/prices/emea/nwe/nl-rtm-rotterdam
- Jean-Paul Rodrigue (2017). The Geography of Transport Systems. The spatial organization of transportation and mobility. New York: Routledge, 440 pages. ISBN 978-1138669574. Available at: https://transportgeography.org
- Rogers H. (2018) The LNG Shipping Forecast: costs rebounding, outlook uncertain. The Oxford institute for energy studies. University of oxford. Available at: https://www.oxfordenergy.org/wpcms/wp-content/uploads/2018/02/The-LNG-Shipping-Forecast-costs-rebounding-outlook-uncertain-Insight-27.pdf
- Clarkssons (2017) Shipping intelligence network. LPG charter rates. Average values for 2017. https://sin.clarksons.net

T17: Shipping CH_4 Liquified (LNG)

Data sheet prepared by/owner: Jonathan Moncada & Andrea Ramirez, Delft University of Technology

Data sheet reviewed by: Eddy van Oort, Frames

Technology Description:

Transport of liquified methane in steam turbine LNG carrier of 160,000 m^3 capacity. The net weight of LNG that can be transported per trip is 68 ktonne (considering restriction boil off losses of 0.15% per day, and "heel" left at the end of each trip of 4%).

Shipping was modelled by considering an operation of 350 days/year, average fuel consumption of 48 tonnes of heavy fuel oil per day and assuming 3 days of loading and unloading (port days). These inputs were gathered from literature and aligned with typical operation figures of LNG carrier.

Single trips were assumed to cover a distance of 8,000 km. Speed was assumed as 19 knots. On an annual basis, a container ship is able to transport 1,911 ktonne of LNG. The analysis presented here only considers one way trips.

Key Performance Indicators (KPIs)

Technological		Economic				Environmental	
		Year	Base year (2019 - 2034)	2030	2050		
TRL (scaled to Nth of a kind)	9	Transportation costs (€/t CH_4.km)	0.000051	N/A	N/A	Fuel type	Heavy fuel oil
Capacity (TJ/ship.y)	95543	Transportation costs (€/t H_2-eq.km)	0.0002	N/A	N/A	Fuel consumption (t/t CH_4.km)	0.00000003
Capacity (ktonne/ship.y)	1911					Heat (MJ/t CH_4.km)	-
Capacity (ktonne H_2-eq/ship.y)	480.3					Electricity (kWh/t CH_4.km)	-
Concentration of transported product (wt.%)	99					GHG emissions (kg CO_2-eq/t CH_4.km)	0.0001

Notes:

- This system assumes an average transport distance of 8,000 km per single trip and 28 trips per year. Return trip was not considered.
- OPEX was estimated using typical cost structure for shipping including the categories: fuel, maintenance and insurance, manning and port charges. Main data inputs can be found below. In case the reader requires further understanding, please visit the calculations tab.
- CAPEX is calculated based on typical LNG charter rates for 2017.
- Boil-off losses were considered as 0.15% per day. Fuel consumption was considered as 48 tonnes of HFO per day. Boil off LNG is also used to produce steam.
- 400€/t average for heavy fuel oil from Ship & Bunker News; 20,000€/day charter costs, from Rogers (2017); 0.5M€/y for manning, from The Geography of Transport Systems; 100,000€/day port charges, from Rogers (2017)

Quality Assessment

The following matrix shows the scores on quality assessment of data inputs and indicators grouped as total system.

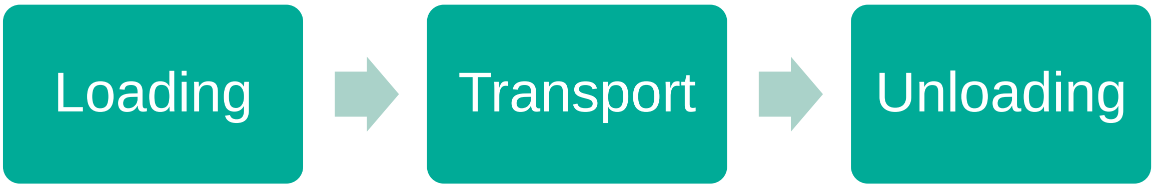
Uncertainty for Data Inputs				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	3	3	3	2
Economic	2	2	3	2
Environmental	3	3	3	3

Uncertainty for Key Performance Indicator Outcomes				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	3	3	3	2
Economic	2	2	3	2
Environmental	3	2	3	1

Notes:

- Transport scored high for technical input parameters as information on LNG carriers is widely available in the public domain and technical specifications can be found in open literature. Economic data inputs are however largely proxy values which can significantly vary from ship to ship such as the case of charter rates. Environmental inputs in this case depends on emissions factor for heavy fuel oil, which has been widely studied during the last decades.
- Scores on technical outputs are well understood as maximum capacities of LNG carriers are known, thus evaluating the amount of product is easily achievable.
- Scores on economic outputs score low relatively high as although the system is well understood, however, it is still model derived data to breakdown costs elements such as fuel consumption and number of trips per year under the assumptions of loading and unloading and port stay
- Environmental outputs are dependent on fuel consumption levels which is uncertain for each case. Average data was used, and validation of emissions was not directly possible to be carried out. However, the approach is considered as best available practice.

Process flow diagram



Notes:

- Transport of synthetic methane using a LNG steam turbine carrier
- Transport only one way. Return trip not considered in calculations

Risks and opportunities

	Risks	Opportunities
Technological	N/A	The system is very well known and has been widely used to transport LNG. Hydrogen economy could benefit from the learning of this supply chain.
Economic	Charter rates highly fluctuate over time and might highly influence overall transport costs.	LNG carriers have been widely used for transporting natural gas. Synthetic methane transport could economically benefit from the bulk transport of this commodity.
Political	Shipping is still a major GHG contributor. Transitioning to renewable bunker fuels is still challenging giving the limited knowledge on the topic.	In order to meet environmental targets bunker fuel decarbonization would be required. This opens the panorama for new research lines and new policy making directions.
Social	N/A	N/A
Environmental	System still fully dependent on fossil fuels, and given the long distances travelled to transfer those commodities, emissions related to transport of renewable goods might represent a key challenge on achieving carbon neutrality.	As renewable energy is aimed to be introduced to the current system, replacing fossil sources for transport would have a large long term GHG emissions reduction.

References:

- Ship & Bunker news (2019) Heavy fuel oil prices. Retrieved from https://shipandbunker.com/prices/emea/nwe/nl-rtm-rotterdam
- Jean-Paul Rodrigue (2017). The Geography of Transport Systems. The spatial organization of transportation and mobility. New York: Routledge, 440 pages. ISBN 978-1138669574. Available at: https://transportgeography.org
- Rogers H. (2018) The LNG Shipping Forecast: costs rebounding, outlook uncertain. The Oxford institute for energy studies. University of oxford. Available at: https://www.oxfordenergy.org/wpcms/wp-content/uploads/2018/02/The-LNG-Shipping-Forecast-costs-rebounding-outlook-uncertain-Insight-27.pdf

T18: Rail Liquid NH_3

Data sheet prepared by/owner: Emile Herben, Yara in collaboration with Gasunie

Data sheet reviewed by: Jonathan Moncada & Andrea Ramirez, Delft University of Technology

Technology Description: Ammonia can and is often transported in gas rail tank cars. The min. load per rail is about 55 ton of ammonia. A tank car (International Union of Railways (UIC): tank wagon) is a type of railroad car (UIC: railway car) or rolling stock designed to transport liquid and gaseous commodities. Many variants exist due to the wide variety of liquids and gases transported. Tank cars can be pressurized or nonpressurized, insulated or non-insulated, and are designed for single or multiple commodities. Non-pressurized cars have various fittings on the top and may have fittings on the bottom. Some of the top fittings are covered by a protective housing. Pressurized cars have a pressure plate, with all fittings, and a cylindrical protective housing at the top. Loading and unloading are done through the protective housing.

Tank cars are specialized pieces of equipment. As an example, the interior of the car may be lined with a material, such as glass, or other specialized coatings to isolate the tank contents from the tank shell. Care is taken to ensure that tank contents are compatible with tank construction.

Key Performance Indicators (KPIs)

Technological		Economic				Environmental	
		Year	**Base year (2019 - 2034)**	**2030**	**2050**		
TRL	9	Transportation costs (€/t NH_3)	60			Fuel type	
Capacity (TJ/y)		Transportation costs (€/t H_2-eq.km)	343			Fuel consumption (L/t.km)	
Capacity (ktonne/y)						Heat (MJ/t.km)	
Capacity (ktonne H_2-eq/y)						Electricity (kWh/t.km)	
Concentration of transported product (wt.%)	99.5					GHG emissions (kg CO_2-eq/t.km	

Notes:

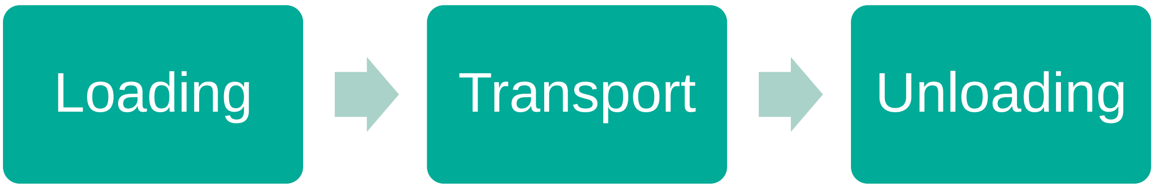
- Transport only one way. Return trip not considered in calculations.

Quality Assessment

The following matrix shows the scores on quality assessment of data inputs and indicators grouped as total system.

Uncertainty for Data Inputs/KPIs				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical				
Economic	1	1	0	1
Environmental				

Process flow diagram



Risks and opportunities

	Risks	Opportunities
Technological		Transport of chemicals is an already mature technology, that can be used today without risk.
Economic		Rail transport is efficient and economical.
Political		
Social	Public perception of chemicals transport is fairly bad, even though safety statistics are good. This may have something to do with the fact that rail transport in the EU often comes close to residential areas.	
Environmental		

References:

- Company internal data
- VTG (2019). Gas Rail Tank Cars for Ammonia. Retrieved from: https://www.vtg.com/wagon-hire/our-fleet/g86095c/
- VTG (2019). Gas Rail Tank Cars for Ammonia (C Track) Retrieved from: https://www.vtg.com/wagon-hire/our-fleet/g86104d/
- Wikipedia (2019). Tank Car. Retrieved from: https://en.wikipedia.org/wiki/Tank_car

Storage

S1: Gaseous storage - geologic bulk storage (salt caverns)

Data sheet prepared by/owner: Albert van den Noort & Nicolien van der Sar, Gasunie

Data sheet reviewed by: Jonathan Moncada & Andrea Ramirez, Delft University of Technology

Technology Description: Caverns are created in salt dome and/or layers to store gases and/of liquids. This is also done for hydrogen. Currently the H_2 storage in salt caverns are related to the chemical industry, however this way of storing can also be applied to store large amounts of energy in the future using H_2 as an energy carrier.

