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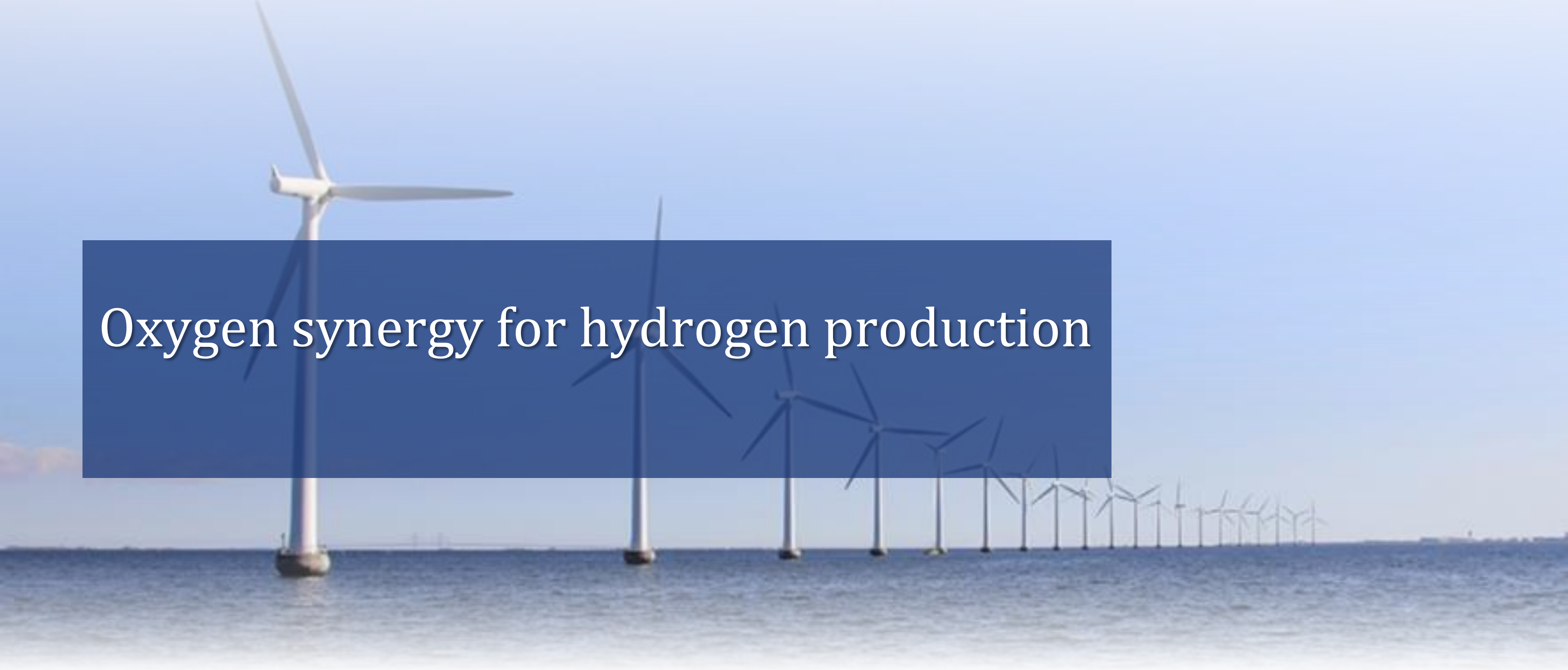
Oxygen synergy for hydrogen production



Oxygen synergy for hydrogen production

TESN118016 - Waterstofversneller

Participants: TNO (coordinator or penvoerder), EBN, Gasunie and NOGEPA

Other parties involved: Berenschot

Project period: January 2019 – October 2019

The project was performed using subsidy from the Dutch Ministry of Economic Affairs and Climate, National regulation EZK-subsidies, Topsector Energy carried out by Netherlands Enterprise Agency.

Het project is uitgevoerd met subsidie van het Ministerie van Economische Zaken, Nationale regelingen EZ-subsidies, Topsector Energie uitgevoerd door Rijksdienst voor Ondernemend Nederland.

