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Abstract

To achieve the objectives of the Agreement from Paris and reduce global warming to well below 2 degrees Celsius, the Dutch government wants to reduce CO_2 emissions by 55% (beyond 49%) in 2030 (compared with 1990) and further towards 95% CO_2 reduction by 2050. Almost a third of the CO_2 savings target, or 14 of the 45 megatons (Mton), must come from the industry. This means that the Dutch industry needs to shift from the current reliance on coal, oil, and natural gas for its electricity, heat, and fuel need to a CO_2-neutral feedstock. In order to achieve climate targets, we already need to take significant steps.

Electricity from wind and solar energy will play an increasingly important role in the industry, just like in the rest of society. But not everything can easily be electrified. Factories and refineries need very high temperatures, which cannot be achieved yet by electricity alone. In addition, we still have too few wind- and solar-parks in the Netherlands to meet Dutch electricity needs, let alone the total energy needs; there will also be a considerable shortage in 2050. Finally, the current renewable solutions are insufficient to make the industry already climate-neutral and sustainable. Many renewable projects often are small-scale, commercially unprofitable and require a long development time need to be able to contribute substantially to lower the CO_2 emissions in the Netherlands.

Here, hydrogen can play a crucial role. Because with H_2, high temperatures and electricity can be generated. H_2 with CCS can already be used on a large scale as a climate-neutral energy carrier before 2030, a part of the energy supply of chemistry, refining, and electricity production. Furthermore, H_2 production is already in operation on a large scale, which is suitable for the decarbonization requirements of the chemical industry.
However, there is still a need for investigation on the specific application of H_2 + CCS for decarbonization of large industrial clusters like the Rotterdam port area. The objective of this document is to study the technical, economic, and financial feasibility of the application of H_2 + CCS routes keeping in view the Rotterdam port area. To give a comparative perspective in the difference in the choice of technology routes and its sensitivity towards the specific characteristics of the Rotterdam port area. These characteristics include the scale of production facilities, the position of production facilities, the source of the feedstock of reforming gas (e.g., methane or refinery gas), and keeping in mind the maximum use of available infrastructure. To give a view of probable ownership structure for the H_2 production facilities and H_2 users. Furthermore, to compare the distribution in the use of electricity, energy, CAPEX, and OPEX of different technology options.

As conclusions, the report summarizes that:

- The scale of technology has a significant impact on the Levelized Cost of production of H_2 (LCOH). At the size of up to 100 K tonne/annum, SMR + CCS is estimated as the most cost-effective option; however, at scales close to 500 K tonnes/annum, ATR + CCS are also cost-competitive. The estimates are based on specific assumptions for the calculated case of Rotterdam.
- SMR has been the leading technology in terms of the number of plants build worldwide for the production of H_2. However, in recent years, increasing examples of ATR and POX have been reported. The ATR/ POX technology routes have a much more significant portion of their total CO_2 emissions in the form of process-based emissions from the reforming unit which is at high volume % CO_2. This difference has a substantial impact on the cost CO_2 capture for the different technology routes.
- The quality of input gas available, desired output gas composition along with the cost of CCS, will determine the suitability of the technology for use at the Rotterdam port. The main difference between the steam methane reforming versus the partial oxidation reforming is the essential use of the catalyst for the former reforming method. Partial oxidation reforming can take place also in the absence of catalyst, making it a suitable candidate for hydrocarbon feed gas with a higher level of impurity.

Note that the results reported here are generic for Rotterdam and updated with the Dutch case study scoping that has taken place with the companies in the Rotterdam port area (the Industrial Platform, also called the: H-vision). The industrial platform includes 16 parties, predominantly from the port industry area of Rotterdam, which has investigated the techno-economic feasibility of a new "H_2 + CCS" production factory, which converts refinery gasses to H_2 and CO_2. The produced H_2 can be used for heat and electricity, and CO_2 is transported to the North Sea (Porthos) or greenhouses. The project plan studies the feasibility of CO_2 emission reduction of 2 Mton in 2025 up to 6 Mt in 2030. After 2030 there is the possibility to expand this unless renewable hydrogen replaces H_2+CCS.

Therefore this deliverable has been updated based on the outcomes from the Industrial Platform in the H-vision project and the alignment with the broader perspective for the Dutch case study in Elegancy. There is no need for an update of cost figures since the earlier reported cost estimations are in the range of the specific cost estimation of H-vision. The useful tools from WP3 on business case, market failures, and risks and the spatial model of WP4 have been applied to develop and define the solution space for the Dutch case in the Rotterdam port. Also, cost data on hydrogen production is aligned with the input from the industrial members.

This report will be an essential basis for the deliverable "ROADMAP for the introduction of a low carbon industry in the Rotterdam Region D5.2.6", together with the development of a dedicated business case model for Hydrogen.

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1 INTRODUCTION AND OBJECTIVE

The objective of this document is to provide a comparative view on the costs of production of H_2 specifically, capital expenditure (CAPEX) and operating expenditure (OPEX) using different technologies for integration towards the needs of the Rotterdam port area in the near future. The comparison shows the distribution in the use of electricity, energy, CAPEX, and OPEX of different technology options. The cost of carbon capture, transport and storage will be included in the cost estimates. Furthermore, a view of probably ownership structure for the H_2 production facilities is presented. The needed H_2 requirements are included and based on the elegancy deliverable 5.1.1.

The cost figures are in view of the outcomes of the H-vison project updated. With input from the stakeholders in the Rotterdam area, a possible envisaged ownership structure for the H_2 production facilities is presented. The H-vision project is the result of the industrial member's group for the steering the Dutch case study, via a pre-feasibility project that has been set up in conjunction with ELEGANCY project milestones. A.o: M5.2.1: Industrial Platform established and monthly meetings initiated; M5.2.2 :Coordination with WP1 should provide a basic concept for H_2 production; M5.2.4 : Consensus reached with power producers at the Port about the introduction of clean H_2 for fuel.

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2 H_2 REQUIREMENT IN THE ROTTERDAM HARBOUR

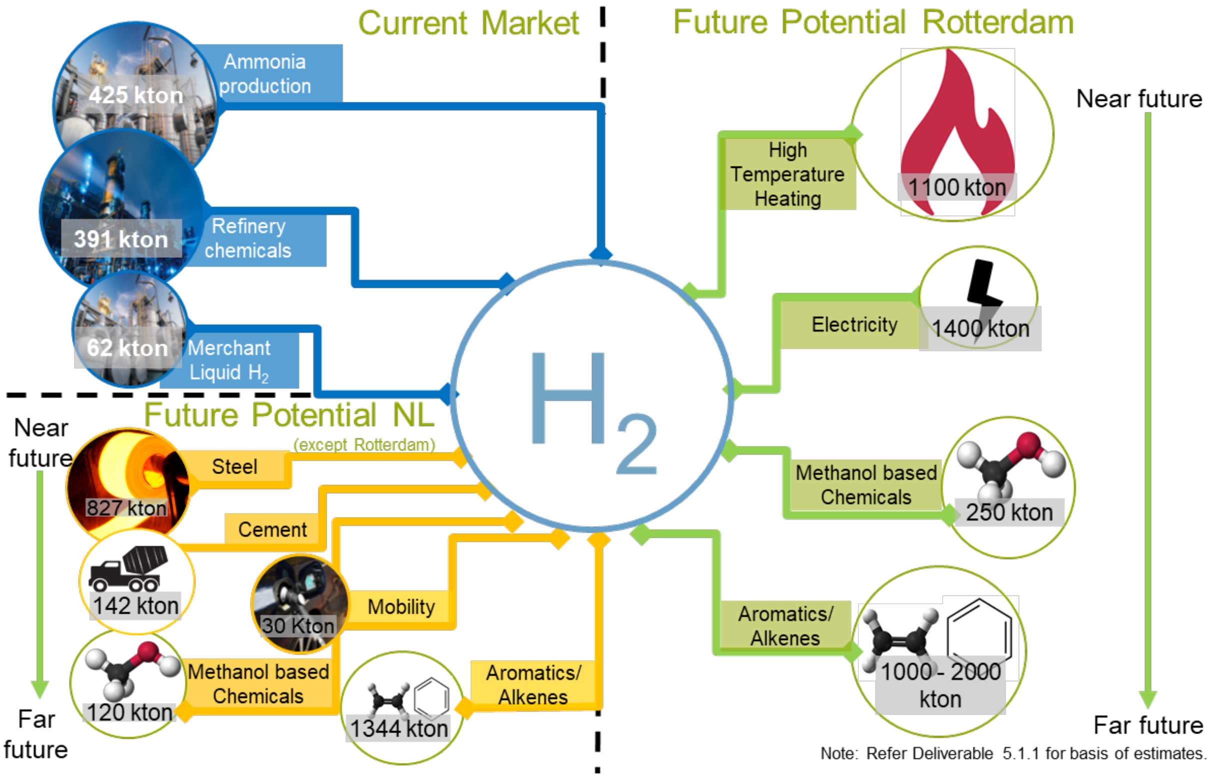

Figure 2.1: Overview of current market and future potential for the requirement of H_2 in the Netherlands, with a particular focus on future potential in the Rotterdam harbour (from deliverable 5.1.1).

Figure 2.1 shows the overview of H_2 capacity (Ktonnes/annum) required under the current market conditions in the Netherlands and its future potential in the Netherlands and the Rotterdam Port. The overview is divided into three parts, 1) The current production of H_2 (mostly via steam methane reforming) in the Netherlands, 2) future potential of H_2 requirement in the Rotterdam petrochemical region, and 3) future potential of H_2 demand in the Netherlands (except Rotterdam). The following table 2.1 shows an expected distribution of H_2 production in the Netherlands in the coming years.

Table 2.1: H2 utilization (in t/y) scenario for Dutch case study.