For the design of the hydrogen cavern, as a rule of thumb a daily pressure gradient of 10 bar/d is applied. Based on a 1,000,000 m^3 (geometric volume) cavern (volume located between Last Cemented Casing Shoe at 1,000 meter and bottom of cavern at 1,500 meter), this results in a daily withdrawal and injection volume in the range of 4,800,000 m^3(n) [17,067 MWh] and 5,400,000 m^3(n) [19<200 MWh]. The range is not constant as it is dependent on actual pressures and temperatures. The average flow in and out of the cavern is therefore between 200,000 m^3(n)/h [711 MWh/hr] and 230,000 m^3(n)/h [817 MWh/hr] (i.e. 18,000 kg/h – 20,400 kg/h). The peak capacity for withdrawal can be significantly higher, but has to be calculated on a case to case basis.

The available working gas volume for a cavern this size is between 50,000,000 m^3(n) [177,778 MWh]and 70,000,000 m^3(n) [248.889 MWh], i.e. 4,450,000 – 6,150,000 kg. This depends on the final choice of cavern and the detailed thermodynamic calculations to estimate the effect of temperature changes on the cavern inventory in more detail.

Note: compression(injection)/production(withdrawal) facilities are not included in this data sheet as this is heavily dependent on the usage of the H_2 storage e.g. seasonal vs fast cycle.

Key Performance Indicators (KPIs)

Technological		Economic				Environmental	
		Year	Base year (2019 - 2034)	2030	2050		
TRL (scaled to N^{th} of a kind)		Equipment Cost (M€)				Water consumption (m^3/GJ)	
Round trip efficiency (%)		CAPEX (M€)	50,000,000			Water withdrawal (m^3/GJ)	
Capacity (TJ/y)	0.235	Annualized CAPEX (€/y)	1,111,111			Heat (GJ/GJ)	Min
Capacity (ktonne/y)	6,100	Annualized CAPEX (€/GJ)				Electricity (kWh/GJ)	Min
Capacity (ktonne H_2-eq/y)		Annualized CAPEX (€/kg H_2-eq)				GHG emissions (kg CO_2-eq/GJ)	0
Product concentration, purity (wt.%)	in = out	OPEX (€/y)	44,444			Land footprint (m_2/GJ)	
Volumetric energy density (GJ/m^3)		OPEX (€/GJ)					
Losses during storage (%)		OPEX (€/kg H_2-eq)					

Notes:

- GHG emissions become 0 because injection and withdrawal are not taken into account
- OPEX = 3-5% of annual CAPEX costs, here we use 4%.
- Depreciation = 45 years (see H21 North of England, 2018); used annualized capex = capex/depreciation (as approx)

Quality Assessment

The following matrix shows the scores on quality assessment of data inputs and indicators grouped as total system.

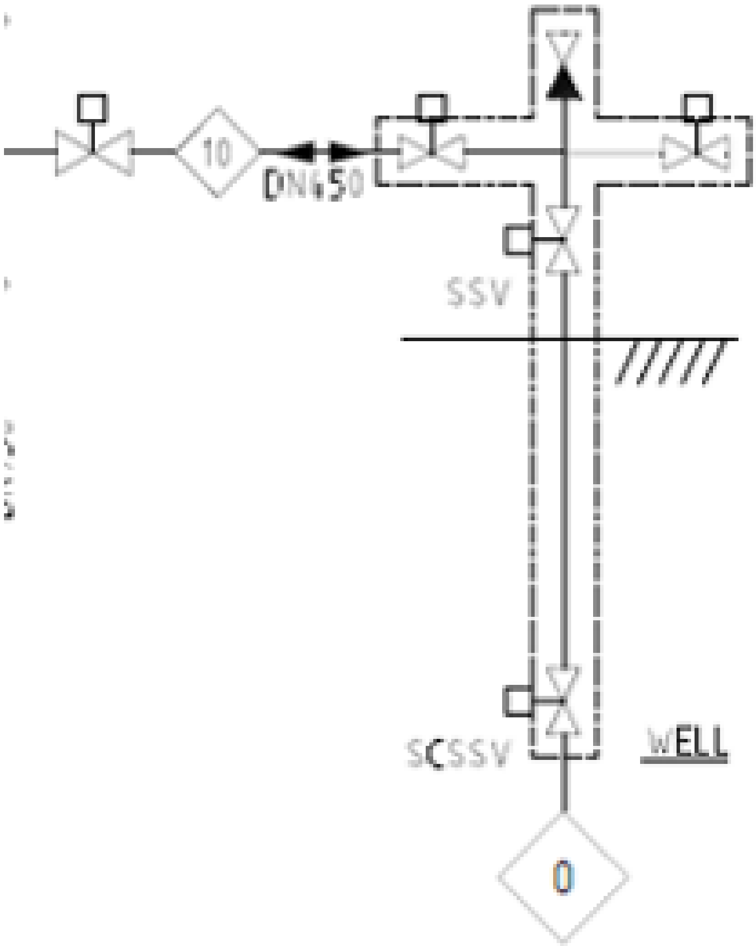
Uncertainty for Data Inputs				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	3	2	3	1
Economic	1	2	1	0
Environmental	1	1	1	1

Uncertainty for Key Performance Indicator Outcomes				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	3	2	3	1
Economic	1	2	1	0
Environmental	1	1	1	1

Notes:

- Environmental scores based on limited available knowledge; used same estimates for data inputs as for KPIs; data is not model derived.
- Economic data based on internal knowledge in Gasunie and from H21 North of England (2018).

Process flow diagram



Risks and opportunities

	Risks	Opportunities
Technological	No technical standards exist with respect to H_2 storage. Technical specifications are the IP of several large industrial gas / chemical companies	Large storage potential e.g. 235 GWh per cavern
Economic	Converting electricity into hydrogen is costly process	Storing large energy amounts for the long term >4 hrs is very cost effective compared to alternatives e.g. battery storage.
Political	Depending on the area more or less support is given to large scale energy storage	Storing large amounts of energy to support the energy transition e.g. in time of no wind or sun still renewable energy available.
Social	Depending on the area more or less support is given to large scale energy storage	Storing large amounts of energy to support the energy transition e.g. in time of no wind or sun still renewable energy available.
Environmental	Acceptance of subsidence.	Storing large amounts of energy to support the energy transition e.g. in time of no wind or sun still renewable energy available.

References:

- H21 North of England (2018) H21 NoE Report. Retrieved from: https://www.northerngasnetworks.co.uk/h21-noe/H21-NoE-26Nov18-v1.0.pdf
- Gasunie
- Hystock

S2: Gaseous storage - geologic bulk storage (gas field)

Data sheet prepared by/owner: Albert van den Noort & Nicolien van der Sar, Gasunie

Data sheet reviewed by: Jonathan Moncada & Andrea Ramirez, Delft University of Technology

Technology Description: Storing hydrogen in depleted gas fields in large volumes is an interesting option for strategic and seasonal storage of energy. For the Netherlands TNO estimates a capacity of 93 bcm onshore and 60 bcm offshore (TNO, 2018). In the past depleted gas field have been used for storage of town gas (> 50% H_2). Storing pure hydrogen in these fields is not performed to date.

There are some considerations:

1. Geological tightness of a porous formation cap rock against hydrogeneous gas depends on the cap rocks ability to withstand gas infiltration both mechanically and hydraulically.

2. During storage there is the risk to trigger geo-chemical reactions with rock minerals and reservoir fluids

3. Biological integrity: some microbes can metabolise hydrogen and therefore reduce the hydrogen content and quality.

4. Borehole integrity needs to be ensured.

Key Performance Indicators (KPIs)

Technological		Economic				Environmental	
		Year	**Base year (2019 - 2034)**	**2030**	**2050**		
TRL (scaled to Nth of a kind)	2	Equipment Cost (M€)	unknown			Water consumption (m^3/GJ)	None
Round trip efficiency (%)		CAPEX (M€)	unknown			Water withdrawal (m^3/GJ)	
Capacity (TJ/y)	153	Annualized CAPEX (M€/y)				Heat (MJ/GJ)	
Capacity (ktonne/y)		Annualized CAPEX (€/GJ)				Electricity (kWh/GJ)	unknown
Capacity (ktonne H_2-eq/y)		Annualized CAPEX (€/kg H_2-eq)				GHG emissions (kg CO_2-eq/GJ)	
Product concentration, purity (wt.%)	attention needed	OPEX (M€/y)	unknown			Land footprint (m_2/GJ)	Underground
Volumetric energy density (GJ/m^3)		OPEX (€/GJ)					
Losses during storage (%)	attention needed	OPEX (€/kg H_2-eq)					

Notes:

- Low TRL for storage of hydrogen in depleted gas fields. Potential capacity in the Netherlands is large (93+60 bcm), but the technology is not proven.

Quality Assessment

The following matrix shows the scores on quality assessment of data inputs and indicators grouped as total system.

Uncertainty for Data Inputs				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	1	1	1	1
Economic	0	0	0	0
Environmental	0	0	0	0

Uncertainty for Key Performance Indicator Outcomes				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	1	1	1	1
Economic	0	0	0	0
Environmental	0	0	0	0

Notes:

- No economic data available; storage of hydrogen in depleted gas fields is low TRL; no environmental data available. Input based on 2 sources (research by TNO and in UK).

Risks and opportunities

	Risks	Opportunities
Technological	1. Geological tightness of a porous formation cap rock against hydrogeneous gas depends on the cap rocks ability to withstand gas infiltration both mechanically and hydraulically. 2. During storage there is the risk to trigger geo-chemical reactions with rock minerals and reservoir fluids 3. Biological integrity: some microbes can metabolise hydrogen and therefore reduce the hydrogen content and quality. 4. Borehole integrity needs to be ensured.	Large storage potential
Economic		Storing large energy amounts for the long term >4 hrs is very cost effective compared to alternatives e.g. battery storage.
Political	Depending on the area more or less support is given to large scale energy storage	Storing large amounts of energy to support the energy transition e.g. in time of no wind or sun still renewable energy available.
Social	Depending on the area more or less support is given to large scale energy storage	Storing large amounts of energy to support the energy transition e.g. in time of no wind or sun still renewable energy available.
Environmental		Storing large amounts of energy to support the energy transition e.g. in time of no wind or sun still renewable energy available.

References:

- TNO (2018). Ondergrondse Opslag in Nederland - Technische Verkenning
- H21 North of England (2018) H21 NoE Report. Retrieved from: https://www.northerngasnetworks.co.uk/h21-noe/H21-NoE-26Nov18-v1.0.pdf

S3: Liquid storage: Liquid (cryogenic) H_2 tank

Data sheet prepared by/owner: Data provided by Vopak

Data sheet reviewed by: Data sheet reviewed but comments not applied.

Technology Description:

Large refrigerated storage tanks, probably stored under cold temperatures (-253ºC) and pressure.

Not all parameters were calculated due to uncertainties and logistic assumptions which could change the data. Please for purity and energy contents of carrier please consult the carrier production sheet. Storage amount needed per case dependent on throughput which is dependent on the scenario. Only large scale storage is being defined (50,000 m^3 per tank).