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Management summary

Management summary

Introduction and motivation

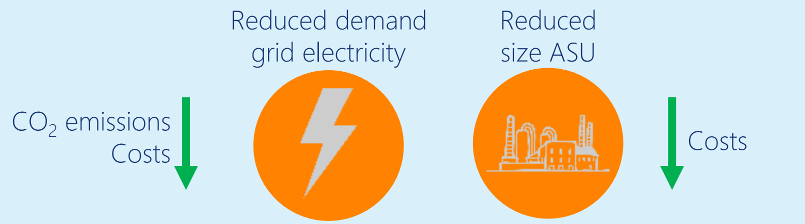
Hydrogen will play a role in our future energy needs. It is an energy carrier that can be used in a large variety of situations. The question how the upscaling of hydrogen as an energy source will take place is still open for debate. Hydrogen production by electrolyzers will produce oxygen as a byproduct. Currently, this oxygen is vented. In other processes oxygen is needed, this oxygen is typically produced by Air Separation Units that extract oxygen from the air.

Oxygen synergy is what we have called the effective use of the oxygen from electrolyzer in other processes that use oxygen.

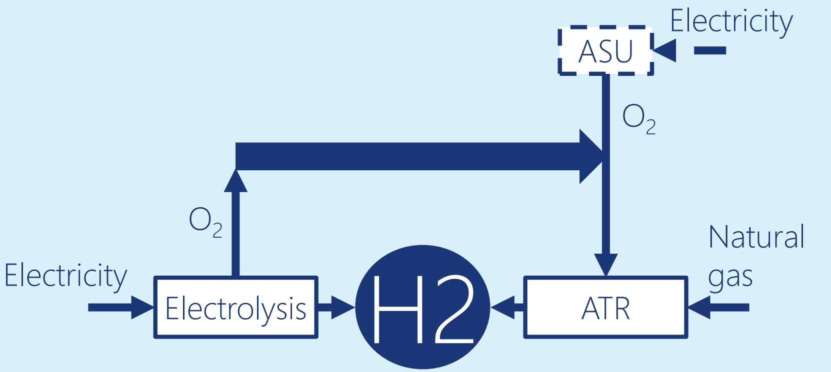
Aim of the project

The aim of this project is to investigate whether oxygen synergy will have economic and/or technical potential. This will be performed by providing insight in the technical and economical aspects of oxygen synergy and by investigating oxygen synergy within the institutional framework. Furthermore, this project shows how oxygen synergy can be demonstrated and tested.

Intended advantages of oxygen synergy



Oxygen synergy case: the hydrogen accelerator



Management summary

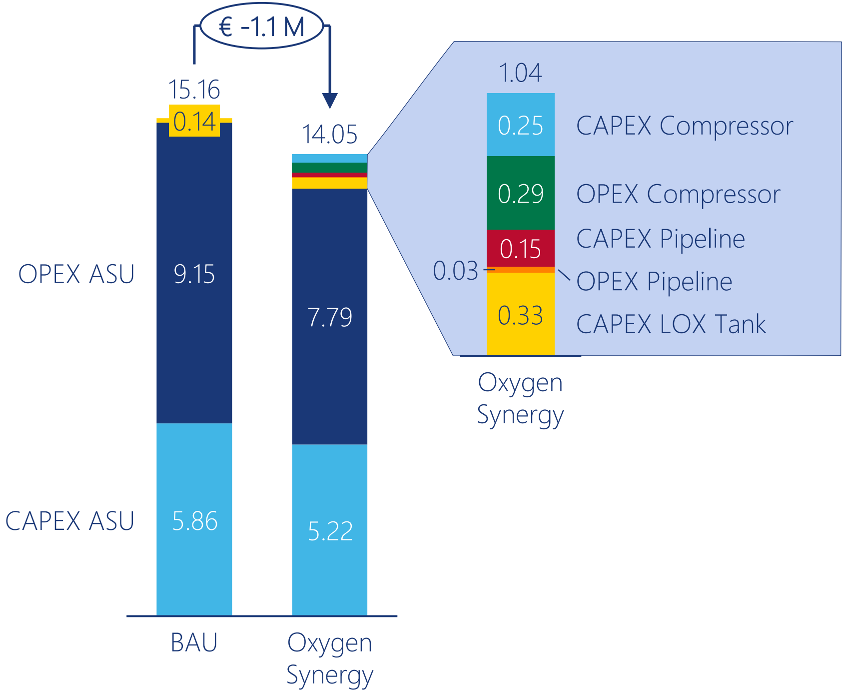
Hydrogen accelerator

In order to investigate the benefits of this oxygen synergy, a techno-economic analysis has been performed on oxygen synergy with hydrogen production from natural gas (a process that needs oxygen). This case was built up from envisioned projects within the Rotterdam harbor area. The subpart of green hydrogen production was matched to reflect proposed projects in the Rotterdam harbor area. Parameters for blue hydrogen production were chosen in accordance to H-vision, that uses an autothermal reformer (ATR).