Sector	Location	Cumulative use of H_2 (Ktonnes/year)			
		2017/8	2021	2030	2035
Transport	Northern-Netherlands			30 Ktonnes	
Industry	Rotterdam	400 Ktonnes	400 - 500 Ktonnes	400 - 650 ktonnes	400 - 800 ktonnes
Grid balancing			0 – 45 ktonnes	0-90 ktonnes	0-90 ktonnes
Industry	Southern Netherlands	425 ktonnes	425 ktonnes	425 ktonnes	425 ktonnes

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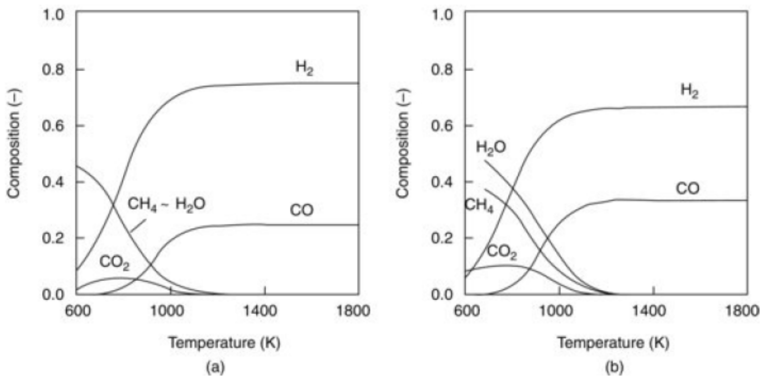
3 MAIN REACTIONS AND TECHNOLOGIES FOR THE PRODUCTION OF H_2

Main reactions of the H_2 production are:

	Δ H (KJ/mol)	
$CH_4 + H_2O \leftrightarrow CO + 3\ H_2$	206	(1)
$CH_4 + CO_2 \leftrightarrow 2\ CO + 2\ H_2$	247	(2)
$CH_4 \leftrightarrow C + 2\ H_2$	75	(3)
$CO + H_2O \leftrightarrow CO_2 + H_2$	-41	(4)
$2\ CO \leftrightarrow C + CO_2$	-173	(5)
$CH_4 + ½\ O_2 \leftrightarrow CO + 2\ H_2$	-36	(6)
$CH_4 + 2\ O_2 \leftrightarrow CO_2 + 2\ H_2O$	-803	(7)
$CO + ½\ O_2 \leftrightarrow CO_2$	-284	(8)
$H_2 + ½\ O_2 \leftrightarrow H_2O$	-242	(9)

Three technologies dominate the current production of H_2 from methane, namely steam methane reforming (SMR), autothermal reforming (ATR), and partial oxidation (POX)[1]. Methane reforming by steam is mainly governed by the reforming reaction (1) and water gas shift reaction (4). Side reactions resulting in the formation of coke may also occur by decomposition of methane (3) or by the Boudouard reaction (5).
Partial oxidation with integrated water gas shift (ATR) or without water gas shift (POX) is mainly governed by oxidation reaction (6). The side reactions such as complete oxidation of methane to CO_2 and H_2O (7) and oxidation of formed CO and H_2 may also occur reaction (8) and (9).

The extent of conversion by main reactions to desired products H_2 (and CO) is dependent on the reaction conditions (temperature and pressure). Broadly, endothermic reactions (1-3) are dominant at high temperatures, and exothermic reactions (4-9) are dominant at lower temperatures. The extent of product formation is governed by temperature of the reactions and possible removal of products. The effect of temperature for the production of H_2 is shown in figure 3.1 below[1]. The increase in the pressure for main reactions is not thermodynamically favorable due to the high number of molecules formed at the product side of reactions. Nonetheless, reforming reactions are still operated at high pressures due to the lower smaller size of the reactor and hence, better economics.



[1] Moulijn, J. A., Makkee, M., & Van Diepen, A. E. (2013). Chemical process technology. John Wiley & Sons.

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Figure 3.1: Equilibrium gas compositions at 1 bar as a function of temperature for (a) steam methane reforming and (b) partial oxidation reforming of methane; O_2/CH_4 = 0.5 mol/mol[1].

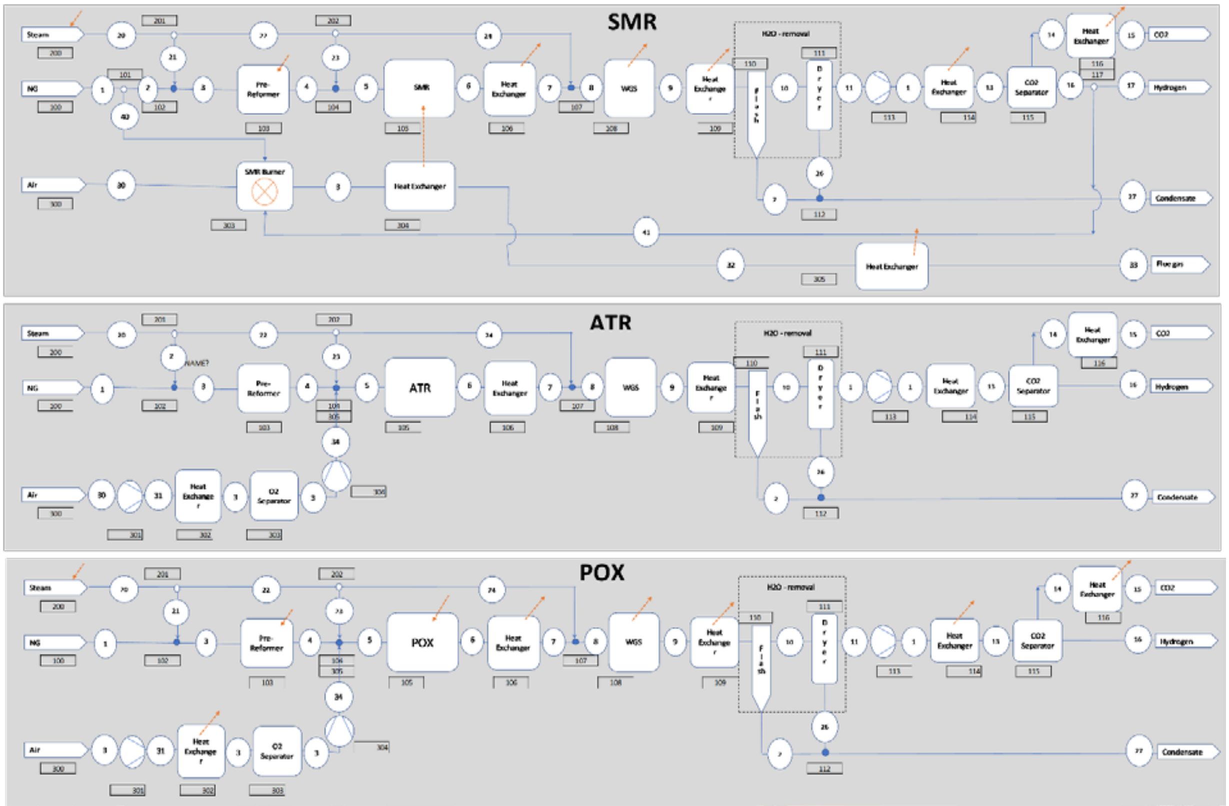

Figure 3.2: Flowsheet diagram for the production of H_2 via different technologies namely SMR, ATR, and POX. Note that the carbon capture and storage part is not included in this flow sheet. For a more precise image, please refer to the appendix.

3.1 Technology case for hydrogen production at Rotterdam update

Within the H-vision study (Industrial Platform), there was a dedicated team reviewing the technical concepts for hydrogen production. This assessment was supported by the early technology assessment in this work package, WP5. Therefore, based on the literature review, thermodynamic models based on Enssim excel tool , and input received from Equinor and Air Liquide, a high-pressure Auto-Thermal Reforming (ATR) unit has been considered most suitable and recommended by the (Industrial Platform). There was no usefull link with WP1 for the technology selection for the Dutch Case. Mainly due to the timing of the technology selection activities by the industrial parties at an early stage of the project.

Based on the quantifiable KPIs defined in WP4, the most relevant for the Dutch Case study is selected. Plant efficiency and CO_2 intensity:

Plant efficiency [%]:

$$Plant\ Efficiency = \frac{\dot{m}_{H2} * LHV_{H2}}{\dot{m}_{fuel} * LHV_{fuel} + Power\ consumption} * \%$$

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Plant efficiency is the total hydrogen production heat content divide by the total energy in.

CO_2 Intensity (CI) [g CO_2/GJ]:

$$CI = \frac{m_{CO2}}{GJ_{H2}}$$

The carbon intensity (CI) is the total amount of CO_2 emissions per unit of energy supplied to the end-user. GHG emissions are to be quantified for H_2-CCS chains, including natural gas supply and end-use technologies. In a conventional scheme, the most significant fraction of the CO_2 emissions is related to the final utilization of the energy sector (i.e., fossil fuel). There is next to the primary emission source from the end-utilization also the CO_2 emission that comes with the hydrogen production process. Part of the resulting CO_2 will not be captured and will be vented to the atmosphere. The H_2 fuel will not be 100% pure, so CO_2 will still be emitted by the end-user due to carbon-containing impurities such as CO_2 and CH_4.

Based on these two KPIs, high-pressure ATR stands out compared to the alternatives and has the following additional advantages:

- ✓ First and foremost , at the capacity required for the Rotterdam case, the economy of scale is crucial for limiting CAPEX, and ATRs have by far the highest capacity per train.
  - SMR and POX technologies encounter manufacturing limitations at lower scales.
  - Operating at high pressure is CAPEX efficient, but comes at the expense of CO_2 capture because a higher percentage of methane is present in the blue H_2 fuel.
- ✓ ATRs have demonstrated extremely high reliability in operation for mega-methanol plants, with recorded availabilities as high as 99.7%.
- ✓ Broad operating range and very high flexibility
  - According to Air Liquide, an ATR can be operated at 30-110% of its nominal capacity, with minor design adjustments.
  - Even an extensive unit can be operated with ramp-up and ramp-down rates as fast as 1.5% (of its size) per minute.
  - These are both very important, considering the complex phasing of the project and the expected intermittency in demand for the H_2-rich fuel.
- ✓ High-pressure operation reduces the cost of capturing CO_2 from the syngas, as well as the cost of compressing the H_2-rich fuel.
- ✓ Higher carbon conversion compared to an SMR
- ✓ Better maintainability
- ✓ SMR have more components in the creep range, limited to ~100,000 operating hrs
- ✓ Compared to POX, and the burner lifetime is much longer for ATRs

A high-pressure ATR is suitable for producing H_2 from a mixture of NG with RFG, but the gas pre-treatment section must be adapted to cope with the higher H_2S content and C2+ molecules in RFG. This is a relatively standard technology for reforming plants and is expected to increase CAPEX by less than 5%.

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It is worth noting that in the H-vision project, Air Liquide recommended using their Rectisol physical absorption technology to capture the CO_2, instead of HP amine capture. According to Airliquide, it is expected to have a lower CAPEX, and higher energy efficiency thought that this but must be reviewed during the conceptual design phase of the H-Vision project.

As such, the technology selection for the Dutch case study in Elegancy is mainly based on interaction with the industrial members, using the quantifiable KPIs. The design parameters of the HP ATR production units used are presented in appendix C.