Key Performance Indicators (KPIs)

Technological		Economic				Environmental	
		Year	**Base year (2019 - 2034)**	**2030**	**2050**		
TRL (scaled to Nth of a kind)		Equipment Cost (M€)				Water consumption (m^3/GJ)	
Round trip efficiency (%)		CAPEX (M€)	500			Water withdrawal (m^3/GJ)	
Capacity (TJ/y)		Annualized CAPEX (M€/y)				Heat (MJ/GJ)	
Capacity (ktonne/y)	50,000	Annualized CAPEX (€/GJ)				Electricity (kWh/t)	See notes
Capacity (ktonne H_2-eq/y)	4	Annualized CAPEX (€/kg H_2-eq)				GHG emissions (kg CO_2-eq/GJ)	
Product concentration, purity (wt.%)		OPEX (M€/y)	0.025			Land footprint (m^2/GJ)	
Volumetric energy density (GJ/m^3)		OPEX (€/GJ)					
Losses during storage (%)		OPEX (€/kg H_2-eq)					

Notes:

- Storage capacity needed is dependent on the throughput.
- Each tank used is 50,000 m^3 volume per tank
- Model should error when throughput requires smaller/bigger tanks
- Minimum of 2 tanks required
- Tank lifetime 30 years
- LNG storage has ~20 kWh/t from which this technology is expected to be higher. How much higher is unknown.
- Only storage taken into account, not the remaining infrastructure needed at a terminal to accommodate for the product transfers.

Quality Assessment

The following matrix shows the scores on quality assessment of data inputs and indicators grouped as total system.

Uncertainty for Data Inputs				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	**4**	**?**	**?**	**3**
Economic	**1**	**1**	**2**	**1**
Environmental	**0**	**0**	**0**	**0**

Uncertainty for Key Performance Indicator Outcomes				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	**-**	**-**	**-**	**-**
Economic	**-**	**-**	**-**	**-**
Environmental	**-**	**-**	**-**	**-**

Notes:

- Large scale hydrogen storage is not yet done. Only articles with estimations are supporting the data.

Process flow diagram

Risks and opportunities

	Risks	Opportunities
Technological	Extremely low temperatures, specialized storage is therefore required	Storage is already being done on a larger scale by space agencies for rocket fuel. Still further development of technology can be expected when the market increases
Economic	Extremely low temperatures, specialized storage is therefore required	When the demand for LH_2 rises and the technology will be developed further decrease in costs can be expected.
Political	-	-
Social	-	-
Environmental	Slightly acidic reagent	-

References:

- IEA (2015): Hydrogen and Fuel Cells Roadmap. Technical Annex
- Vopak internal data

S4: Liquid storage (LOHC)

Data sheet prepared by/owner: Data provided by Vopak

Data sheet reviewed by: Data sheet reviewed but comments not applied.

Technology Description:

Dibenzyltoluene is a non flammable heating oil. It can be stored in conventional tanks needed for K4 products (or even unclassified products).

Not all parameters were calculated due to uncertainties and logistic assumptions which could change the data. Please for purity and energy contents of carrier please consult the carrier production sheet. Storage amount needed per case dependent on throughput which is dependent on the scenario. Only large scale storage is being defined (50,000 m^3 per tank).

Key Performance Indicators (KPIs)

Technological		Economic				Environmental	
		Year	**Base year (2019 - 2034)**	**2030**	**2050**		
TRL (scaled to Nth of a kind)		Equipment Cost (M€)				Water consumption (m^3/GJ)	
Round trip efficiency (%)		CAPEX (M€)	12.5			Water withdrawal (m^3/GJ)	
Capacity (TJ/y)		Annualized CAPEX (M€/y)				Heat (MJ/GJ)	
Capacity (ktonne/y)	50,000	Annualized CAPEX (€/GJ)				Electricity (kWh/t)	1
Capacity (ktonne H_2-eq/y)	52	Annualized CAPEX (€/kg H_2-eq)				GHG emissions (kg CO_2-eq/GJ)	
Product concentration, purity (wt.%)		OPEX (M€/y)	0.025			Land footprint (m^2/GJ)	
Volumetric energy density (GJ/m3)		OPEX (€/GJ)					
Losses during storage (%)		OPEX (€/kg H_2-eq)					

Notes:

- Not all parameters were calculated due to uncertainties and logistic assumptions which could change the data.
- Storage capacity needed is dependent on the throughput.
- Each tank used is 50,000 m^3 volume per tank.
- Model should error when throughput requires smaller/bigger tanks.
- Minimum of 2 tanks required.
- Tank lifetime 30 years.
- Only storage taken into account, not the remaining infrastructure needed at a terminal to accommodate for the product transfers.

Quality Assessment

The following matrix shows the scores on quality assessment of data inputs and indicators grouped as total system.

Uncertainty for Data Inputs				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	4	3	3	4
Economic	3	3	3	4
Environmental	3	3	3	4

Uncertainty for Key Performance Indicator Outcomes				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	4	3	3	4
Economic	3	3	3	4
Environmental	3	3	3	4

Notes:

- Quality assessment based on existing data, no new technology discussed

Process flow diagram

Risks and opportunities

	Risks	Opportunities
Technological	-	Already used in large scale, no significant opportunities expected due to maturity of technology.
Economic	-	Already used in large scale, no significant opportunities expected due to maturity of technology.
Political	-	Already used in large scale, no significant opportunities expected due to maturity of technology.
Social	-	Already used in large scale, no significant opportunities expected due to maturity of technology.
Environmental	Could have long lasting effects on aquatic life, toxic when swallowed.	Already used in large scale, no significant opportunities expected due to maturity of technology.

References:

- Vopak internal data

S5: Liquid storage (NH_3)

Data sheet prepared by/owner: Data provided by Vopak

Data sheet reviewed by: Data sheet reviewed but comments not applied.

Technology Description:

Ammonia is a toxic product that needs to be stored with care. The product is stored as a liquid with tanks similar to those used for LPG.

Key Performance Indicators (KPIs)

Technological		Economic				Environmental	
		Year	**Base year (2019 - 2034)**	**2030**	**2050**		
TRL (scaled to Nth of a kind)		Equipment Cost (M€)				Water consumption (m^3/GJ)	
Round trip efficiency (%)		CAPEX (M€)	50			Water withdrawal (m^3/GJ)	
Capacity (TJ/y)		Annualized CAPEX (M€/y)				Heat (MJ/GJ)	
Capacity (m^3)	50,000	Annualized CAPEX (€/GJ)				Electricity (kWh/GJ)	
Capacity (ktonne H_2-eq/y)		Annualized CAPEX (€/kg H_2-eq)				GHG emissions (kg CO_2-eq/GJ)	
Product concentration, purity (wt.%)		O&M (% of investment	2.50%			Land footprint (m^2/GJ)	
Volumetric energy density (GJ/m^3)		OPEX (€/GJ)				Electricity (kWH/t)	10
Losses during storage (%)		OPEX (€/kg H_2-eq)					

Notes:

- Storage capacity needed is dependent on the input.
- Each tank used is 50,000 m^3 volume per tank.
- Model should error when throughput requires smaller/bigger tanks.
- Minimum of 2 tanks required.
- Tank lifetime 30 years.
- Only storage taken into account, not the remaining infrastructure needed at a terminal to accommodate for the product transfers.

Quality Assessment

The following matrix shows the scores on quality assessment of data inputs and indicators grouped as total system.

Uncertainty for Data Inputs				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	4	3	3	4
Economic	3	3	3	4
Environmental	3	3	3	4

Uncertainty for Key Performance Indicator Outcomes				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	4	3	3	4
Economic	3	3	3	4
Environmental	3	3	3	4

Process flow diagram

Risks and opportunities

	Risks	Opportunities
Technological	Proven technology	Already used on large scale
Economic	-	Already used on large scale
Political	Strict regulation	Already used on large scale
Social	Resistance possible due to toxicity and smell	Already used on large scale
Environmental	Highly toxic, Harmful	Already used on large scale

References:

- Vopak internal

S6: Liquid storage (Formic Acid)

Data sheet prepared by/owner: Data provided by Vopak

Data sheet reviewed by: Data sheet reviewed but comments not applied.

Technology Description:

Formic acid is a corrosive product which needs to be stored in stainless steel tanks for chemicals with the right appendages to accomodate for it characteristics.

Not all parameters were calculated due to uncertainties and logistic assumptions which could change the data. For purity and energy contents of carrier please consult the carrier production sheet. Storage amount needed per case dependent on throughput which is dependent on the scenario. Only large scale storage is being defined (50,000 m^3 per tank).

Key Performance Indicators (KPIs)

Technological		Economic				Environmental	
		Year	**Base year (2019 - 2034)**	**2030**	**2050**		
TRL (scaled to Nth of a kind)		Equipment Cost (M€)				Water consumption (m^3/GJ)	
Round trip efficiency (%)		CAPEX (M€)	30			Water withdrawal (m^3/GJ)	
Capacity (TJ/y)		Annualized CAPEX (M€/y)				Heat (MJ/GJ)	
Capacity (ktonne/y)	50,000	Annualized CAPEX (€/GJ)				Electricity (kWh/t)	1.5
Capacity (ktonne H_2-eq/y)	61	Annualized CAPEX (€/kg H_2-eq)				GHG emissions (kg CO_2-eq/GJ)	
Product concentration, purity (wt.%)		OPEX (M€/y)	0.025			Land footprint (m^2/GJ)	
Volumetric energy density (GJ/m^3)		OPEX (€/GJ)					
Losses during storage (%)		OPEX (€/kg H_2-eq)					

Notes:

- Not all parameters were calculated due to uncertainties and logistic assumptions which could change the data.
- Storage capacity needed is dependent on the throughput.
- Each tank used is 50,000 m^3 volume per tank.
- Model should error when throughput requires smaller/bigger tanks.
- Minimum of 2 tanks required.
- Tank lifetime 30 years.
- Only storage taken into account, not the remaining infrastructure needed at a terminal to accommodate for the product transfers.

Quality Assessment

The following matrix shows the scores on quality assessment of data inputs and indicators grouped as total system.

Uncertainty for Data Inputs				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	4	3	3	4
Economic	3	3	3	4
Environmental	3	3	3	4

Uncertainty for Key Performance Indicator Outcomes				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	4	3	3	4
Economic	3	3	3	4
Environmental	3	3	3	4

Notes:

- Quality assessment based on existing data, no new technology discussed

Process flow diagram

Risks and opportunities

	Risks	Opportunities
Technological	Stainless steel tanks needed due to acidity, highly corrosive product which could damage materials.	Already used in large scale, no significant opportunities expected due to maturity of technology.
Economic	-	Already used in large scale, no significant opportunities expected due to maturity of technology.
Political	-	Already used in large scale, no significant opportunities expected due to maturity of technology.
Social	-	Already used in large scale, no significant opportunities expected due to maturity of technology.
Environmental	No environmental containment, highly biodegradable.	Already used in large scale, no significant opportunities expected due to maturity of technology.

References:

- Vopak internal data.

S7: Liquid storage (Methanol)

Data sheet prepared by/owner: Data provided by Vopak

Data sheet reviewed by: Data sheet reviewed but comments not applied.