Results

Overall, the use of oxygen was found to be a cost-effective decarbonization measure. This result is found in multiple cases, differing in both scale and market conditions. The largest benefits exist when the oxygen synergy allows for a smaller ASU. This was achieved by using a larger than normal liquid oxygen tank (LOX), that would serve as a buffer for the intermittent oxygen production from the electrolyzer.

CAPEX and OPEX difference due to oxygen synergy within the hydrogen accelerator with a large liquid oxygen buffer tank



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The following was noted about the cost effectiveness:

- In all cases, less grid electricity was needed to produce oxygen. This leads to both a reduction in carbon emissions and costs.
- A greenfield situation has an additional advantage. The size of the Air Separation Unit (ASU) can be reduced. This leads to an even better financial result.
- The cost-effectiveness depends on the distance between supply and demand of oxygen. Project revenues are witnessed up to a distance of 25 km. Therefore, a synergy is especially cost-effective within large industrial clusters and in case of existing oxygen infrastructure.

Demonstration project and test program

A possible demonstration case for the oxygen synergy concept was identified in the Rotterdam industrial harbor, involving two industrial companies located next to each other.

Company A generates power on site and is currently evaluating the opportunity to convert part of this electricity into hydrogen via electrolysis. Company B is located in the vicinity of company A, and uses pure O_2 in its production process.

To demonstrate the concept, a demo project is proposed. The intention is to build and operate a flexible 5 MW electrolyzer. Co-produced O_2 from this unit will be supplied to company B and integrated within the existing O_2 supply system.

Market condition	Capacity green hydrogen	Effect on CAPEX (+ extra cost, - saving)	Effect on OPEX (- is a saving)	Total cost (- is a saving)*	Payback period	Effect on price green hydrogen	Abatement costs
Retrofit	250 MW	6.0 M€ & 0.4 M€/year	-1.1 M€/year	-0.7 M€/year	8.6 years	€ -0.04	-43 €/tonCO_2
Greenfield	250 MW	-0.3 M€ & -0.1 M€/year	-1.0 M€/year	-1.1 M€/year	-0.3 years	€ -0.07	-68 €/tonCO_2
Greenfield	1650 MW	28.9 M€ & 2.0 M€/year	-4.1 M€/year	-2.1 M€/year	13.8 years	€ -0.02	-35 €/tonCO_2

Management summary

The demonstration project will show the integration of an intermittent flow of oxygen from an electrolyzer within an industrial process. A demonstration and test program is developed in order to test the integration of an intermittent flow of oxygen from an electrolyzer within an industrial process. The following is key in developing such projects:

1. Field acceptance/commissioning tests + operator training
2. Demonstrate safe and reliable operation + operator training
3. System flexibility testing and long-term monitoring

Other demonstration projects, like H-vision could focus on integration of a large LOX buffer and the flexible operation of an ASU.

Institutional framework

Oxygen is a well-known industrial gas, and therefore institutions do not limit the application of oxygen synergy. Initiatives involving the production of green hydrogen can directly apply this synergy. Among others, this project could be of interest to the following initiatives:

- Initiatives of large industrials. BP, TATA Steel, RWE, Innogy and Nouryon announced large green hydrogen projects recently.
- H-vision; development of a blue hydrogen plant in the Rotterdam harbor area with a large demand for oxygen.
- Magnum power plant; development of a hydrogen power plant in the Groningen area with blue hydrogen.
- The GW-project; focusses on developing a GW-size electrolyzer in the large industrial clusters in the Netherlands.

Though, applicability does not equal simplicity. Realizing oxygen synergy demands collaboration between different industries within one project. Mutual trust and coordination is key in projects involving industrial symbiosis.