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4 INTEGRATION AND SCOPING

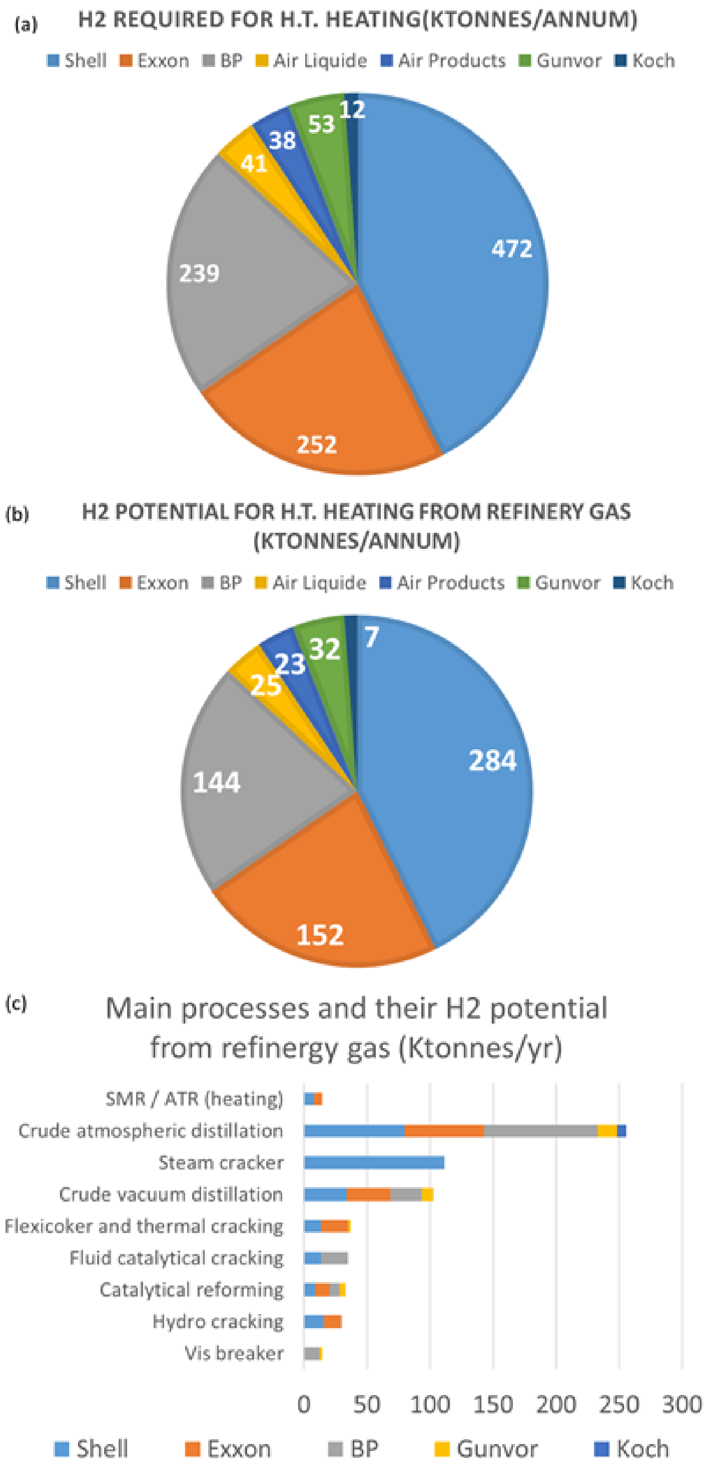

Figure 5.1: (a) Potential of H_2 production for H.T. heating, (b,c). by use of refinery gas in Rotterdam industrial cluster.

The integration with existing businesses and ownership structure for the H_2 infrastructure in the Rotterdam area directly relates to the potential use of H_2. In the near future, the possible use of H_2 for the supply of heat and electricity is an attractive starting point for the use of H_2 because of three primary reasons. Firstly, heating in refineries and the production of electricity are the most significant contributor (>80%) of CO_2 emissions in the Rotterdam area. Secondly, the refinery gas is a by-product of existing processes and is currently used for heating of processes. Conversion of refinery gas to make H_2 for the provision of heat can be a route for coupling available materials for the decarbonization route. Thirdly, the technologies for converting H_2 to heat and electricity are at a more higher level of technical maturity than other possible ways of using H_2, such as conversion to liquid fuels and chemicals. Thus, the business case and the ownership structure focus on the use of H_2 for heat and electricity in the Rotterdam area.

4.1 Specific potential of H_2 production for heating in the Rotterdam Industrial Cluster.

Figure 5.1 (a) shows the distribution of potential H_2 requirements for high-temperature heating per user at the Rotterdam port area. The basis of calculation is the total amount of heat used by individual processes in the refinery processes per user. Figure 5.1 (b) shows the potential use of H_2 when produced from refinery gas already consumed in the high-temperature processes. The estimates

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are shown in Figure 5.1 (b) are different from Figure 5.1 (a) because of two primary reasons/ assumptions. Firstly, we assume that the refinery gas provides 80% of the total heat required for high-temperature processes in the refineries. The rest of the heat is considered to be supplied by natural gas. This assumption is based on the CBS data[2] which reports ~ 17% heat use from residual (see appendix for details). Secondly, we assume the reforming reactions achieve a 75% conversion when transforming the hydrocarbon content in the refinery gas (mainly methane) to H_2. Due to these reasons, an estimated maximum of about 667 Ktonnes of H_2 can be produced by the conversion of refinery gas into H_2 for high-temperature heating. This corresponds to approximately 60% of the overall need for energy for high-temperature processes in the refineries. Furthermore, additional possibilities for providing the remainder of the heat need to be investigated. These can be the use of unconverted or partially converted tail gas from the reforming unit with/ without CCS or reforming of existing natural gas sources or other sources, e.g. reforming of syngas from polymer gasification or biomass gasification.

4.2 The specific potential of H_2 production for electricity in the Rotterdam Industrial Cluster.

(a)

Power plant name	Power* (MW)	Fuel Source
Uniper Maasvlakte	2110	Mixed fuel coal based
Uniper RoCa	340	Fossil gas
ENECOGEN V.O.F.	870	Fossil gas
Eurogen CV	130	Fossil gas
ENGIE Energie NL N.V.	800	Mixed fuel coal based
MaasStroom Energie C.V.	427	Fossil gas
Pergen V.O.F.	300	Fossil gas
Rijnmond Energie CV	820	Fossil gas

* Rated power at full operational capacity.

(b)

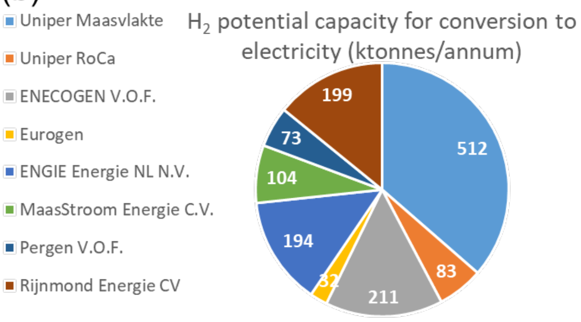

Figure 4.2 (a) Distribution of power production in the Rotterdam port area by different companies. (b) Distribution of H_2 capacity for conversion to electricity at full load.

Figure 4.2 (a) shows the rated power of various power plants in the Rotterdam area obtained from the database of enstoe[3]. It must be noted that the power plants need not operate on full capacity and can operate at a flexible capacity based on expected demand. Figure 5.2 (b) shows the potential estimate of H_2 required if all the mentioned power plants use H_2 as a feed for the generation of power. These estimates calculated the H_2 potential with an assumption that all the power plants run on full capacity. The calculation for the Hydrogen demand estimates is based on an H_2 fired power plant with an energy efficiency of 54% for the lower heating value of H_2.

[2] https://opendata.cbs.nl/statline/#/CBS/en/dataset/83140ENG/table?dl=A945 (accessed 30-09-2018)
[3] https://www.entsoe.eu/data/map/ (accessed on 30-09-2018)

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4.3 Implementation in refineries update

For the application of blue hydrogen at refineries reducing CO_2 emissions requires that particular technical challenges will be overcome:

- High overall system reliability is required
- Fired heater burners have to be equipped with fuel-flexible burners, which can fire fuel with high H_2 content
- Ability to switch back to refinery gas. Instrumentation, safeguarding, and controls around the furnaces also have to be upgraded to enable bumpless switching between fuels while in operation.
- H_2 fuel distribution systems have to be installed
- Firing an H_2-rich fuel increases burner flame temperatures, resulting in higher NOx emissions. This is generally not regarded as a show-stopper, and ultra-low NOx burner technology is under development. Multi cluster combustion or multi-nozzle combustion concept are needed. The cost estimates for furnace modifications need to account for the additional cost for this, and in particular, cluster combustion has great potential; however, it will require some prototyping, see figure 4.3.
- Fuel gas containing H_2S has to be exported from the refineries to a central H_2 production plant. As a consequence of various process upsets, the H_2S concentration in refinery fuel gas frequently spikes up to levels of 10,000ppmv and above. The current frequency is several times per year, so it's essential to address this.

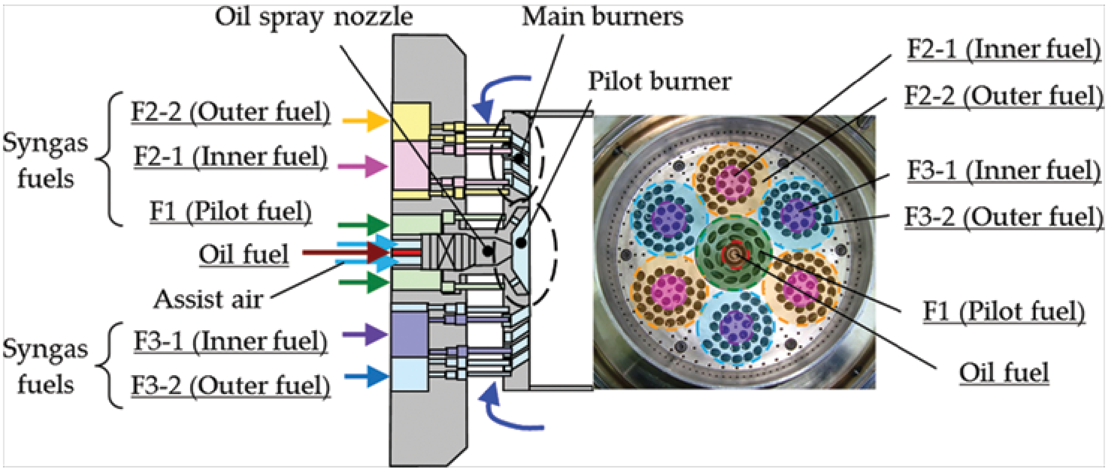

Figure 4.3 The multi-cluster combustors for the IGCC plant that have been developed under the "Innovative Zero-Emission Coal Gasification Power Generation Project Development of Low NOx Combustion Technology for High-Hydrogen Syngas in IGCC" by the New Energy and Industrial Technology Development Organization (NEDO) of Japan.

The H_2 production plant needs to cope with a wide range of feedstock compositions, reflecting different refinery operating modes, turnaround cases, and upset scenarios.
A separate distribution network is therefore needed to supply blue H_2 to the furnaces that have been upgraded. Figure 4.4 below shows schematically how such a dual fuel distribution network

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could work, minimizing the impact of switching to the low carbon fuel. This also allows introducing renewables-based green hydrogen as it gradually becomes available in the future.