Technology Description:

For methanol chemical tanks can be used with the appendages needed for K1 products. Vapour treatment and fire fighting measures are needed.

Not all parameters were calculated due to uncertainties and logistic assumptions which could change the data. Please for purity and energy contents of carrier please consult the carrier production sheet.

Storage amount needed per case dependent on throughput which is dependent on the scenario. Only large scale storage is being defined (50,000 m^3 per tank).

Key Performance Indicators (KPIs)

Technological		Economic				Environmental	
		Year	Base year (2019 - 2034)	2030	2050		
TRL (scaled to Nth of a kind)	9	Equipment Cost (M€)				Water consumption (m^3/GJ)	
Round trip efficiency (%)		CAPEX (M€)	15			Water withdrawal (m^3/GJ)	
Capacity (TJ/y)		Annualized CAPEX (M€/y)				Heat (MJ/GJ)	
Capacity (ktonne/y)	50000	Annualized CAPEX (€/GJ)				Electricity (kWh/t)	1.5
Capacity (ktonne H_2-eq/y)	39.6	Annualized CAPEX (€/kg H_2-eq)				GHG emissions (kg CO_2-eq/GJ)	
Product concentration, purity (wt.%)		OPEX (M€/y)	0.025			Land footprint (m^2/GJ)	
Volumetric energy density (GJ/m^3)		OPEX (€/GJ)					
Losses during storage (%)		OPEX (€/kg H_2-eq)					

Notes:

- Not all parameters were calculated due to uncertainties and logistic assumptions which could change the data.
- Storage capacity needed is dependent on the throughput.
- Each tank used is 50,000 m^3 volume per tank.
- Model should error when throughput requires smaller/bigger tanks.
- Minimum of 2 tanks required, one for loading and one for unloading.
- Tank lifetime 30 years.
- Only storage taken into account, not the remaining infrastructure needed at a terminal to accommodate for the product transfers.

Quality Assessment

The following matrix shows the scores on quality assessment of data inputs and indicators grouped as total system.

Uncertainty for Data Inputs				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	4	3	3	4
Economic	3	3	3	4
Environmental	3	3	3	4

Uncertainty for Key Performance Indicator Outcomes				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	4	3	3	4
Economic	3	3	3	4
Environmental	3	3	3	4

Notes:

- Quality assessment based on existing data, no new technology discussed.

Process flow diagram

Risks and opportunities

	Risks	Opportunities
Technological	Flammable product.	Already used in large scale, no significant opportunities expected due to maturity of technology.
Economic	-	Already used in large scale, no significant opportunities expected due to maturity of technology.
Political	-	Already used in large scale, no significant opportunities expected due to maturity of technology.
Social	-	Already used in large scale, no significant opportunities expected due to maturity of technology.
Environmental	No environmental containment, highly biodegradable.	Already used in large scale, no significant opportunities expected due to maturity of technology.

References:

- Vopak internal data

S8: Solids storage - $NaBH_4$ hydrides

Data sheet prepared by/owner: Jonathan Moncada & Andrea Ramirez, Delft University of Technology

Data sheet reviewed by: Eddy van Oort, Frames

Technology Description:

Storage of $NaBH_4$ in iron steel drums containing 50 kg each. Storage involves packaging with aluminium inner bags to control humidity and air as $NaBH_4$ reacts with both. Aluminum bags have a capacity of 10 kg each.

Operational costs were estimated based on number of FTE required to fill the bags and pack the drums. An overall packing time of 20 min per drum was assumed. Storage time was assumed as 30 days in the drums.

Key Performance Indicators (KPIs)

Technological		Economic				Environmental	
		Year	**Base year (2019 - 2034)**	**2030**	**2050**		
TRL (scaled to Nth of a kind)	9	Equipment Cost (M€)	N/A	N/A	N/A	Water consumption (m^3/t $NaBH_4$)	-
Round trip efficiency (%)	-	CAPEX (€ per drum)	27	N/A	N/A	Water withdrawal (m^3/t $NaBH_4$)	-
Capacity (MJ/drum)	1520	Annualized CAPEX (€/drum/y)	22	N/A	N/A	Heat (MJ/t $NaBH_4$)	-
Capacity (kg/drum)	50	Annualized CAPEX (€/t $NaBH_4$)	40	N/A	N/A	Electricity (kWh/t $NaBH_4$)	-
Capacity (kg H_2-eq/drum)	5.3	Annualized CAPEX (€/t H_2-eq)	379	N/A	N/A	GHG emissions (kg CO_2-eq/t $NaBH_4$)	-
Product concentration, purity (wt.%)	98	OPEX (€/t $NaBH_4$)	9	N/A	N/A	Land footprint (m^2/kg $NaBH_4$)	-
Volumetric energy density (GJ/m^3)	-	OPEX (€/t H_2-eq)	87	N/A	N/A		
Losses during storage (%)	-						

Notes:

- Capacity is expressed per drum as well as OPEX and CAPEX.
- OPEX was estimated using typical categories: maintenance and repair, labor. Packaging was assumed as a manual operation, thus fuel or electricity were not involved.
- Storage cycle time was estimated by considering packaging time of 20 min and an overall storage time of 30 days.
- CAPEX per drum includes the costs of inner bags. Annualized CAPEX was calculated for a period of 5 years and interest rate of 5% for the Iron steel drums. In the case of Aluminum inner bags, lifetime was assumed as that of the overall storage cycle and that those are not reused.

- Costs related to storage location such as land and rent were not included.

CAPEX as function of capacity

As NaBH4 storage is done is iron steel drums processing low volumes, it was here not assessed the effect on storing at larger capacities due to lack of information.

Quality Assessment

The following matrix shows the scores on quality assessment of data inputs and indicators grouped as total system.

Uncertainty for Data Inputs				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	2	2	2	2
Economic	2	2	2	2
Environmental				

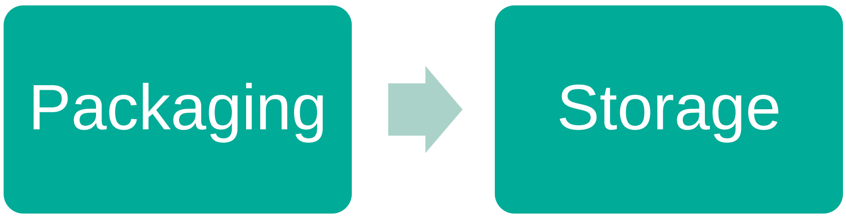
Uncertainty for Key Performance Indicator Outcomes				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	2	2	2	2
Economic	2	2	3	1
Environmental				

Notes:

- Although information on the practice of storing $NaBH_4$ in iron drums is publicly available, specific information such as specification of drums and handling and packaging $NaBH_4$ was difficult to gather. Literature is broad and it was difficult to select one specific type of drum and inner bags for packaging. Information from a supplier in Alibaba was available and used in this datasheet. That brings extra uncertainties as technical input parameters can vary widely in literature. Also cycling times were assumed inputs to estimate KPIS. Validation process for data inputs scores low as there is not enough evidence in cycling times.

- Regarding outputs, the only certain parameter was the capacity that each drum can handle. Cycling times were here assumed, and those highly influence economic outcomes. Although the system is well understood, most data is model derived. Direct validation was not possible and thus validation process scores low.

Process flow diagram



Notes:

- Storage of NaBH4 in aluminum inner bags and iron drums

Risks and opportunities

	Risks	Opportunities
Technological	Storage in aluminum inner bags and iron steel drums might hinder large scale deployment of hydride. However, this is the only currently known practice due to potential hazard of $NaBH_4$.	Packing in drums can favor pallet arrangements for later intermodal transport.
Economic	Small scale storage penalizes economically the supply of $NaBH_4$ at large scales. Handling significantly increases overall production costs.	Small scale storage applications may favor in reaching fuel cell markets easily in comparison to large scale handling.
Political	NaBH4 is classified as a dangerous chemical as it can easily react with water and air. Safety restrictions might restrain large scale applications.	Possible applications in fuel cells might incentivize its small scale handling and storage
Social	Hazardness of the material can significantly change the social perception of storing large volumes of $NaBH_4$.	N/A
Environmental	The use of inner aluminum bags could become an important contributor to environmental impacts. Life-time of bags and circularity should be accounted for.	N/A

References:

- Alibaba data on Iron Drums suppliers and aluminum inner bags.
- Roth C. (2017) $NaBH_4$ safety data sheet. Retrieved from https://www.carlroth.com/downloads/sdb/en/4/SDB_4051_GB_EN.pdf

S9a: Liquid storage - DME Spherical tank

Data sheet prepared by/owner: Jonathan Moncada & Andrea Ramirez, Delft University of Technology

Data sheet reviewed by: Eddy van Oort, Frames

Technology Description:

Storage of Liquified DME in 40 ft ISO container pressurized to 10 bar and ambient temperature.

To calculate operational costs in this datasheet, loading and unloading pumping costs were included. Labor costs adds to operational costs.

Storage cycle time was estimated by considering an injection rate of 20 tonne/h, and withdrawal rate of 57 tonne/h (matching pumping calculations of DME transport in trucks). The overall retention time was assumed as 20h. Injection and withdrawal rates differ as different pumping needs are required for upstream and downstream operations.

The ISO container capacity is 43,500 liters. The ISO container was modeled as an LPG container but adapted to the DME case.

Key Performance Indicators (KPIs)

Technological		Economic				Environmental	
		Year	**Base year (2019 - 2034)**	**2030**	**2050**		
TRL (scaled to Nth of a kind)	9	Equipment Cost (M€)	N/A	N/A	N/A	Water consumption (m^3/t DME)	-
Round trip efficiency (%)	-	CAPEX (k€)	385	N/A	N/A	Water withdrawal (m^3/t DME)	-
Capacity (GJ)	826	Annualized CAPEX (k€/y)	35	N/A	N/A	Heat (MJ/t DME)	-
Capacity (tonne)	28	Annualized CAPEX (€/t DME)	3	N/A	N/A	Electricity (kWh/t DME)	211
Capacity (tonne H_2-eq)	3.7	Annualized CAPEX (€/t H_2-eq)	26	N/A	N/A	GHG emissions (kg CO_2-eq/t DME)	147.4
Product concentration, purity (wt.%)	99	OPEX (€/t DME)	5	N/A	N/A	Land footprint (m^2/kg DME)	-
Volumetric energy density (GJ/m^3)	-	OPEX (€/t H_2-eq)	35	N/A	N/A		
Losses during storage (%)	-						

Notes:

- OPEX was estimated using typical categories: Electricity, maintenance and repair, labor.
- Storage cycle time was estimated by considering an injection rate of 20 tonne/h, and withdrawal rate of 57 tonne/h (matching pumping calculations of DME transport in trucks). The overall retention time was assumed as 20h.
- The annualized CAPEX was calculated for a period of 6 years and interest rate of 5% for the ISO container. Same interest rate was applied to the pump but lifetime was assumed as 20 years. capital costs of a pump were estimated approx. to 350,000.