Management summary

A coherent stimulation program is required to kick-start the hydrogen economy. The government should take an active role in this. The H-vision project suggested four roles the government should take to stimulate hydrogen. Recent discussions concerning the SDE+/SDE++ subsidies indicate the urgency to do so.

Conclusions and recommendations

The main conclusions of our studies are:

- Oxygen synergy leads to reduced CO_2 emissions and reduced costs and therefore deserves to be taken into account in hydrogen projects.
- Hydrogen initiatives can apply oxygen synergy together with other parties; focusing on the flexible integration of oxygen flows.
- Oxygen synergy contributes to the adoption of green hydrogen, but the upsides are insufficient for it to be a breakthrough technology.

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Hydrogen will play an important role in the energy transition: 3-4 GW installed base-load of electrolyzers in 2030, scaling-up towards 2050

Hydrogen is one of the emission-free energy carriers that will play an important role in the energy transition.

In order to reach the goals of the Paris Agreement, many measures have to be taken. One is using CO_2-emission-free hydrogen. Hydrogen could be used in many different sectors, examples of the possible use of hydrogen:

- Industry: feedstock, steelmaking, fuel for high temperatures
- Mobility: long distance transport
- Electricity: balancing intermittent sources of electricity
- Built environment: carbon neutral peak power for heat networks, “green” gas

The “Klimaatakkoord” plans for 3-4 GW electrolyzers producing hydrogen in 2030.

The Klimaatakkoord mentions hydrogen more than 100 times in its text.

In many scenarios for 2050 hydrogen will play an even greater role.


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Three main routes for hydrogen production: grey, blue and green

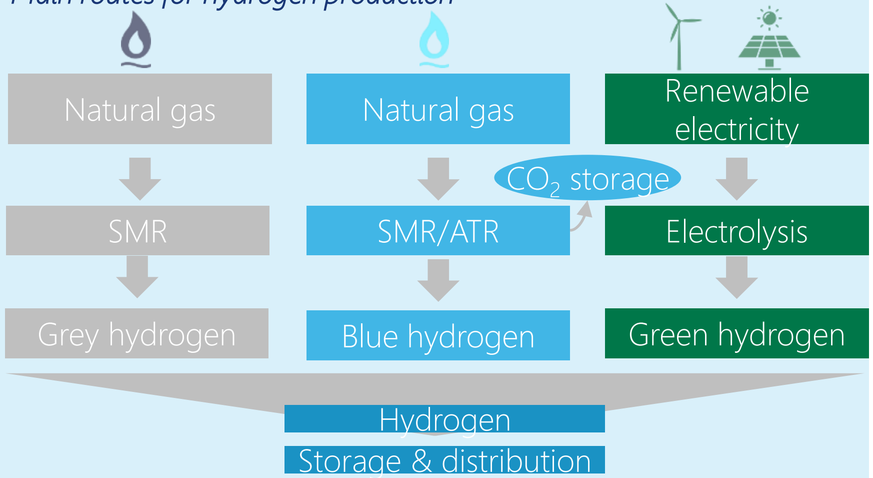
Hydrogen can be produced in three different ways:

- Grey production: hydrogen is produced by steam methane reforming of natural gas; this is currently the most common way to produce hydrogen.
- Blue production: carbon neutral hydrogen production by reforming natural gas and carbon capture and storage; the H-vision project envisions a blue hydrogen plant (Autothermal reformer: ATR) in the Rotterdam area, in the Groningen area a similar project is focused around the Magnum powerplant.
- Green production: hydrogen from renewable electricity via electrolysis; several projects in the Netherlands. Scale is still limited.

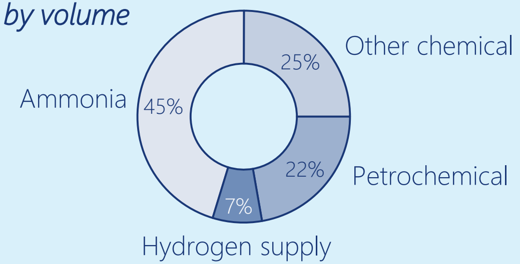
Current use of hydrogen by volume

The main use of hydrogen is in chemical plants for the production of ammonia and as a feedstock for other chemical products. Furthermore it is widely used in refineries for cracking.