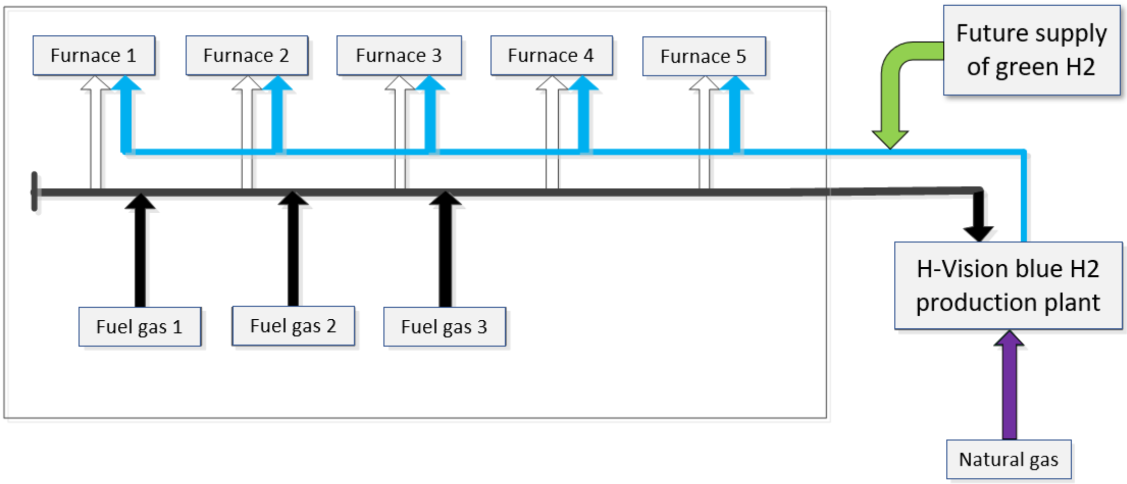

Figure 4.4: The proposed way to integrate within existing fuel gas grids (source H-vision).

4.4 Implementation at power generation update

The maximum theoretical potential for power generation was estimated, starting from the installed capacity of power plants in the Rotterdam area, see figure 4.2.

Demand for H_2 fuel from the power sector will be significantly smaller, because:

- It's not possible to completely replace existing coal-fired capacity with H_2 (without replacing the existing boilers). For the conventional coal-fired power plants, 4 concepts will be studied.
- Not all of the gas-fired power plants in this list have turbines that could be easily retrofitted for H_2 firing. For instance, Gas Turbines equipped with diffusion type burners have some significant limitations. NOx formation in a diffusion combustor is a bottleneck and, Diffusion burners have the risk of flashbacks because of the large flame propagation. Mitigation by steam and water injection is required, resulting in an efficiency drop.
- Actual power production is much lower than installed capacity:
    - Most of these power plants are expected to run as peak-producers, creating large and rapid fluctuations in fuel demand
    - H_2 production will either have to be very flexible or coupled with H_2 storage to cope with these demand fluctuations
- Some of the power generation capacity in this area could be decommissioned due to the projected increase in renewable energy generation

The hydrogen repowering of the existing coal-fired power plant options will be an approach, based on 4 different concepts, and it is worth noting that the existing coal-fired power plant might be switched from coal to biomass type fuels. The energy input in the boiler will be reduced due to the slightly lower heating value of biomass compared to coal. Also, due to the biomass firing, the boiler combustion chamber will have some input limitations. The hydrogen might be able to compensate for the flaws in the energy input. The following concepts will be reviewed:

- Concept 1: Hydrogen firing in existing boilers

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This concept very straightforward and requires new or replacement of the burners in the boiler and rearrangement of the heat exchangers in the boiler. The impact of hydrogen firing in the boiler is unknown and, therefore, will require CFD analyses. Hydrogen will be co-fired together with biomass in the boilers.

- Concept 2: Integration Gas Turbine in feed water preheater cycle

Hydrogen is fired in the Gas turbines, and the respective flue gas is used for the pre-heating of the boiler feedwater. See figure 4.5 provided by Mitsubishi Hitachi boilers.

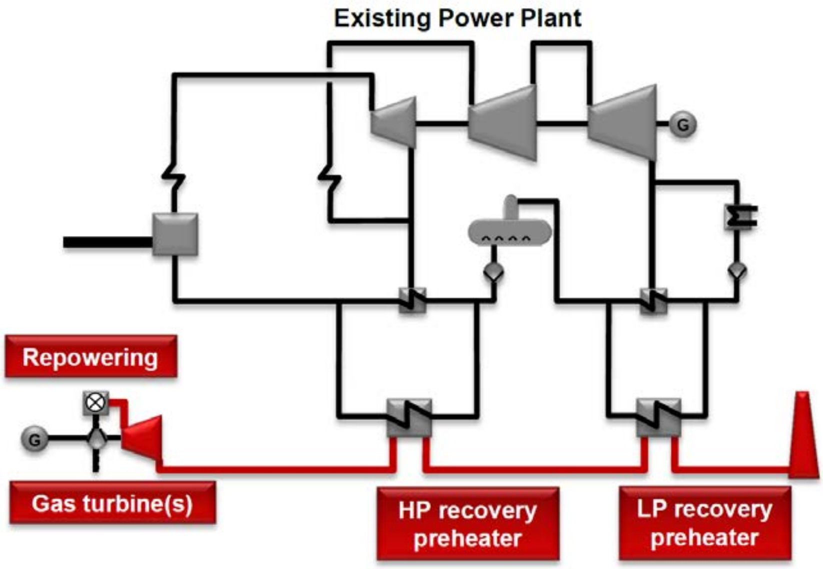

Figure 4.5: Integration GT in FW preheater cycle repower concept (source MHI).

- Concept 3: Integration GT in FW preheater cycle and IP steam cycle

Identical to concept 2 hydrogen is fired in the gas turbine, and the flue gas is used for steam generation and preheating of the boiler feedwater. See figure 4.6 that is provided by Mitsubishi Hitachi boilers.

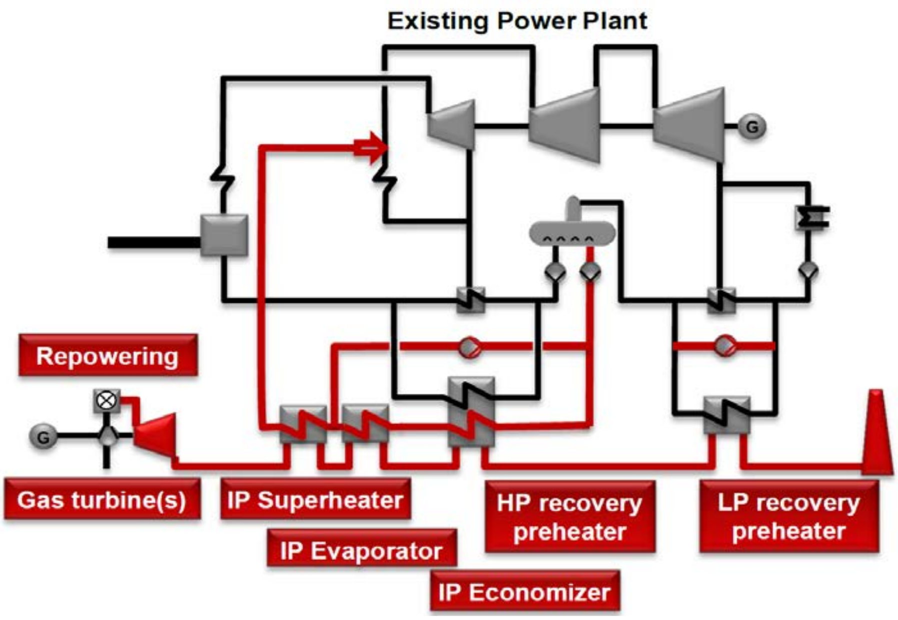

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Figure 4.6: Integration GT in the FW preheater cycle and IP steam cycle repowering concept (source MHI).

- Concept 4: Topping GT / Replacement for Boiler Air Preheater

The topping cycle repowering concept is often used to upgrade existing steam power plants without replacing the existing boiler. The existing boiler and steam turbine are retained while the overall steam cycle is improved to achieve higher efficiency and some additional power capacity. In particular, the larger steam power plants with higher, more-efficient steam pressures are the suitable options for this repowering concept: because the existing steam cycle will provide the majority of the repowered cycle's power and hence will have a significant impact on the resulting unit efficiency.

The different concepts for the existing coal units have been assessed based on a generic approach: a high-level thermodynamic system model. It will be required to do some detailed CFD analyses on the boiler performance on a validated model based on Hydrogen and biomass.

4.5 Scope update for the Dutch case study

In the Dutch case study with the industrial platform members, an estimation of hydrogen capacity has been calculated for the power plants that are able to switch to hydrogen. The nominal hydrogen production will be in the range of 2 GW up to 2,8 GW for power generation. The total hydrogen utilization, subject to the running hours of the power plants, will be in the range of 20PJ up to 40PJ. There are three cases defined

With the Industrial Platform of H-vision, the solution space and technical development concept cases have been assessed for the Dutch feasibility study, to limit the possible solutions and to focus on the value drivers. Defining the solutions space/scoping at an early stage of the project, it will provide for a common understanding of the project objectives, assumptions, development concepts, market scenarios, and important stakeholder value drivers. As such a bottom-up approach assessment, with input from the industrial parties, including power generation, was used to provide hydrogen demand estimates corresponding to the following three development concept cases:

- **Low case: 2 Mtpa of CO_2 captured**
- **Reference case: 6 Mtpa of CO_2 captured**
- **High case: 10 Mtpa of CO_2 captured**

4.6 H_2 fuel gas infrastructure update

Based on the initial spacial model tool WP4, the initial analyses have been used to assess the H_2. See figure 4.7 for some initial results from the spatial model tool analyses. Applying the spatial tool for the Dutch case in view of Rotterdam area seems to be useful, however the infrastructural development in the port of Rotterdam is a largely defined. The use of the spatial model tool will be of more interest for a larger area for the Netherlamds, as such the model will be expanded for the Netherlands towards other industrial clusters.

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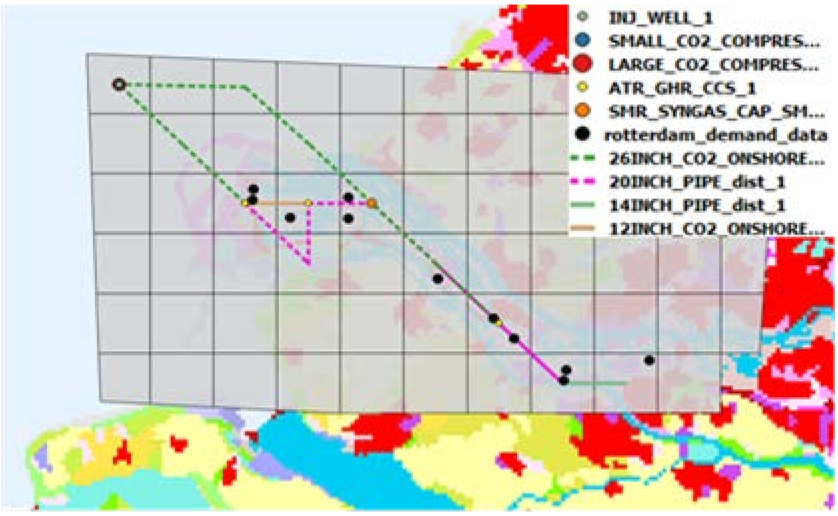

Figure 4.7 spatial model analyses, review of the tool for the Rotterdam case.

The preference for a central production has been given by the industrial parties nearby the large power generators. As such, by selecting a central production plant implies that the H_2-rich fuel needs to be transported and distributed to the end-users in the industrial area. A dedicated H_2 distribution network is proposed and included in the project cost estimate. For the high case, it is assumed that the Rotterdam Hydrogen network would be connected to the country-wide H_2 infrastructure network planned by Gasunie, granting access to H_2 storage facilities at Zuidwending. Using underground H_2 storage reduces overall CAPEX by reducing the required capacity of the hydrogen production plant. Locating the H-vision plant in the area around Maasvlakte has the advantage of minimizing the length of the pipelines transporting H_2 fuel to the two large power plants. The estimated costs for the entire distribution network range between 28.3M€ for the low case to 72.7M€ for the high case example. Overview maps representing the H-vision reference case shown below in figure 4.8.