- 60,000€/y average annual personnel salary; 35,000 € average ISO container costs; 350,000€ pumping costs estimated in Aspen Plus

Quality Assessment

The following matrix shows the scores on quality assessment of data inputs and indicators grouped as total system.

Uncertainty for Data Inputs				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	2	2	2	2
Economic	2	2	2	2
Environmental	3	3	3	3

Uncertainty for Key Performance Indicator Outcomes				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	2	2	2	2
Economic	2	2	3	1
Environmental	2	2	3	1

Notes:

- Storage scored low for all input technical parameters as most information on ISO containers is widely available in the public domain for LPG but not necessarily available for DME, furthermore, cycling times are unknown and will exclusively depend on demand and production volumes. Thus injection and withdrawal are uncertain. Validation process for data inputs scores low as there is not enough evidence in cycling times for DME storage in ISO containers. Environmental inputs in this case depends on emissions factor for electricity, which may change as the mix in the grid changes over time.
- Given the uncertainties on cycling times, technical outputs scored low, however, storage capacities for ISO containers are well documented in the public domain.

- Although the system is well understood for storing DME, most data is model derived. Direct validation was not possible and thus validation process scores low.
- Environmental outputs are dependent on electricity use which was estimated using modelling approaches. Validation of emissions was not directly possible to be carried out as very little information on storage emissions can be found in literature.

Process flow diagram

Notes:

- Storage of DME in ISO container

Risks and opportunities

	Risks	Opportunities
Technological	Storage in ISO containers might not be beneficial for large scale applications specially for shipping and large distribution systems.	Small scale DME storage can benefit decentralized operations and can be an applicable technology for pumping stations.
Economic	ISO containers might not benefit from economies of scale when large processing volumes are to be considered.	ISO containers storage is a current practice which may benefit flexible operation. On top, ISO containers can also be adapted for transport, thus providing the possibility to serve as dual functionality.
Political	N/A	N/A
Social	Risk of explosion due to high pressure. Safety can change the perception of the technology.	N/A
Environmental	The major contributor to emissions is in this case electricity needed for cooling and pressurization. Transition to renewable electricity from the grid is not possible to be captured with current numbers.	N/A

References:

- Alibaba costs of ISO containers.
- Müller & Hübsch (2000) Dimethyl ether. Ullmann's Encyclopedia of Industrial Chemistry.
- ELGAS (2019) LPG transport. Retrieved from https://www.elgas.com.au/blog/1715-how-lpg-propane-is-transported-ships-trucks-rail-pipelines

S9b: Liquid storage - DME Iso container

Data sheet prepared by/owner: Jonathan Moncada & Andrea Ramirez, Delft University of Technology

Data sheet reviewed by: Eddy van Oort, Frames

Technology Description:

Storage of Liquified DME in Spherical tank pressurized to 10 bar and ambient temperature.

To calculate operational costs in this datasheet, loading pumping costs were included. Labor were also included as part of the operational costs.

Storage cycle time was estimated by considering an injection rate of 50 tonne/h, and withdrawal rate of 120 tonne/h (for shipping applications). As spherical tanks can handle higher storage capacities than ISO containers for DME storage, injection and withdrawal rates are higher.

The overall retention time was assumed as 9 days.

The spherical tank capacity is 3,800 m^3. The tank was modeled as an LPG container but adapted to the DME case.

Key Performance Indicators (KPIs)

Technological		Economic				Environmental	
		Year	Base year (2019 - 2034)	2030	2050		
TRL (scaled to Nth of a kind)	9	Equipment cost (M€)	N/A	N/A	N/A	Water consumption (m^3/t DME)	-
Round trip efficiency (%)		CAPEX (k€)	1850	N/A	N/A	Water withdrawal (m^3/t DME)	-
Capacity (TJ)	72	Annualized CAPEX (k€/y)	148	N/A	N/A	Heat (MJ/t DME)	-
Capacity (ktonne)	2	Annualized CAPEX (€/t DME)	1	N/A	N/A	Electricity (kWh/t DME)	3
Capacity (ktonne H_2-eq)	0.3	Annualized CAPEX (€/t H_2-eq)	0	N/A	N/A	GHG emissions (kg CO_2-eq/t DME)	2.1
Product concentration, purity (wt.%)	99	OPEX (€/t DME)	1	N/A	N/A	Land footprint (m^2/t DME)	0.2
Volumetric energy density (GJ/m^3)	5.8	OPEX (€/t H_2-eq)	7	N/A	N/A		
Losses during storage (%)	-						

Notes:

- OPEX was estimated using typical categories: Electricity, maintenance and repair, labor.
- Storage cycle time was estimated by considering an injection rate of 50 tonne/h, and withdrawal rate of 120 tonne/h.The overall retention time was assumed as 9 days.
- The annualized CAPEX was calculated for a period of 20 years and interest rate of 5%.
- 60,000€/y average annual personnel salary; 1,400,000 € spherical tank costs; 450,000€ pumping costs estimated in Aspen Plus.

Quality Assessment

The following matrix shows the scores on quality assessment of data inputs and indicators grouped as total system.

Uncertainty for Data Inputs				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	**2**	**2**	**2**	**2**
Economic	**2**	**2**	**2**	**2**
Environmental	3	3	3	2

Uncertainty for Key Performance Indicator Outcomes				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	**2**	**2**	**2**	**2**
Economic	**2**	**2**	**3**	**1**
Environmental	**2**	**2**	**3**	**1**

Notes:

- Storage scored low for all input technical parameters as most information on spherical containers is widely available in the public domain for LPG but not necessarily a for DME, furthermore, cycling times are unknown and will exclusively depend on demand and production volumes. Thus injection and withdrawal are uncertain. Validation process for data inputs scores low as there is not enough evidence in cycling times for DME storage. Environmental inputs in this case depends on emissions factor for electricity, which may change as the mix in the grid changes over time.
- Given the uncertainties on cycling times, technical outputs scored low, however, storage capacities for spherical tanks are well documented in the public domain.
- Although the system is well understood for storing DME, most data is model derived. Direct validation was not possible and thus validation process scored low.
- Environmental outputs are dependent on electricity use, which was estimated using modelling approaches. Validation of emissions was not directly possible to be carried out as very little information on storage emissions can be found in literature.

Process flow diagram

Notes:

- Storage of DME in spherical tank.

Risks and opportunities

	Risks	Opportunities
Technological	Injection and withdrawal cycles would exclusively depend on production volumes and demand, which can ultimately affect overall storage time.	Large scale storage can provide enough buffer capacity for supplying DME
Economic	N/A	Spheric tanks storage requires lower capital investment in comparison to other technologies
Political	N/A	N/A
Social	Risk of explosion due to high pressure.	N/A
Environmental	The major contributor to emissions is in this case electricity needed for cooling and pressurization.	Compared to storage in ISO containers, storage in Spherical tanks showed lower GHG emissions. This might represent an opportunity at the long term deployment of DM

References:

- Alibaba costs of ISO containers.
- Müller & Hübsch (2000) Dimethyl ether. Ullmann's Encyclopedia of Industrial Chemistry.
- ELGAS (2019) LPG transport. Retrieved from https://www.elgas.com.au/blog/1715-how-lpg-propane-is-transported-ships-trucks-rail-pipelines

S10: Liquid storage - LNG

Data sheet prepared by/owner: Data provided by Vopak

Data sheet reviewed by: Data sheet reviewed but comments not applied.

Technology Description:

LNG storage takes place in specially designed, large-scale 'full containment tanks'. These tanks comprise a metal inner tank and a fully concrete outer tank. Thermal insulation between the steel inner tank containing the LNG (-160°C) and the concrete outer tank reduces the LNG daily evaporation rate to approximately 0.07% of the tank capacity per day. These vapours are collected and mixed with the gas send-out to the gas pipeline system.

Not all parameters were calculated due to uncertainties and logistic assumptions which could change the data. Please for purity and energy contents of carrier please consult the carrier production sheet. Storage amount needed per case dependent on throughput which is dependent on the scenario. Only large scale storage is being defined (50,000 m^3 per tank).

Key Performance Indicators (KPIs)

Technological		Economic				Environmental	
		Year	**Base year (2019 - 2034)**	**2030**	**2050**		
TRL (scaled to Nth of a kind)		Equipment Cost (M€)				Water consumption (m^3/GJ)	
Round trip efficiency (%)		CAPEX (M€)	75			Water withdrawal (m^3/GJ)	
Capacity (TJ/y)		Annualized CAPEX (M€/y)				Heat (MJ/GJ)	
Capacity (ktonne/y)	50000	Annualized CAPEX (€/GJ)				Electricity (kWh/t)	20
Capacity (ktonne H_2-eq/y)	23	Annualized CAPEX (€/kg H_2-eq)				GHG emissions (kg CO_2-eq/GJ)	
Product concentration, purity (wt.%)		O&M (% of investment)	2.5%			Land footprint (m^2/GJ)	
Volumetric energy density (GJ/m^3)		OPEX (€/GJ)					
TRL (scaled to Nth of a kind)		Equipment Cost (M€)				Water consumption (m^3/GJ)	

Notes:

- Not all parameters were calculated due to uncertainties and logistic assumptions which could change the data.
- Storage capacity needed is dependent on the throughput.
- Each tank used is 50,000 m^3 volume per tank.
- Model should error when throughput requires smaller/bigger tanks.
- Minimum of 2 tanks required
- Tank lifetime 30 years.
- Only storage taken into account, not the remaining infrastructure needed at a terminal to accommodate for the product transfers

Quality Assessment

The following matrix shows the scores on quality assessment of data inputs and indicators grouped as total system.

Uncertainty for Data Inputs				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	4	3	3	4
Economic	3	3	3	4
Environmental	3	3	3	4

Uncertainty for Key Performance Indicator Outcomes				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	4	3	3	4
Economic	3	3	3	4
Environmental	3	3	3	4

Notes:

- Quality assessment based on existing data, no new technology discussed.

Process flow diagram

Risks and opportunities

	Risks	Opportunities
Technological	Refrigerant, insulated tanks needed for cryogenic storage	Already used in large scale, no significant opportunities expected due to maturity of technology.
Economic	-	Already used in large scale, no significant opportunities expected due to maturity of technology.
Political	-	Already used in large scale, no significant opportunities expected due to maturity of technology.
Social	-	Already used in large scale, no significant opportunities expected due to maturity of technology.
Environmental	-	Already used in large scale, no significant opportunities expected due to maturity of technology.

References:

- Gate Terminal. (2019). Terminal informationRetrieved from https://gate.nl/en/home.html
- Vopak internal data**:**

Reconversion

R1: $NaBH_4$

Data sheet prepared by/owner: Jonathan Moncada & Andrea Ramirez, Delft University of Technology

Data sheet reviewed by: Eddy van Oort, Frames

Technology Description:

Technology consists of the hydrolysis of $NaBH_4$ to yield H_2 back. The reaction takes place at 80 ºC and atmospheric pressure. The products are hydrogen and sodium metaborate. Hydrogen is recovered from the mixture by a flash unit, whereas sodium metaborate is separated from water using a filtration unit. Hydrogen storage is not included within the boundaries of the system.