Main routes for hydrogen production



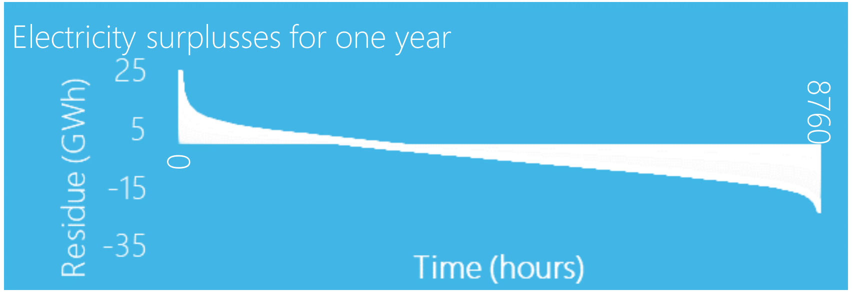
Current use of hydrogen by volume



Currently, the uptake of large scale green hydrogen production is limited

The amount of green electricity now and in the future is not sufficient to produce large quantities of green hydrogen.

- At the moment only 15% of our electricity is renewable.
- In 2030 70% of the electricity production (~84 TWh) should be renewable according to the Klimaatakkoord. Most of this electricity can be used directly and only a small portion of the electricity is a surplus.
- In order to produce large scale green hydrogen, we need even more renewable electricity production. Either by creating more hours of surpluses or by reserving dedicated renewable electricity.



The production of green hydrogen is still expensive, but cost-reductions are foreseen.

- The marginal cost price of green hydrogen is 5-6 €/kg. Compared to natural gas, the cost of using hydrogen as a source of energy is about 8-9 times as high. This leads to a CO_2-abatement cost of 543 - 668 €/ton CO_2.
- Cost reductions are foreseen for the two main cost items in green hydrogen production, but it is uncertain when these will occur and how large they will be:
  - The price of electricity from solar and wind power is decreasing. In the past 9 years the LCOE for solar power has dropped by 88% and for wind power by 69%. By using as many surplus hours as possible electrolyzers could also operate with relatively low electricity prices.
  - The price of electrolyzers is expected to drop by 59% in 2020 compared to 2015. Continuation of this trend would result in large cost reductions.

Vision: from grey production to green supported by blue

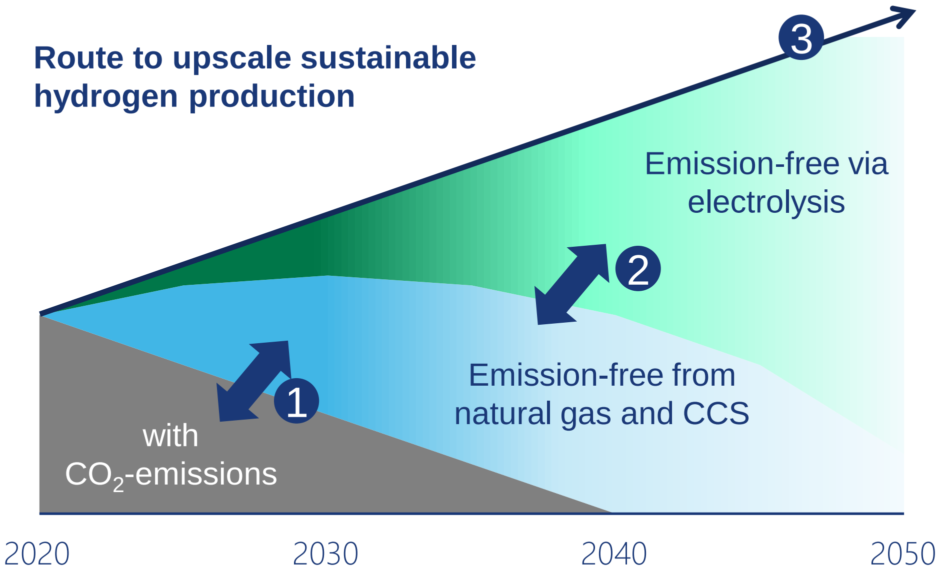
The transition towards a green hydrogen future, will start at grey hydrogen and will be supported by blue hydrogen.

The adoption of hydrogen as a decarbonization solution for several different sectors will only work if hydrogen is readily and cheaply available.