4.7 CO2 export infrastructure update

For the Dutch case study, the CO_2 export facilities are assumed to be out of scope and part of the Porthos project, see more details in the H-vision report. The H-vision site is intended to deliver high purity CO_2 at a pressure of approx. 20 bar, but this can be varied easily in the design if necessary. A tie-in line to reach the main Porthos pipeline from the location of the hydrogen plant is a cost number that falls within the accuracy margins of the current estimates. Given the location and scale of the selected hydrogen production unit, it might be located nearby a dedicated export facility with a separate offshore pipeline landing. As an alternative, in case there isn't sufficient capacity available to evacuate the CO_2 via the Porthos facilities.

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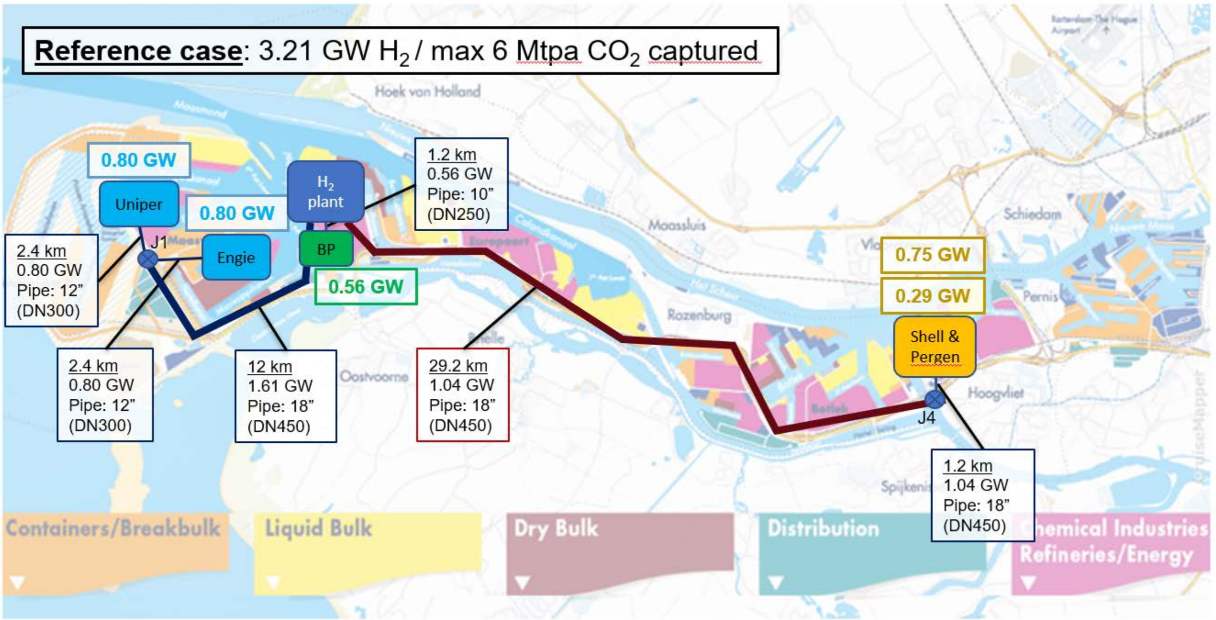

Figure 4.8: Reference case overview of the H2 production and transport infrastructure for the Rotterdam port, including both RFG and NG heating demand from end-users.

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5 CAPEX AND OPEX ESTIMATES.

The estimates of capital and operating costs for the production of H_2 with CO_2 capture, storage, and transport (CCS) have been estimated by several reports[4,5,6,7,8]. The estimates in this report are built upon, adapted and later compared with a view of the application of these technologies in the socio-economic conditions in the Rotterdam port area.

5.1 Levelized costs for H2 production

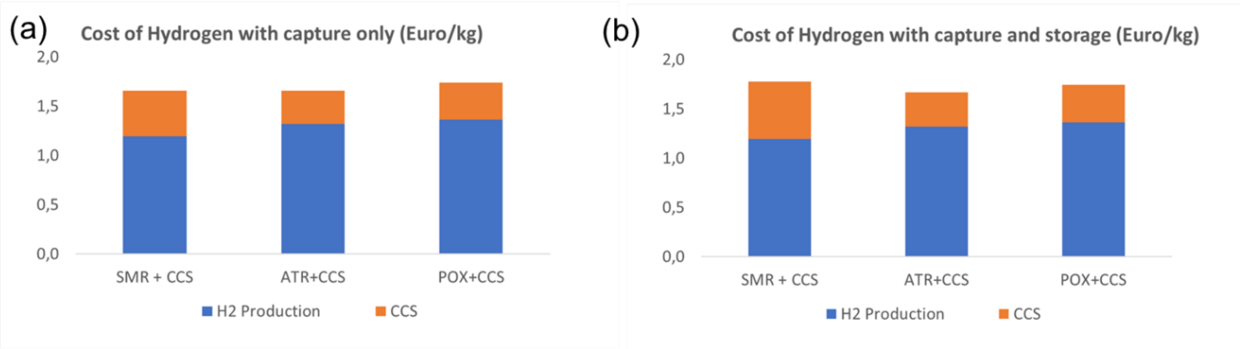

Figure 5.1: Summary of the cost comparison of different technologies for production of H_2 (500 Ktonnes/annum) along with carbon capture, transport and storage at 90% CO_2 capture . (a) Transport and underground storage is not included in the cost. (b) Transport and underground storage is included in the cost. Refer appendix for details on assumptions for estimates.

Figure 5.1 shows that the cost contribution of carbon capture and storage is significant for the H_2 production route using SMR in comparison to ATR and POX. The higher contribution in cost for SMR is because of higher energy and equipment requirement for separation of CO_2 from the low concentration flue gas exhaust (~8% CO_2 by volume) from SMR. This constitutes ~ 30 – 50% of total CO_2 emission from the SMR unit. On the other hand, CO_2 leaving the POX/ATR unit is of relatively high purity (~50% CO_2 by volume). The cost of POX and ATR technologies scale similarly due to similarity in the processes. A major difference between the two processes lie in the placement of water gas shift (WGS) unit. In ATR, the WGS unit resides in the ATR reactor itself while in the POX, it resides as a separate unit. The separation of unit is advantageous to prevent catalyst deactivation when feedstocks with high impurities and high temperatures is used. Finally, the cost of H_2 production alone is higher for ATR and POX than ATR. Table 5.1 shows the differences in costs and compares them with the base literature for H_2 production. The differences in costs are because of several reasons which are detailed in the following section.

---

[4] Techno-Economic Evaluation of SMR Based Standalone (Merchant) Hydrogen Plant with CCS, IEAGHG, 2017.

[5] BOC HPU CCS study (CCS in SMR), Foster Wheeler, 2014.

[6] Concepts for Large Scale Hydrogen production, NTNU, 2016

[7] Jens R. Rostrup-Nielsen and Thomas Rostrup-Nielsen, Large scale Hydrogen production, Topsoe technologies

[8] Life Cycle Assessment of Hydrogen Production via Natural Gas Steam Reforming, 2001

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Table 5.1 Comparison of cost estimates from literature reports and the Rotterdam case.

CASE Description	Levelized cost of Hydrogen, LCOH (euro/kg)			Remarks
	SMR + 90% CCS	ATR + 90% CCS	POX + 90% CCS	
Reference report: IEAGHG, 2017.	1,85	Not estimated	Not estimated	~ 100 Ktonne/yr; lifetime 25 years; Heat or CH_4 – € 6/GJ.
Reference report: NTNU, 2016.	1,71	1,59	Not estimated	~ 500 Ktonnes/yr; lifetime 25 years; Heat or CH_4 – € 4/GJ.
Rotterdam Case (this report)	1,83	1,75	1,89	~ 500 Ktonnes/yr; lifetime 20 years; Heat or CH_4 – € 4.5/GJ.

5.2 CAPEX-OPEX distribution of the Levelized cost

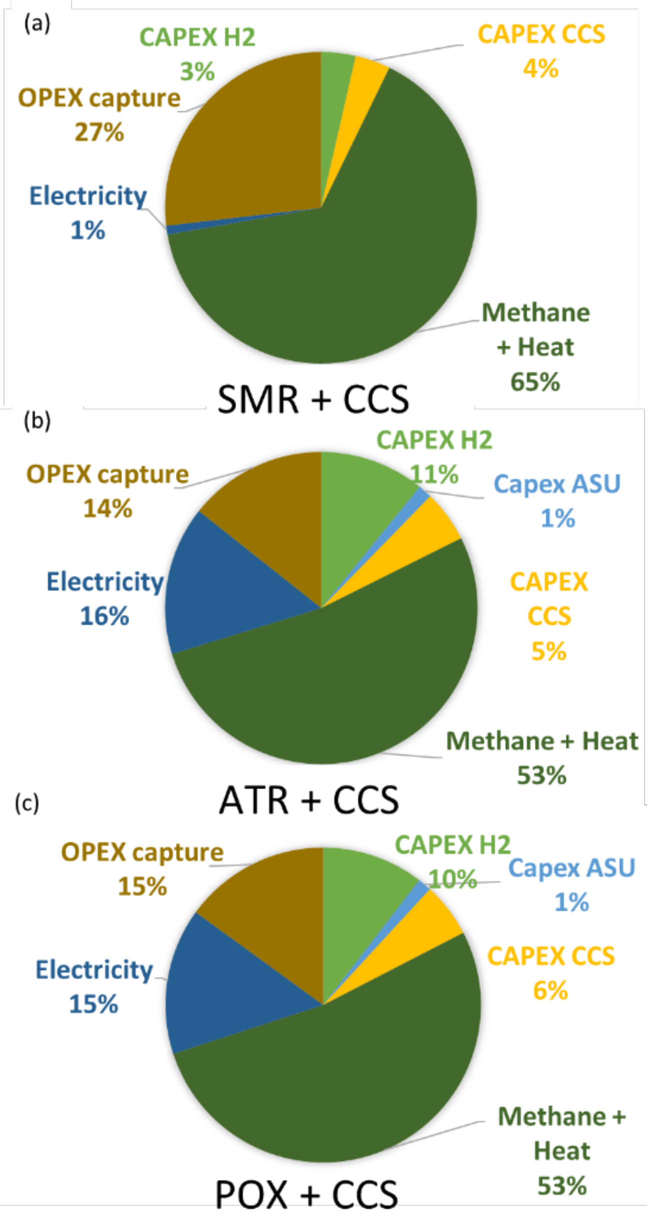

Figure 5.2: Distribution of CAPEX and OPEX contribution to the Levelized costs for the production of H_2 (500 Ktonnes/annum) using different technologies. Refer appendix for details on assumptions for estimates.