The technology size was set to match the output flow rate of $NaBH_4$ presented in the corresponding datasheet. In this technology, the annual production of hydrogen is 10 ktonne. Hydrogen produced with this cracking technology does not match the initial mass of hydrogen contained in $NaBH_4$ (2.5 ktonne H_2 equivalent/y, see $NaBH_4$ data sheet) as the hydrogen contained in the water used to hydrolyze the hydride is also released. Note that in the final hydrogen released, only 25% (in mass) comes from $NaBH_4$, and the remaining 75% from the water input used to hydrolyse the hydride.

$NaBO_2$, can be hydrogenated back to $NaBH_4$, however, this step was not considered in this data sheet. Following a conservative approach, $NaBO_2$ is considered as a non-value stream.

Key Performance Indicators (KPIs)

Technological		Economic				Environmental	
		Year	**Base year (2019 - 2034)**	**2030**	**2050**		
TRL (scaled to Nth of a kind)	2	Equipment Cost (M€)	0.73	N/A	N/A	Water consumption (m^3/kg H_2)	0.002
Round trip efficiency (%)	0.47	CAPEX (M€)	3	N/A	N/A	Water withdrawal (m^3/kg H_2)	0.6
Capacity (TJ H_2 produced/y)	1181	Annualized CAPEX (M€/y)	0.2	N/A	N/A	Heat (MJ/kg H_2)	2.9
Capacity (ktonne H_2 produced/y)	10	Annualized CAPEX (€/kg H_2)	0.02	N/A	N/A	Electricity (kWh/kg H_2)	0.09
Capacity (ktonne H_2-eq produced/y)	10	Annualized CAPEX (€/kg H_2-eq)	0.02	N/A	N/A	GHG emissions (kg CO_2-eq/kg H_2)	0.3
Product concentration, purity (wt.%)	99	OPEX (M€/y)	50	N/A	N/A	Land footprint (m^2/kg H_2)	N/A
Volumetric energy density (GJ/m^3)	0.01	OPEX (€/kg H_2)	5	N/A	N/A		
Losses during storage (%)	-	OPEX (€/kg H_2-eq)	5	N/A	N/A		

Notes:

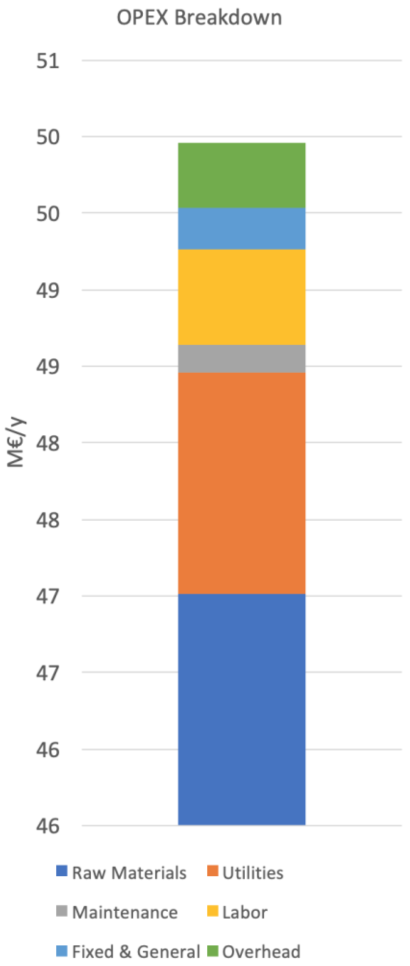
- The technology was set to process a $NaBH_4$ input flow of 47 ktonne/y. This flow matches that shown in $NaBH_4$ production data sheet. Base year 2017
- This technology was modelled in Aspen Plus as there was no available data reporting on the mass and energy balances of the hydrolysis of $NaBH_4$ to hydrogen. Equipment costs were estimated in Aspen Economic Analyzer. CAPEX was estimated using typical factors which can be found in the calculations tab.
- OPEX was estimated based on the mass and energy balances estimated in Aspen Plus, and using additional inputs such as prices. The environmental indicators were also estimated based on mass and energy balances. For clarification see the Calculations tab.
- The annualized CAPEX was calculated for a period of 20 years and interest rate of 5%.

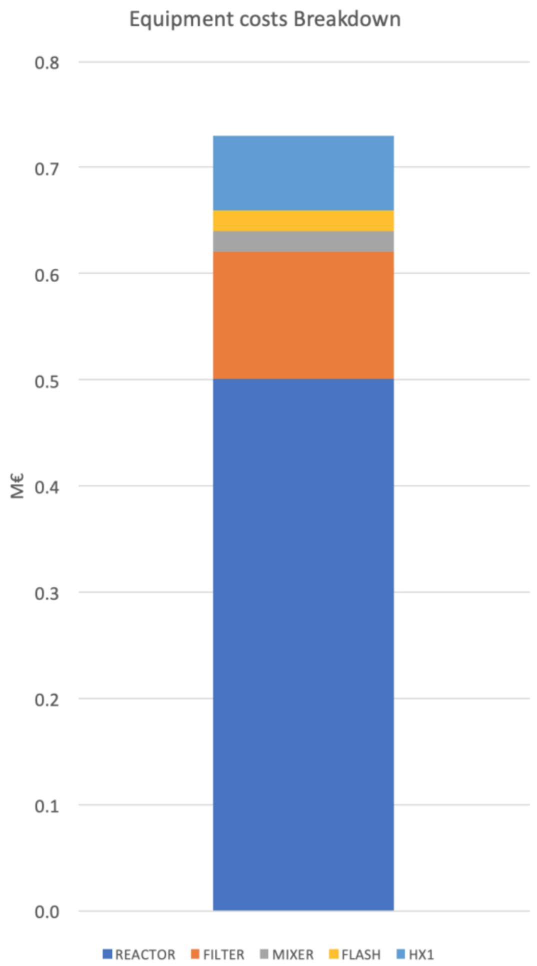
- Costs for 2030 and 2050 are not available for this technology.
- LHV of $NaBH_4$ @99wt% is 30.4 MJ/kg. LHV of H_2 is 117.9 MJ/kg.

CAPEX as a function of capacity

	ktonne/y		M€		M€
Capacity 1	5	Equipment cost 1	0.5	CAPEX	1.7
Capacity 2	10	Equipment cost 2	0.7	CAPEX	2.6
Capacity 3	15	Equipment cost 3	0.9	CAPEX	3.4

Equipment	ktonne/y	Scaling factor	Cost €
REACTOR			501
FILTER			119.7
MIXER			19.9
FLASH			18.6
HX1			70.4
Total equipment costs at capacity 2			729.6





Notes:

- Although the equipment list is known, it is difficult to identify the individual capacity factors and assumptions to scale each individual equipment.
- The six-tenth rule of thumb is then used

Quality Assessment

The following matrix shows the scores on quality assessment of data inputs and indicators grouped as total system.

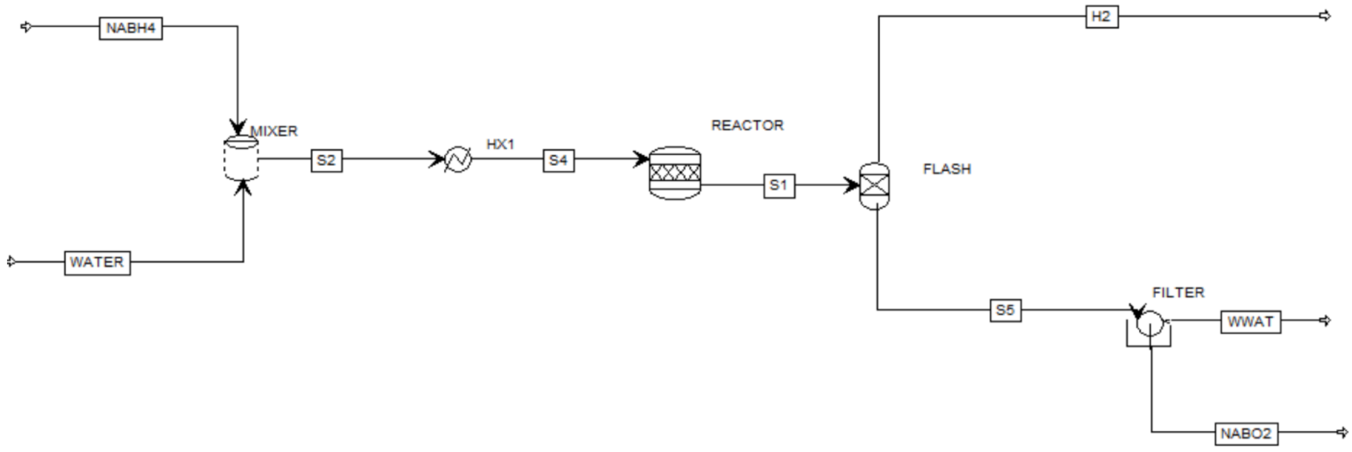
Uncertainty for Data Inputs				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	1	2	2	0
Economic	1	2	2	1
Environmental	1	2	2	1

Uncertainty for Key Performance Indicator Outcomes				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	2	2	3	0
Economic	1	2	2	0
Environmental	1	1	1	0

Notes:

- This technology scores low in data inputs as there are not many studies on the hydrolysis of $NaBH_4$ for hydrogen production. Available literature discusses the concept, but not does not clearly provide performance indicators about the technology. There was very limited availability (to the authors' knowledge) of data regarding the technology. Only a couple of studies reporting the main conversion steps and reactions were available. This information was therefore used to model the process. Validation process for technical data inputs was not possible.
- Technical, economic and environmental data is based on data derived from a technical model. The model is mild resolution.
- Reliability on the environmental indicators is unknown. Emission factors are those from the current electricity mix in the Netherlands, and steam for industry. Emission factors do not take into account possible transition to renewables.
- Validation process was not possible.

Process flow diagram



Notes:

- Details on inputs, products and waste streams flow rates can be found in the calculations tab. WWAT; waste water

Risks and opportunities

	Risks	Opportunities
Technological	Technology is still immature and development is still at a very early stage. Large scale production of H_2 from $NaBH_4$ is still not proven.	The technology appears to be flexible in terms of production volumes. In literature, the hydrolysis of NaBH4 is aimed to be carried out in cars engines. Thus, the use of $NaBH_4$ could offer flexible production of hydrogen. Metaborate can be recycled to produce $NaBH_4$.
Economic	The concept provided in this datasheet needs to be corroborated and it needs to be considered whether technology updates would be required. This can directly affect capital investment needs and energy consumption levels.	The overall flexibility of the system might be beneficial for scaling the technology or deploying it at different scales depending on demand.
Political	The handling of metaborate needs to properly be taken into account as it may represent a major safety risk.	Fuel cell application are foreseen as most promising.

Social	Handling of metaborate and $NaBH_4$ can affect social perception of the technology regarding safety.	The types of jobs is expected to be skilled workforce at the factory level
Environmental	Handling of metaborate and $NaBH_4$ can affect social perception of the technology regarding safety.	Opportunity to recycle metaborate back would relieve pressure on waste management and disposal.