Currently, there isn't such an abundance of wind and solar power that green hydrogen can be produced in large quantities. To start reducing CO_2 emissions as early as possible and start using hydrogen, blue hydrogen could pave the way for the hydrogen economy. Blue hydrogen is relatively cheap and the technology for large scale deployment is already available. The hydrogen mix will gradually become greener, as electrolyzers replace blue hydrogen production.

However, for this green hydrogen future it is essential to start the production of green hydrogen now in order to extend the duration of the learning curve and have a higher chance of meeting the targets for cleaner energy and lower production costs by 2050.

Three hydrogen routes will coexist in the coming decades



Electrolyzers produce hydrogen and as a byproduct oxygen; Oxygen is the second largest industrial gas, with various applications

An electrolyzer produces hydrogen from electricity with oxygen as a byproduct.

The general equation governing an electrolyzer is the following:

$$2H_2O \rightarrow 2H_2 + O_2$$

Oxygen is produced as a byproduct and is typically vented into the air. However, having 3-4 GW of electrolyzers in the Netherlands in 2030 would result in an oxygen production of roughly 1.8 to 2.4 million tons of oxygen per year (considering 4000 full load hours). This would be roughly half of the Dutch industrial oxygen sales in 2018, about 3.9 million tonnes.[1]

Following nitrogen, oxygen is the most used industrial gas. In 2006 the worldwide capacity for oxygen production was 1.2 million tons per day.[2] This capacity stems from Air Separation Units or ASUs.

Oxygen is mainly used in the metal sector and in chemical processes. Networks of pipelines for oxygen transport exist in the Netherlands. The oxygen can be stored in cryogenic oxygen tanks.

An oxygen network in Belgium and the Netherlands

Source: AirLiquide

Oxygen tanks

Source: Linde

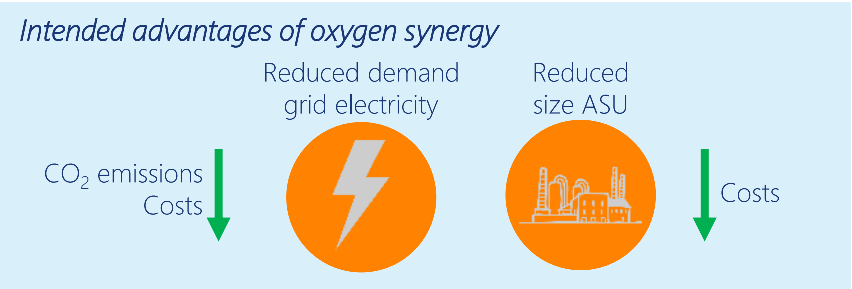
1: CBS statline, Verkopen; industriële producten naar productgroep (ProdCom), geraadpleegd 17-10-2019
2: https://www.gasworld.com/oxygen-global-market-report/1277.article

Oxygen synergy leads to cost reductions and energy efficiency

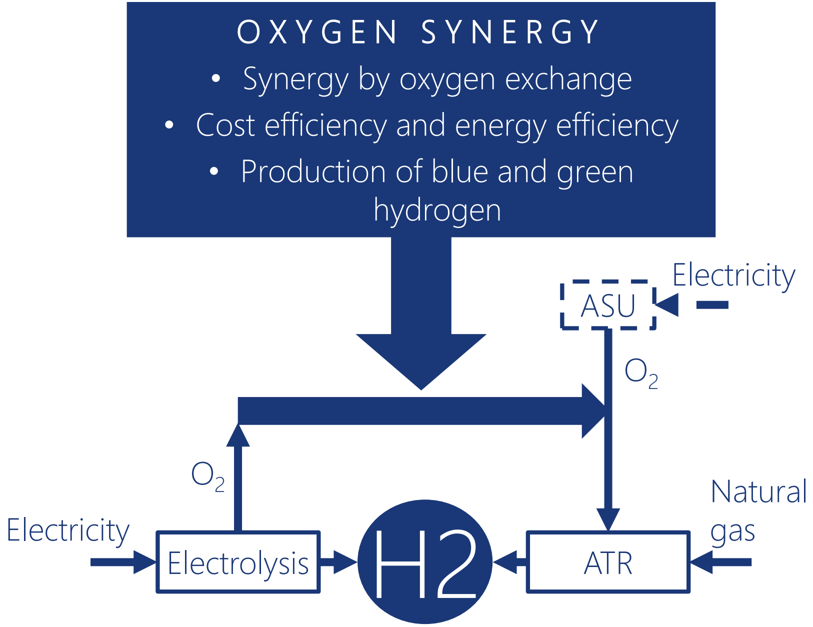
Oxygen synergy and the hydrogen accelerator as an example.