Figure 5.2 shows that all the technology routes are dominated by the cost of feedstock (CH_4) and heat. This contribution is specifically high for the SMR + CCS route due to the higher use of heat in the production process than POX and ATR. Additionally, electricity has a significant contribution to the cost of ATR and POX in comparison to SMR route. This is due to the power used in the air separation unit which is not present in the SMR route. Finally, the opex contribution for CO_2capture is significantly higher in the SMR unit due to the capture of low-quality CO_2 discussed in the previous section.

Table 5.2 shows the uncertainty in the estimates of the cost. We expect an error margin of -30% to +50% in these estimates because of two reasons. Firstly, most of the costs calculations are based on established literature data[2-6], vendor quotes, and suggestions from the experts. Secondly, the technology of H_2 production and CCS is a mature technology for which data is reliable and reproducible. It must be noted that these estimates are sensitive towards various parameters such as feedstock prices, utility prices, the scale of operation, quality and operating conditions of feedstock and products, etc. A revisit to these estimates is recommended when changes to the above-mentioned parameters are made.

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Table 5.2: Accuracy of current estimate vary from -30% to +50% are calculated below.

Process	Cost (Euro /kg)		
	Base reference	Low Limit	High Limit
SMR	1,31	0,92	1,96
SMR + CCS	1,89	1,33	2,84
ATR	1,40	0,98	2,10
ATR+CCS	1,75	1,23	2,63
POX	1,45	1,02	2,18
POX+CCS	1,83	1,28	2,75

5.3 Integrated cost estimation updated

The CAPEX estimation for H-vision is based on three cases: low, reference, and High, as already discussed. Though that scope is only for the contributing industrial companies and the Dutch case will be limited in line with the Porthos project CO_2 storage capabilities. As such, in case of extension of the scope, an extension of CO_2 storage will be required.

The low case is basically a minimal investment case, and the high case is based on the maximum possible CO_2 emission reduction. The cost for H-vision is summarized and added up in Table 5.3 , giving an indication of the overall blue H2 chain investment costs for each of the cases.

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Table 5.3: Overview of expected required capacity per case, and resulting CAPEX estimates for the different blue H_2 chain elements

			Low case	Reference case	High case
H_2 demand	Ref / petrochem replacing RFG	[MW]	500	1170	1770
	Ref / petrochem replacing NG	[MW]	90	140	640
	Pergen steam & power	[MW]	143	286	571
	Engie & Uniper power plants	[MW]	407	1611	2221
	Total (max)	**[MW]**	**1139**	**3207**	**5202**
Capacity reduction enabled by underground H_2 storage buffer		[MW]	-	-	1000
Installed H_2 production capacity (10% lower than max demand)		**[MW]**	**1040**	**2920**	**3820**
Max NG + RFG input required (rounded up)		[MW]	1470	4120	5390
Max NG supply to the H_2 plant (rounded up)		[MW]	970	2950	3620
Total plant cost for H_2 production		[M€]	528.4	1317.5	1568.9
Costs of furnace modifications		[M€]	88.5	196.5	361.5
Power plant upgrade costs		[M€]	110	325	385
Salt cavern storage CAPEX		[M€]	-	-	190
NG supply pipeline CAPEX		[M€]	54	102	125
RFG transfer pipelines		[M€]	13.1	17.8	27.8
NG & RFG compressors		[M€]	16.8	25.2	37.9
H2 distribution costs		[M€]	28.3	49.8	72.7
Total CAPEX		**[M€]**	**839.1**	**2033.8**	**2769.0**

There is no need for an update of cost figures since the earlier reported cost estimations are in the range of the specific cost estimation of H-vision.

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6 OWNERSHIP STRUCTURE FOR THE BUSINESS CASE UPDATE

The business tools in WP3 are used for a closer look at the business case. The market failure tool, risk assessment tool, and policy gaps have been discussed and partly followed by the industrial members in industrial experts workshop sessions. The tools developed in WP3 provided guidance and a quick start on the relevant topics to be addressed for the Dutch case in Rotterdam. See figure 6.1 the used heat map.

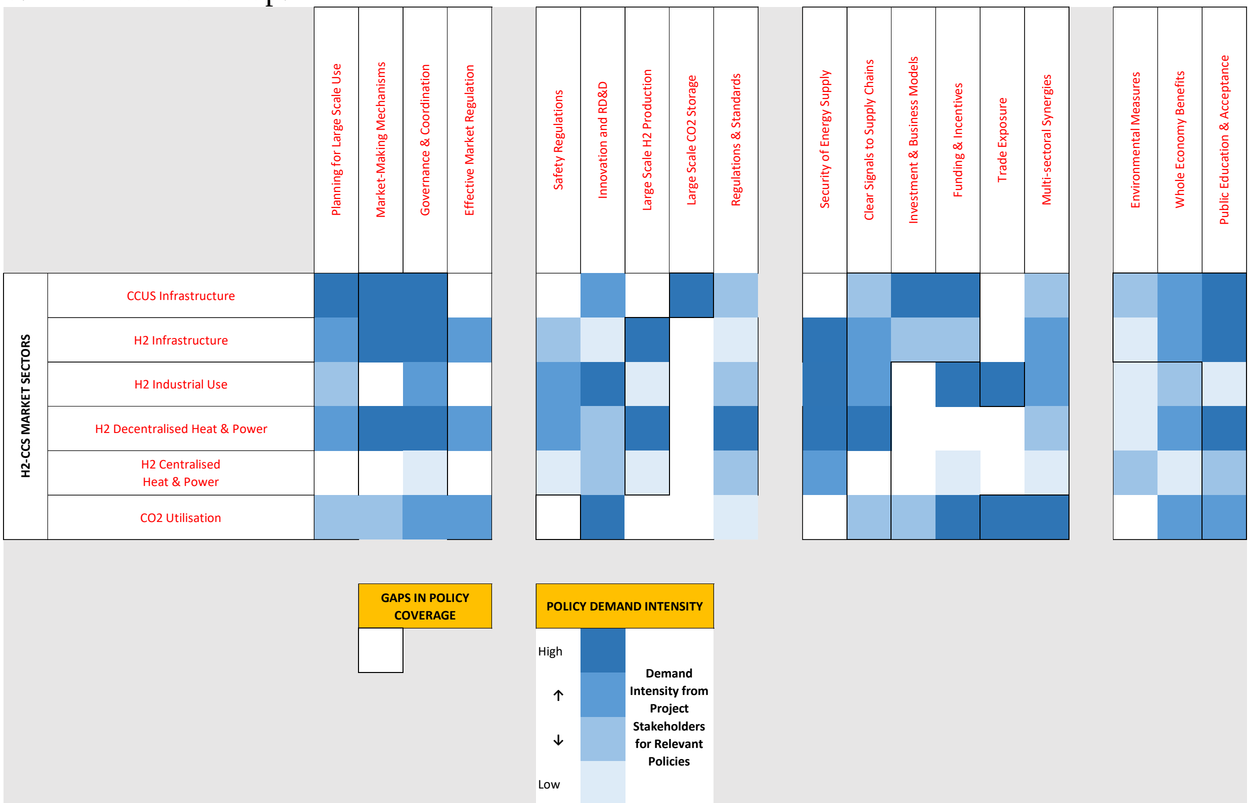

Figure 6.1 example of the used heat map from the WP3 tools for the risk assessment.

The value chain is represented in figure 6.2. For the realization of the Dutch case study, it is critical that all elements of the value chain are covered.

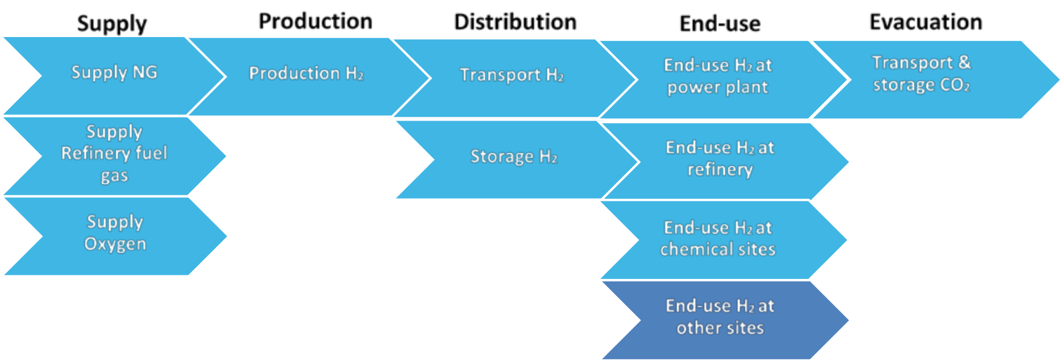

Figure 6.2 value chain for the Dutch case study (source H-vision).

To have good project governance, nine partner roles are necessary; from the natural gas supplier (wholesaler) at the beginning of the value chain to the CO_2 transport & storage supplier at the end

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of the value chain. One partner role can cover one or more activities, e.g., the industrial gas supplier may supply oxygen, produce H_2, and maybe an end-user for H_2, whereas a refinery plant operator may supply refinery fuel gas, provide H_2 and be an end-user for H_2. From the risk assessment, not having coverage of the entire value chain is one of the significant project risks that need to be addressed before the project goes into the next stage of development.

The project scoping (defining the solution space) and technical concepts and ownership structure, etc., are essential topics that already need now a lot of attention. Also, public perception, changing economics, emission reduction and CAPEX estimates are considered critical risks. Based on the WP3 risk toolbox, the identified risks in all phases of the project (following a stage-gate project development) approach, are categorized, and mitigations are proposed. Especially the long-term uncertainties about commodity and CO_2 emission prices constitute a significant obstacle to get the Dutch case study in Rotterdam started as they have a substantial impact on the business cases. Public support in the form of participation, contracts for differences, risk baring loans or subsidies are required.

With the nine partner roles, all activities in the value chain can be covered, visualized in Figure 6.3 below.