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- The technology was modeled in Aspen Plus to build mass and energy balances. Equipment costs were estimated in Aspen Economic Analyzer.

R2: LOHC (Dehydrogenation)

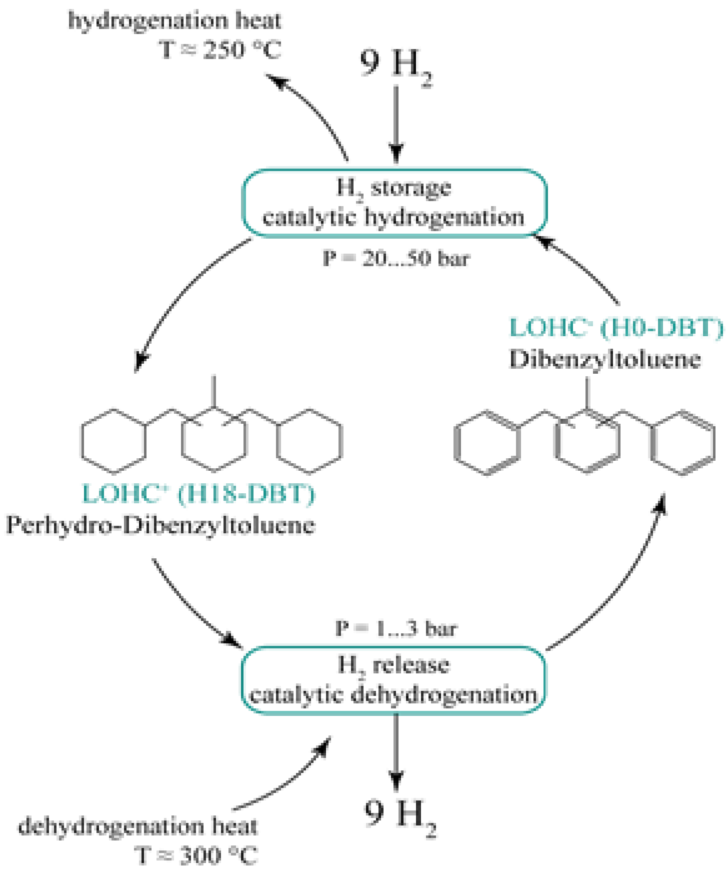
Data sheet prepared by/owner: Tim Lauret, Frames

Data sheet reviewed by: Jonathan Moncada & Andrea Ramirez, Delft University of Technology

Technology Description: The LOHC technology is based on the reversible catalytic hydrogenation and dehydrogenation of an organic carrier oil (in this case Dibenzyltoluene (DBT)).

The LOHC-technology is described by three steps:

1. In the hydrogen storage process, DBT is loaded with 9 molecules of hydrogen in a catalytic hydrogenation process, which results in a hydrogen storage density of 6,23 wt.% (57 kg /m³). This volumetric storage density is comparable to high pressure storage at >1,200 bar. The hydrogenation process runs at 25 to 50 bar and ~250 °C. Due to the exothermy of the reaction, 8 kWh_{th}/kg_{H2} of usable heat is released during the process.
2. During the storage/transport step the hydrogenated DBT can be stored and transported at ambient conditions in today's fossil fuel infrastructure. Due to the lack of high pressures and low temperatures the LOHC can be handled very conveniently.
3. The hydrogen release process is an endothermic reaction requiring 11 kWh_{th}/kg_{H2} of thermal energy input, at a temperature level of ~300 °C. After dehydrogenation, the unloaded DBT can be reused as hydrogen carrier. Due to its high temperature stability, DBT exhibits high cycle and long-term stability.



Key Performance Indicators (KPIs)

Technological		Economic				Environmental	
		Year	**Base year (2019 - 2034)**	**2030**	**2050**		
TRL (scaled to Nth of a kind)	6	Equipment Cost (M€)	2.9	1.54		Water consumption (m^3/GJ)	-
Round trip efficiency (%)	70%	CAPEX (M€)	4.1	1.9		Water withdrawal (m^3/GJ)	0.8
Capacity (TJ/y)	64.79	Annualized CAPEX (M€/y)	0.33	0.15		Heat (GJ/GJ)	0.33
Capacity (ktonne/y in loaded LOHC)	9.5	Annualized CAPEX (M€/GJ)				Electricity (kWh/kg H_2-eq)	1-2
Capacity (ktonne H_2-eq/y)	0.54	Annualized CAPEX (M€/kg H_2-eq)	6.09249E-07	2.82335E-07		GHG emissions (kg CO_2-eq/GJ)	0.0003
Product concentration, purity (wt.%)	99.999	OPEX (M€/y)	1.015	0.65		Land footprint (m^2)	35
Volumetric energy density of loaded LOHC (GJ/m^3)	6.8	OPEX (M€/GJ)					
Losses during storage (%)	5%	OPEX (M€/kg H_2-eq)	1.87963E-06	1.2037E-06			

Notes:

- Capacity: ReleasePLANT 1,5 tonnes per day of hydrogen release
- The release of 0,54 kt/y of hydrogen leads to a loaded DBT amount of 9,5 ktonne/y.
- Density: 57kg H_2/m^3 LOHC
- Annualized capex calculated for a period of 20 years and interest rate of 5%
- OPEX is including utilities (heat demand supplied by electricity), service maintenance and labor costs, but excluding raw costs of hydrogen
- Electricity: 1-2 kWh/kg H_2-eq is without electricity demand for heat (see "heat"-row before. Price: 0,10€/kWh)

- Water withdrawal: Water for cooling purposes is not consumed, but circulated in a closed process cycle.
- Heat: Endothermic hydrogenation, which is requiring 11 kWh/kg H_2-eq. Heat is in this case supplied by electricity (in OPEX), but can also be supplied by other sources (natural gas, hydrogen, excess heat source).

CAPEX as a function of capacity

	ktonne/y		M€		M€
Capacity 1	0.54	Equipment cost 1	2.8	CAPEX	4
Capacity 2	0.72	Equipment cost 2	3.4	CAPEX	4.7
Capacity 3		Equipment cost 3		CAPEX	

Equipment	ktonne/y	Scaling factor
Reactor	1.8	0.6
Catalyst	1.8	0.99
Vessels, pumps, fittings, piping	1.8	0.3
Thermal heat unit	1.8	0.3

Notes:

- Dehydrogenation
- Data based on known cost data of today (see Technology KPIs for target costs)

Quality Assessment

The following matrix shows the scores on quality assessment of data inputs and indicators grouped as total system.

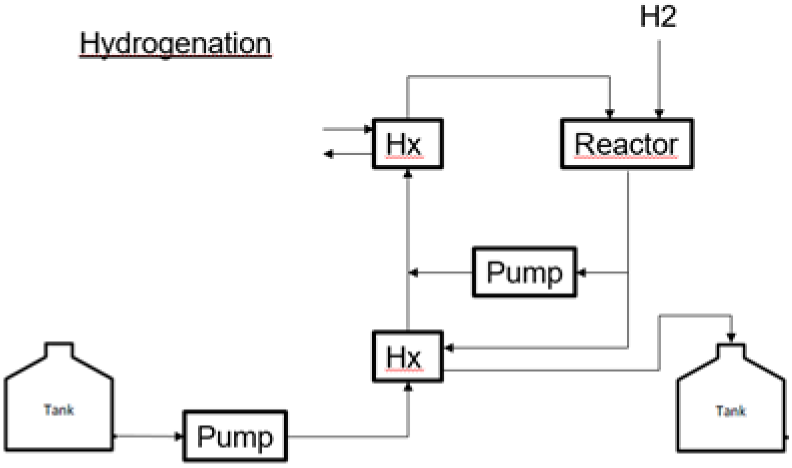
Uncertainty for Data Inputs				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	4	4	3	2
Economic	4	3	3	3
Environmental	4	4	3	2

Uncertainty for Key Performance Indicator Outcomes				
Areas	**Proxy**	**Empirical basis**	**Methodological rigour**	**Validation process**
Technical	4	4	3	2
Economic	4	4	2	2
Environmental	4	4	3	2

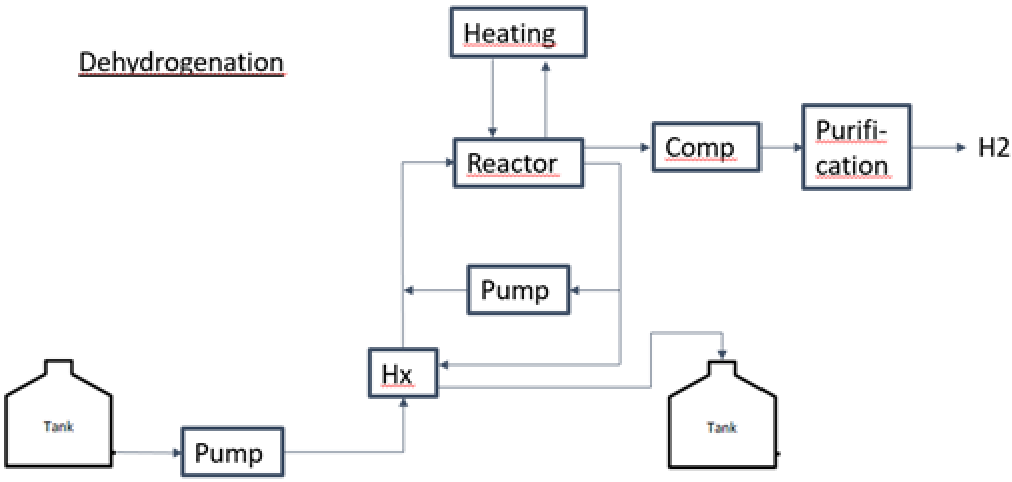
Notes:

- LOHC scores high in the indicator proxy because only directly measured values are used in technical and economic models.
- Empirical data is excellent for Technical and Environmental since values stem from focused experiments and direct measurements. Economic relies on historic data.
- Models use common approaches.
- Validation process of LOHC scores medium because there are not independent studies to compare with.