As described, the production of green hydrogen results in large amounts of oxygen as a byproduct. Oxygen synergy is the use of the oxygen in another process. Usually, oxygen is produced by an Air Separation Unit (ASU). The expected benefits are therefore twofold. Firstly, no grid electricity is required to run the ASU. This is an advantage in terms of both costs and energy efficiency. Secondly, less ASU capacity is required, which is a cost advantage.

This project investigates the use of oxygen in the production of blue hydrogen: multiple blue hydrogen initiatives intend to use Autothermal Reforming (ATR) to produce hydrogen, a process that requires large volumes of oxygen.



Overview of the hydrogen accelerator



Objective is to determine the techno-economic feasibility and next steps to implement this oxygen synergy

One objective is to examine the **technological and economical feasibility** of oxygen synergy between green and blue hydrogen production.

Another objective is to **map next steps** for oxygen synergy, in order to bring this idea from the drawing board to reality.

Chapter 2 Role of hydrogen → **Chapter 3** Components for oxygen synergy → **Chapter 4** Cases: oxygen synergy applied → **Chapter 5** Demonstration program → **Chapter 6** Institutional framework → **Chapter 7** Conclusions and spin-off

The possible role of hydrogen in various applications is shown.

A model was developed to examine the techno-economic feasibility. The inputs for the model originate from desk research and meetings with experts, concerning all technical components of the value chain. Multiple cases were developed to test the outcomes to different market conditions (retrofit / greenfield development) and stages of the hydrogen economy.

In order to bring this idea from the drawing board to reality, two topics were researched based on desk research and validated by experts in a workshop.

A **demonstration case** is developed with an accompanying test program to structure the developmental phase of this technology.

The institutional framework was drawn, based on limitations for this synergy and the hydrogen economy in general.

Conclusions are drawn and coupled to the multiple hydrogen initiatives in the Netherlands.

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2 Role of hydrogen

Chapter 2: the role of hydrogen

Chapter 2 Role of hydrogen → Chapter 3 Components for oxygen synergy → Chapter 4 Cases: oxygen synergy applied → Chapter 5 Demonstration program → Chapter 6 Institutional framework → Chapter 7 Conclusions and spin-off

Research objectives:

- Comparing hydrogen and other routes to decarbonize.
- Investigating whether the production of blue and green hydrogen will coexist.

Main conclusions:

- Hydrogen has a role to reduce emissions for applications which have little or no other decarbonization options.
- Hydrogen should be limited to these applications, due to the high costs and operational efficiency to produce it.
- The upcoming decennia, blue and green hydrogen will coexist and hence the green oxygen can be used in the blue hydrogen process.

Hydrogen is not the cheapest option in realizing energy transition, but it is also not the most expensive…

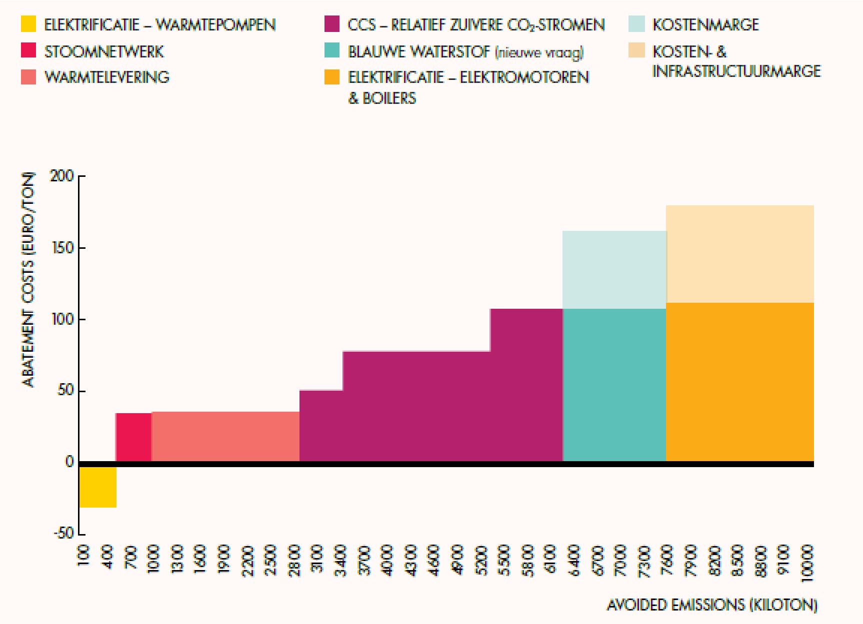
For CO_2-reduction in the industry there are cheaper options than hydrogen…