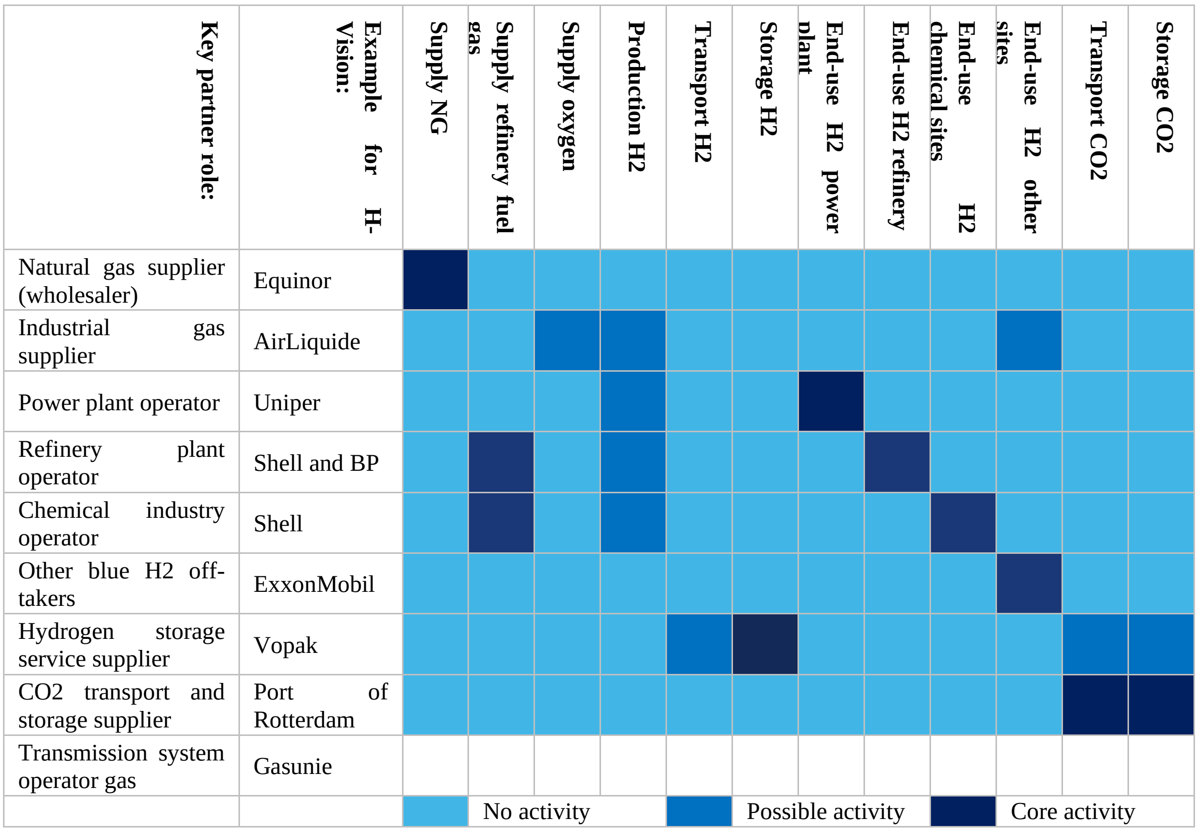

Figure 6.3: Key roles and their activities in the value chain (source H-vison).

Based on an assessment among H-vision project participants, the current situation, the key drivers, and potential risks and bottlenecks are described.

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Thought that the first outline of a possible ownership structure . The Dutch case study identified new investments in hydrogen production and distribution, which is entails a complicated investment timeline with public and private investments. As such it is envisaged that the infrastructure investments will be covered by Port of Rotterdam, Gas Unie, Stedin (DSO), EBN and other other relevant Public bodies. Investments and modifications to existing assets (e.g., replacements of burners, boilers, and connections within the fence of the factory) all happen within the current business models by the companies. The envisaged ownership structure in the various parts of the value chain is illustrated in Figure 6.4.

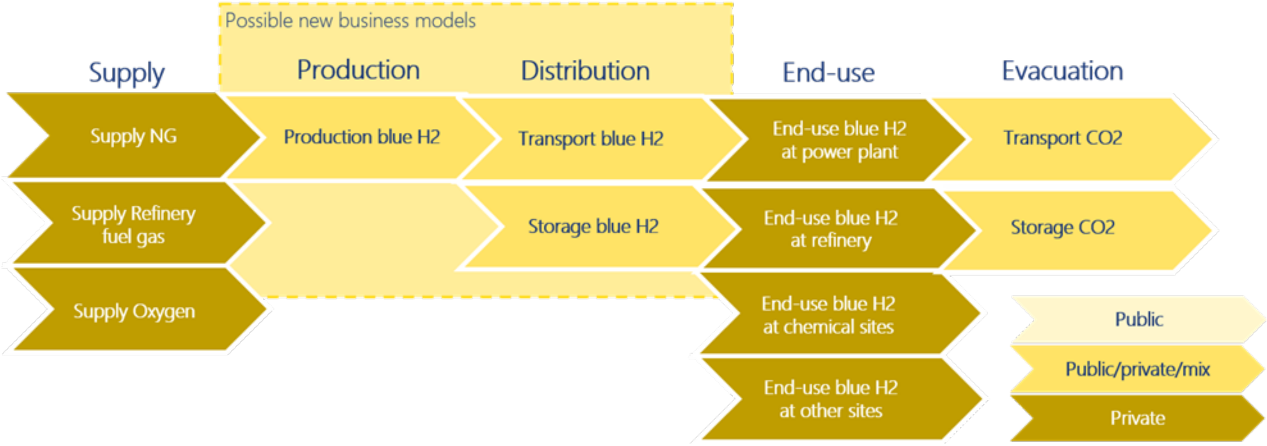

Figure 6.4: Ownership structure (source H-vision)

6.1 Public and private investments update

The Dutch case study requires a gigawatt-scale blue hydrogen production facilities that will need to be built and paid for. At this stage of the project, the ownership and control of these facilities have been left open. In the current business environment, without government support and at the anticipated ETS prices, blue hydrogen is not competitive in the chemical, refinery, and power generation processes, compared to conventional fossil fuels (e.g., natural gas). As a result, an investment in a blue hydrogen production unit will require policy support to make it economical, especially in the early years, when ETS prices are expected to be lower than the cost of producing blue hydrogen. Given the interest of the government, public as well as the private sector, even public/industrial investment models are possible options. Given the dimensions and risk profile of the project, co-investments and innovative methods of support may be required to offset the risks to a level acceptable to private sector investors.

6.2 Distribution and third party access update

The Netherlands has an existing pipeline distribution network for hydrogen that only carries ‘grey hydrogen’ and is privately invested in by only one or a few large suppliers. See also D5.2.1.
In general, it can be concluded that, apart from possible hydrogen specs, the current network has not enough capacity to facilitate the potential demands that are estimated in the Dutch case study. As a result, a new pipeline network (and possibly storage) will need to be constructed or made available (in case of adjustment to an existing gas pipeline).
Third-party access is of importance so that also other future producers of blue and green hydrogen can link into the network, as well as other customers. The end-users, on the other hand, require

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the security of supply through large-scale hydrogen production as such blue hydrogen can facilitate incremental hydrogen supply and demand and, therefore, also smooth the way for investments much needed to support the decarbonization of the industry.

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7 CONCLUSION AND OUTLOOK

Choice of technology for H_2 production: Amongst different reforming technologies (SMR, ATR, and POX) with CCS, the following points stand out:

- The scale of technology has a big impact on the Levelized cost of production of H_2 (LCOH). At the scale of up to 100 K tonne/annum, SMR + CCS is estimated as the most cost-effective option; however, at scales close to 500 K tonnes/annum, ATR + CCS are also cost-competitive. The estimates are based on specific assumptions for the calculated case of Rotterdam, and there is no need for an update of cost figures since the earlier reported cost estimations are in the range of the specific cost estimation of H-vision
- SMR has been the leading technology in terms of the number of plants build worldwide for the production of H_2. However, in recent years increasing examples of ATR and POX have been reported.
- The quality of input gas available, desired output gas composition along with the cost of CCS will determine the suitability of the technology for use at the Rotterdam port. The main difference between the steam methane reforming versus the partial oxidation reforming is the essential use of the catalyst for the former reforming method. Partial oxidation reforming can take place also in the absence of catalyst, making it a suitable candidate for hydrocarbon feed gas with a higher level of impurity.
- The Industrial Platform members (H-vision) has evaluated different hydrogen production thechonolgies and has selected an ATR + CSS, and heat integration with the existing Power Plant.

Integration and ownership structure: The production of H_2 with pre/post-combustion CCS is a promising option for decarbonizing the heat and electricity supply to produce chemicals in the Rotterdam port area. This is particularly applicable to the case of converting refinery gas to H_2 for the provision of heat to the refinery processes. However, the post-combustion (only) option might be considered as lock-in and does not contribute to the energy transition longer-term objectives: creating a hydrogen infrastructure. To produce power, the current available capacity serves both the chemical port complex and the domestic market leading to large fluctuations in power production, as revenue margins are thin. An H_2 production-storage-conversion facility will need to be designed to accommodate these fluctuations in combination with baseload running capacity. Furthermore, for the use of H_2 as a fuel for heating and generating electricity, efforts would be required retrofitting current infrastructures such as furnaces, boilers and gas turbines.

In the future, the scale of decarbonization and application of H_2 is also dependent on the trends of production demands expected in the Rotterdam industrial area. The port area of Rotterdam is highly interconnected with upstream refinery and downstream chemical production. The capacity of the refining of crude oil is dependent on the local demand for fuels and chemicals in the neighborhood and their imports from abroad. A pragmatic approach of decarbonization of emissions starting with heat and electricity and at the same time, keeping a view of changing local-global trends in demand along with looking for new technology improvements in the field of decarbonization is recommended. Additionally, growing experience in the operation of ATR and continuous improvements in the separation of CO_2 are key developmental areas that can have a significant impact on the economic benefits of decarbonization in comparison to other methods.
In this phase, public perception, changing economics, emission reduction% and CAPEX estimates are considered critical risks. In the Dutch case study, all risks in all stages are categorized, and

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mitigations are proposed. Especially the significant long-term uncertainties about commodity and CO_2 emission prices are an obstacle to get H_2-CCS started as they have a significant impact on the business cases. Public support in the form of participation, contracts for differences, risk baring loans or subsidies are required, given its low, non-commercial rate of return. Transport and storage risks of CO_2 are known and manageable and will be available, assuming that the Porthos project will be developed successfully. For successful development, the government has to cover the role of policymaker, insurer & funder, regulator, advocate, and facilitator.

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Appendix:

Appendix A: Use of natural gas and residual gas for refinery heating

Topic		2017** Residual gas	2017** Natural gas
Energy sector own use Oil refineries	PJ	75.2	13.3

Source: CBS

Figure A.1: Data gathered from CBS[7] for the use of refinery/residual gas and natural gas in refineries for the year 2017.

[7] https://opendata.cbs.nl/statline/#/CBS/en/dataset/83140ENG/table?dl=A945 (accessed 30-09-2018)

Appendix B: Assumptions for the estimates of CAPEX – OPEX estimates

A: General assumptions and inputs					
Parameter	**Units**	**SMR**	**ATR**	**POX**	**Basis**
Production of H_2	(Ktonnes/annum)	500	500	500	A size reasonable for expected potential demand
Hours of operation	/year	8322	8322	8322	Roughly corresponds to 95% capacity
Electricity	Euros/MWhr	40	40	40	Historic variations 20 – 80 Euros/MWhr
Heat	Euros/MWhr	20	20	20	EU-NL Natural gas prices, 2018
Economic life time	years	20	20	20	A conservative value of 20 years.
Cost of Methane	eur/tonne	222	222	222	EU-NL Natural gas prices, 2018
Annuity costs (O&M. Bank interest. IT. others)	% CAPEX	10,19%	10,19%	10,19%	interest/((1-(1+(interest))^(-lifetime))
Bank interest	%	8%	8%	8%	Standard value western Europe
O&M costs	% CAPEX	4%	4%	4%	Chemical Engineering textbook basis
Capacity factor	%	95%	95%	95%	Included in overall running time per year
Thermal efficiency	Energy product/ Energy input (Heat + Methane)	73%	78%	78%	Optimistic value taken, variable between 60 - 80%
Other losses (carbon formation and heat)	% CH4 methane input	NA	NA	NA	Losses due to soot formation, catalyst

B: Assumptions and inputs for equipment costing reforming		
Component	**Basis**	**Reference/ comment**

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SMR capex cost	31 Ktonne H2 production unit costs 130 million euros when converted to 2018 costs.	Textbook reference, Sinnott et al, Timmerhaus et al
SMR capex cost	Scale up/down factor chosen as 0.6	Expert guess
SMR methane consumption	4.03 kg CH4/ kg H2	NREL report (Methane for process and heat use)
SMR electricity consumption	1.14 MWhr/kg	NREL report
ASU cost basis	500 tonne/hr O2 (95% purity) production costs ~ 300 Million euros	GTL report
CH4, H2O, O2 requirement for ATR, POX	Stoichiometric reaction ratios	Moulijn et al
Efficiency of CH4 to products (H2) after all losses	75%	Moulijn, Expert guess
Water gas shift reactor CAPEX	40 Ktonne reactor costs 100 M euro	Kreutz et al

C: Assumptions and inputs for equipment costing carbon capture, storage and transport

The cost of capture is estimated on the basis of several internal TNO projects and literature values. While the costs in these references are exhaustive, their representation here is taken on a broad level. Thus, the accuracies of these estimates are expected to be around - 50% to + 75%. A more specific cost estimate would be required to further improve the accuracy of these estimates.