Process flow diagram 1



Process flow diagram 2



Risks and opportunities

	Risks	Opportunities
Technological	The hydrogen released from the dehydrogenation unit might not comply with the required quality standards, preventing the use at a e.g. HRS. Mitigation: Hydrogen released from DBT already has a purity of >99,9%, which is significantly higher than purity of other industrial raw hydrogen sources. Purification technology is well established in industrial settings and if needed, purification technology included in the system can therefore be extended to meet requirements. Dependence on external feedstocks: LOHC production is currently dependent on the supply of toluene. But LOHC faces only minor wear. Thus, toluene has only indirect influence.	The aspect of safety becomes even more relevant than today due to increasing volumes of hydrogen in a semi-public environment. The inherent safety of the LOHC technology provides an existing scalable solution considering these aspects and thus can offer a global infrastructure. Operational flexibility: The storage and release units can be ramped up and down in technical ranges. Just at the time of design the required range has to be defined. 50 - 120% are common. Compatibility with existing infrastructure: Liquid hydrocarbons are widely used and transported. Thus, the LOHC technology is well compatible. Scalability: The technology is scalable in dimensions of the chemical industry. Large scale is therefore favorable for the LOHC-process.
Economic	Economics of the LOHC-devices might not meet the targeted cost assumptions. Mitigation: Both processes, hydrogenation, as well as dehydrogenation are standard processes in the chemical industry with well established cost structures. Suppliers for equipment are available worldwide and will even increase in number with hydrogen becoming more relevant in other industry sectors. Current demand: LOHC technology has not yet seen a large scale market roll-out.	Faster roll-out of new market segments will open an opportunity for the LOHC technology, as more infrastructure for the transport and storage of hydrogen will be required. This will enhance numbering up and therefore cost down potentials. Additionally DBT is a well established thermal oil. Due to that, the channels of distributions are already well established. Current supply: Unloaded LOHC is well available in multi-10,000t-scale. Suppliers are well available, but will number up with increasing demand.
Political	The source of Dibenzyltoluol is from crude oil. The political situation is unstable in some countries, that are hauling crude oil. Mitigation: Crude oil is used over a century without major breakdowns of the international oil industry. Furthermore DBT is cycled and	DBT is produced by companies all over the world. As a result, there will be no DBT-shortage, if there is a trade embargo by one country and hydrogen supply is always secured.

	not consumed, therefore the overall demand for DBT will be lower than for e.g. Diesel.	
Social	As DBT is a hydrocarbon, a small risk exists that the public will see DBT as "not decarbonized". Mitigation: This risk can be mitigated through communication and explanation as the DBT is not consumed and therefore does not lead to carbon emissions Sounds, odor, and visual pollution: Storage - Comparable to current industrial complexes. Release - Comparable to current refueling stations. Public perception and acceptance: No major change in handling compared to current hydrocarbon infrastructure. This enhances the adaptability for hydrogen as an energy carrier, compared to CGH_2, e.g.	Using LOHC, hydrogen is handled like a fluid, not as a gas. As people are used to use fluids for mobile transport the acceptance of a hydrogen fueled mobility and for many other applications will be higher than with existing technologies like compressed hydrogen and liquified hydrogen.
Environmental	The source of Dibenzyltoluol is from crude oil. Mitigation: The thermal oil is not consumed during the hydrogenation and dehydrogenation process. Therefore it is possible to cycle the fluid between the hydrogenation and dehydrogenation processes up to a 1,000 times with a subsequent regeneration step and then be re-used again.	This energy consumption of the dehydrogenation is thermodynamically given, but the source of the thermal energy supply can be changed. The biggest impact on reducing CO_2-emissions is achieved, when thermal energy is provided by burning biogas or by heating electrically using 100 % renewable power. If these two options are not realizable, in countries like Germany one can use natural gas to reduce the CO_2-footprint about 40 – 50 % in comparison to electrical heating with standard power supply. Toxic pollution or risk: LOHC is stored at ambient conditions. It is hardly flammable and not classified as a dangerous good. Recyclability: Main parts: Steel, Catalyst (platin based materials - recyclability is state of the art in catalyst industry), DBT as LOHC (high stability with of over 500 cycles. Can additionally be redistilled after end of lifetime).

References:

This technology was assessed based on 9 years of development work in academia and industry. During this time numerous lab plants were built and many industrial demonstration units were designed, built and brought into operation in different industries and countries. Data, models, correlations, and patents are IP of Hydrogenious Technologies.

General Conclusions

In the end, some technologies were explicitly excluded from these data sheets. During the course of the project, the consortium had many discussions about which technologies to include or exclude. For the most part, technologies were excluded that had a very low TRL level (e.g. below TRL 6), as it was argued that these are not currently able to provide H_2-containing energy carriers at the scale that is necessary in the transition to come. Several low-TRL technologies were in fact included, when it was determined that these had a high potential. In addition to the low-TRL technologies included, additional these technologies may scale up on a relatively short time period and there are many experimental technologies in the lab that if successful may have a disruptive influence on the market. Several technologies exist on the watchlist of major hydrogen knowledge institutes, and recently some have appeared in the news, for example:

- **Photoelectrochemical solar panels** (PEC) convert sunlight directly to chemical energy, without first generating electricity. Water is split by combining photoactive and electrocatalytic materials under sunlight. It has been hailed as a technically challenging but potentially game changing technology which requires few low cost materials (Rongé, 2015). Recently delivered projects at KU Leuven show working prototypes with efficiencies of 15%, improved from 0.1% in four years- all by extracting the required H2O from the water vapor in air. As of yet, no startups or commercial parties have committed to this technology, but the future looks promising.
- **Hydrogen production from seawater** is an effort to find alternatives to the requirement of purified water for fuel production. With the quantities expected to be needed in the future it is unacceptable that fuel production would compete with the requirement of drinking water. Improving electrodes to increase the corrosion resistance from the salts in seawater would open up the use of seawater for hydrogen production. Recent developments show electrodes made from alternative alloys running over a thousand hours as compared to conventional electrodes which would not last a day (Kuang et. al, 2019).
- **Thermochemical hydrogen production** has been around for a long time but continues to be relevant. It allows the production of hydrogen using heat. Under normal circumstances, water falls apart into oxygen and hydrogen at temperatures above 2000C, but catalysts can improve the thermochemical water splitting cycle by reducing the required temperature. Low durability of the water splitting cycle at high temperatures is a challenge that requires further research. (Rosen, 2010)
- **Photobiological hydrogen production** uses microorganisms to convert sunlight into hydrogen, but low yields and lack of control for enzyme activity are challenges which require further research.

Beyond excluding low-TRL experimental technologies, another choice was made to exclude technologies for reconversion - from a H2-containing energy carrier back into hydrogen. The general assumption was that it seemed economically inefficient to convert gaseous hydrogen to another molecule and then back into hydrogen again. The reasoning behind the exclusion of cracking back the carriers is that including additional conversion steps would imply extra investment needs, operating cost which ultimately affect the supply chain hydrogen costs. On top of this, in most cases the overall energy efficiency of the supply chain drops as the number of conversion steps increase. It is indeed more efficient to convert hydrogen to a molecule that can be used as that molecule. Only $NaBH_4$ and LOHC reconversion was included for this reason, as these molecules are exclusively energy **carriers** and not used in this form.

However, there is also good reason to include other reconversion pathways in the future alongside the technologies included. For one, the assumption that conversion and subsequent reconversion is too inefficient to make up for potentially more efficient transportation and storage options for a molecule should be tested. Additionally, there are some supply chain options which are already being considered seriously which include reconversion, for example for ammonia. This indicates that even though it was decided that all of the many reconversion options were outside the scope of this work, this should be included in follow-up work.

It is important to reiterate that the results are not harmonised because of different methods of data collection and data sources. Also this project does not evaluate how technologies can be linked to develop supply chains related to hydrogen economy. Thus, harmonizing (e.g., in terms of size, flowrate how technologies can be added up together needs to be carried out in a follow up stage For this reason, it is impossible to cross-compare these across all of the metrics that were included and this is also outside of the scope of this project. Just the same, there are some metrics which can be compared and there is additional value in considering these aspects. Some of the elements the team discussed comparing include the TRL levels, capacities/scale, and the CAPEX/GJ.

Reflection

Key Conclusions: Current State of Knowledge and Gaps

Will just be a summary of what comes in the section at the end of results

How this Research Supports RVO and Industry Decarbonization Ambitions

This report and the associated database will be placed online at the website of the Institute for Sustainable Process Technology (ISPT). With this database and collection of data sheets, industry parties along the supply chain can use the information to inform their own decision making. In addition to internal decision making, there are many running research and development projects with consortia of organizations in the Netherlands actively working on different aspects of the supply chain. This work can form an important starting point for this work in the following ways:

- Providing a source of key data on technology options - which can be an input for optimization modeling
- Giving an indication of which technologies need further development - as a starting point for identifying innovation opportunities
- Showing the level of the state of knowledge and where uncertainty around technological outcomes exist - for setting research priorities

While the work is quite removed from having a direct impact on CO_2 emission reduction targets, it does play a key supporting role in the decarbonization efforts of industry in the Netherlands. In the TKI report “Outlines of a Hydrogen Roadmap” (Gigler & Weeda, 2018), some of the key ways hydrogen can contribute to decarbonization are outlined, including:

- Providing an alternative option for transportation, particularly where electrification of vehicles is less feasible or economically desirable
- Replacing fossil-based feedstocks for chemical products
- Replacing both high-temperature heat production for industry and low-temperature heat buildings with a low-carbon option
- Serving as a fuel that can balance intermittency in renewable electricity production at a large and economically viable scale

Next Steps

While the information in this report and the database is valuable, it provides merely a static picture of the state of technologies, while innovation is dynamic. As new supply chain technologies become viable, or as the technologies currently included are further developed, it would be ideal if the collection of information was updated or extended accordingly.

We will place this information in the public domain, available to the public from the ISPT website. What this project has achieved is essentially creating the first open source data set on hydrogen technologies, but this will have limited value in a few years if the information is not updated. In order to extend the value of the work that has gone into this project, this should ultimately be kept in a way where updates and additions are possible. This will also make it possible to easily include information on reconversion technologies or the up-and-coming technologies that are not yet at a relevant scale.

This could be implemented, for example, in a format like a Wiki, where peer-reviewed entries can be incorporated over time. Many options exist for free development and hosting of such websites, or it could be hosted by one central organization if someone is willing to take the lead in development.

The MIDDEN initiative is one such open knowledge base for up-to-date decarbonisation options. A platform like this could be an option for storage of the HyChain 3 results to make them open and up for continuous updating. The MIDDEN initiative in particular is not supported by all industry parties, so another alternative option may be preferable.

Beyond general public use of the open data created by this project, the HyChain consortium will use this information immediately in a follow-up project. This project, HyChain 4, aims to pull together the work done within the full HyChain consortium over the past year to evaluate scenarios for the full hydrogen supply chains of the future. The knowledge generated in HyChain 3 will be used to build up and evaluate different supply chain options in full, in order to discover the options that are optimal and likely to play out in the coming transition.

HyChain 4 will help answer key questions that producers and logistics companies are currently facing about how and where hydrogen will be produced, transported, stored, and used in the Netherlands in the coming decades. This will play a key role in supporting all of the supply chain actors in deciding which infrastructure to develop, which technologies to invest in, and which partnerships to establish in the coming decades.

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Colophon

HyChain project partners:

- Nouryon
- DOW
- NV Nederlandse Gasunie
- OCI Nitrogen
- Vopak
- Yara International ASA
- Frames Group BV
- Stedin
- Port of Rotterdam
- Proton Ventures

Subcontractors:

- ECN part of TNO
- TUD-TBM
- Metabolic

Key Project Information

Project Number	TESN118041 (ISPT project number SI-20-06)
Project Title	HyChain 3: technologies for hydrogen based renewable energy and feedstock supply chains
Name Cluster Director	Andreas ten Cate
Name project leader	Jordi Zonneveld (Project Manager, Frames)
Funding	RvO Subsidy funding and ISPT industry consortium
Project start	September 1st, 2018
Project original end date	March 31st, 2019
Project final end date	June 30th, 2019