List of broad assumptions:

1. Cost of carbon capture is largely dependent on the input concentration of the CO2 in the gas stream. The output concentration is assumed as 99.8 % @ 30 bars

% CO2	Costs (euros/ tonne CO_2 capture)
4 - 8%	90 - 120
12 - 18%	40 - 60
40 - 60%	20 - 30

2. The cost of high concentration CO2 capture is highly CAPEX dominant. This is because of the assumed use of cryogenic conditions, which is required multistage compression units.
3. The cost of compression, transport, and underground storage is assumed to be 10 euros/tonne of CO_2 avoided (EBN, 2018).

Referenced reports, literature for assumptions:

Techno-Economic Evaluation of SMR Based Standalone (Merchant) Hydrogen Plant with CCS, IEAGHG, 2017

Peters, M. S., Timmerhaus, K. D., West, R. E., Timmerhaus, K., & West, R. (1968). Plant design and economics for chemical engineers (Vol. 4). New York: McGraw-Hill.

Moulijn, J. A., Makkee, M., & Van Diepen, A. E. (2013). Chemical process technology. John Wiley & Sons.

Sinnott, R. K., & Towler, G. (2009). Chemical engineering design: SI Edition. Elsevier.

National Energy Technology Laboratory, Analysis of Gas-to-Liquid Transportation fuels via Fischer Tropsch, 2013

Possible future retail electricity price, 2012

Life Cycle Assessment of Hydrogen Production via Natural Gas Steam Reforming, 2001

Production of hydrogen and electricity from coal with co2 capture. Kreutz et al

Quarterly Report Energy on European Gas Markets, 2018

BOC HPU CCS study (CCS in SMR), Foster Wheeler, 2014

Modern and prospective Technologies for Hydrogen, Steinberg, 1989

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Concepts for Large Scale Hydrogen production, NTNU, 2016
Rotterdam Climate Initiative - CO2 capture, transport and storage in Rotterdam - report 2009
Rotterdam H-vision report 2019

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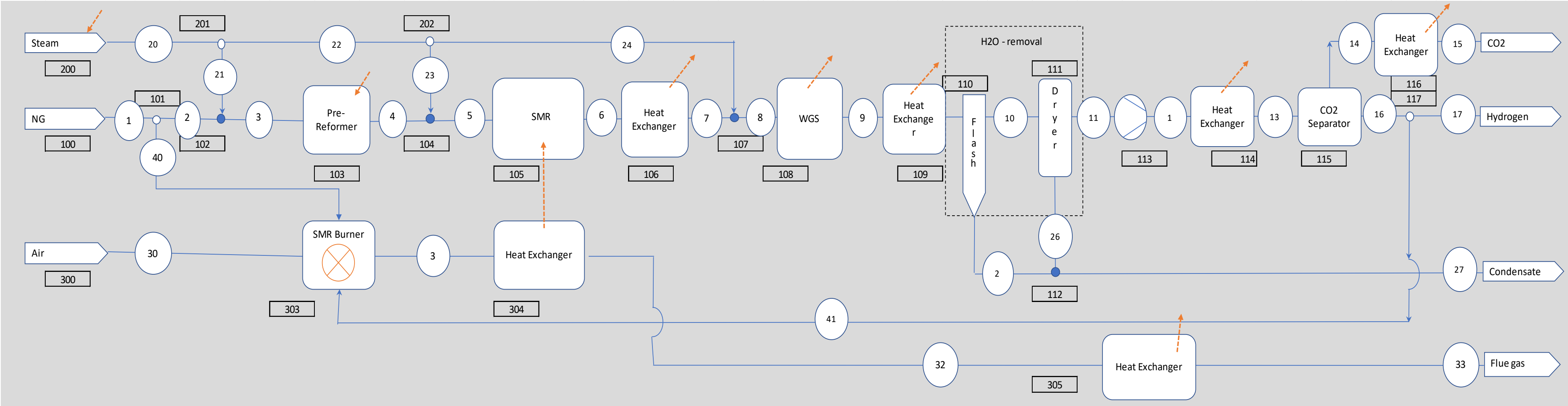
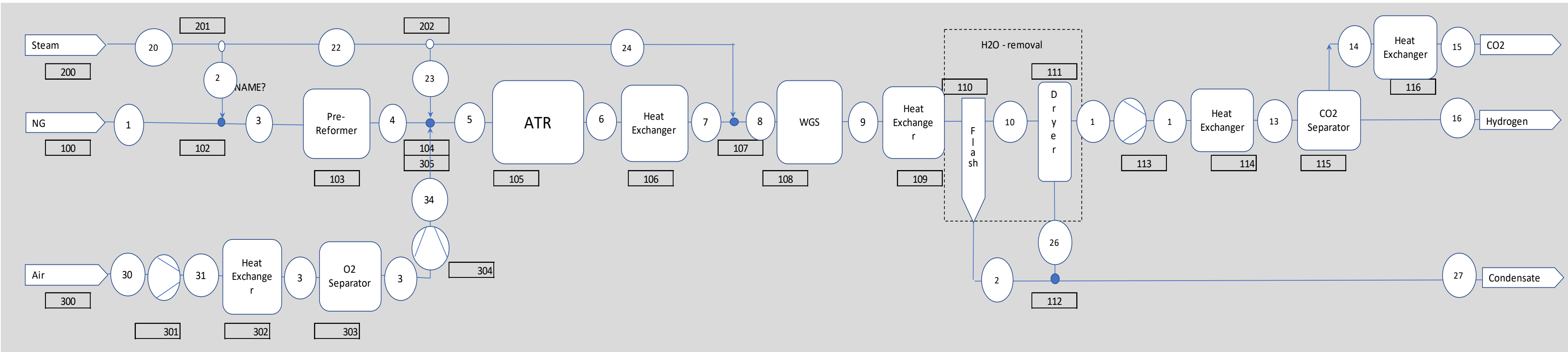
Appendix B: Technology flow sheet for H_2 production:

SMR



ATR



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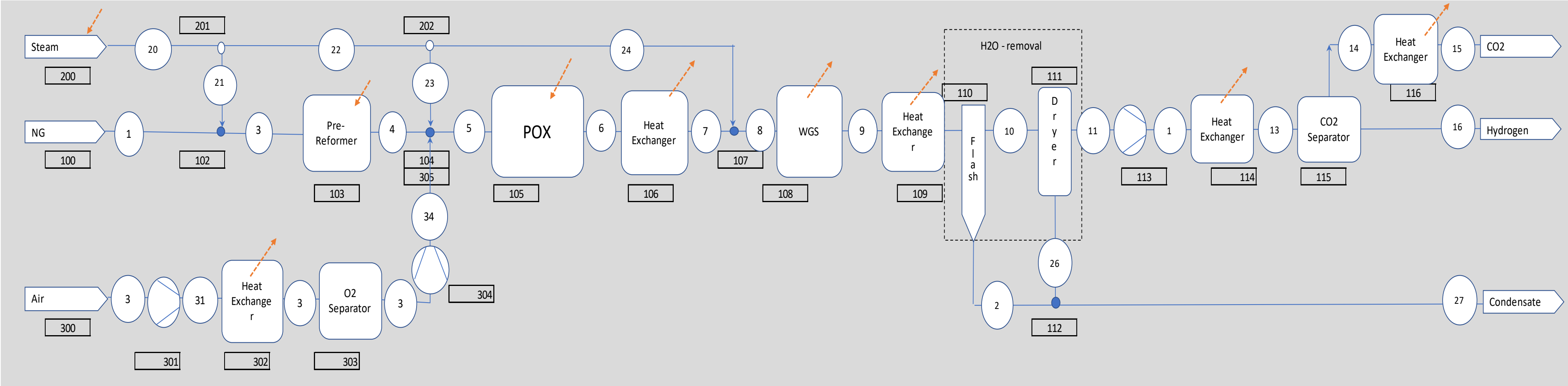
POX:



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Appnedix C: Technology selection hydrogen production:

Key parameters of H_2 production via HP ATR		
ATR+GHR total plant capacity (H_2 output)	700,000	Nm^3/h H_2
H_2 purity in the outlet stream	95.5	%
ATR+GHR total plant capacity (fuel output)	2,400	MW thermal (LHV)
Overall thermal efficiency	78	% on LHV basis
	~82	% on HHV basis
Total feedstock (input of NG + RFG) required	3,130	MW thermal (LHV)
Excess steam production (available for export, with 20°C superheating)	305	t/h HP steam (100 bar)
	100	t/h MP steam (30 bar)
Electricity import	128	MW el
Direct CO_2 emissions at the H-Vision plant	6	t/h CO_2
CO_2 captured at the H-Vision plant	498	t/h CO_2
CO_2 capture & export factor	0.208	t CO_2 / MWh
CO_2 purity in the export stream	99	%
Overall capture rate (including residual carbon)	88	%
Overall CO_2 emissions factor	0.028	t CO_2 / MWh
Total plant cost	910	M€
Fixed OPEX (2.5% of CAPEX annually)	22.8	M€

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Brief Process explanation:

For all reforming technologies show above, broadly, the natural gas stream after desulphurization (OBT) is partially reformed in a pre-reformer to breakdown larger hydrocarbons and then send to the main reformer for the production of syngas (H_2 + CO). The exit gas from reformer is treated in a water gas shift reactor to covert the available CO to CO_2 and H_2 using steam. The exit stream from water gas shift is dried and send to a pressure swing adsorption (PSA) unit in which H_2 is separated and CO_2 is adsorbed. The tail gas from the adsorption unit is send to the burner of the main reformer to supply heat for the process. Several heat exchangers and compressors are used to maintain the conditions (pressure and temperature) and for heat recovery.

The major difference between SMR and POX/ATR is that instead of steam in SMR, oxygen from an air separation unit is used for reforming of methane. Furthermore, in a SMR tail gas and flue gas (with low CO_2 concentration) are both major sources of CO_2 emissions whereas in a ATR/POX, the gas exiting the water gas shift unit is the major source of CO_2 emissions.

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