- The marginal cost price of green hydrogen is 5-6 €/kg. Compared to natural gas, the cost of using hydrogen as a source of energy is about 8-9 times as high. This leads to a CO_2-abatement cost of 543 - 668 €/ton CO_2.
- The costs for blue hydrogen are projected in the H-vision project. The projected avoidance costs of 86-146 €/ton CO_2 are significantly lower than green hydrogen.
- Though, options like energy saving and some electrification and high-purity CCS options have lower avoidance costs.

… but there are also CO_2-measures being taken that are more expensive.

- The average CO_2 abatement costs of all projects with SDE(+)-subsidy as of January 2019 is 303 €/ton CO_2
- The abatement cost for the construction of heat networks 290 €/ton CO_2[1]
- The abatement cost for a per kilometer-tax for personal transport is even higher at 490 €/ton CO_2[1]

Avoidance costs of options in the Rotterdam-Moerdijk region



Source: In drie stappen naar een duurzaam industriecluster Rotterdam-Moerdijk in 2050

1. PBL, 2018, Kosten energie- en klimaattransitie in 2030 – update 2018

… but hydrogen is a solution for applications that are difficult to decarbonize …

Overview of the applicability of solutions for energy transition in different sectors

	Hydrogen	Electrification	Geothermal energy	Biomass	Post-combustion CCS
Built environment	Applicable for all building types	Requires insulation and floor heating	Depending on suitability subsurface	Applicable	
Mobility	Applicable for all modes and distances	Less suited for long-distance transport			
Industry	Applicable both as fuel and feedstock	Only suitable for low temperature heat	Only suitable for heat up to 250 degrees	Applicable both as fuel and feedstock	Only applicable for particular industries
Electricity production	Applicable for both base- and part-load			Applicable for both base- and part-load	Only applicable for baseload plants

… and all solutions have their own limitations

Green hydrogen

- Green hydrogen requires surplus renewable electricity, which is not available yet.
- The costs of green hydrogen are high, and scalability of electrolyzers is limited. Large scale developments depend on innovations.

Blue hydrogen

- Blue hydrogen depends on carbon capture and storage (CCS).
- Furthermore natural gas is the feedstock of blue hydrogen. Therefore, it is dependent on the natural gas price and costs for CCS need to be taken into account.

Geothermal

- Not all locations are suitable for geothermal energy. For example, there is a risk of earthquakes in developing geothermal energy.
- Drilling a geothermal well is CAPEX-intensive and risky. Before drilling, it is unclear how much heat will come from a source.

Electrification

- The electrical infrastructure has a backbone of only ~25 GW. A large emphasis on electrical solutions will require expensive extra infrastructure.
- The availability of renewable electricity depends on the weather conditions. This imposes challenges for integration in the energy system.

Biomass

- The Dutch potential for biomass is limited to approximately 250 PJ in 2050. If the demand exceeds the Dutch production, biomass will be imported from abroad.
- Furthermore energetic use of biomass will always compete with biomass as a raw material.

Post-combustion CCS

- For post-combustion CCS, investments have to be made for installations in the industry. This will make the CCS system less flexible: investments could become sunk costs.
- It is not possible for all processes: for its economic viability depends on large point streams of CO_2 and high full load hours of the equipment.

Hydrogen should play a role in decarbonizing applications which have little alternative decarbonization methods

Examples of applications with little alternatives:

- **Industry:** industrial processes which require hydrogen as a feedstock should be decarbonized. Furthermore, processes requiring high temperature heat have few decarbonization options.
- **Built environment:** peak supply of heat has little other options to decarbonize. Two methods exist to supply this peak demand. Firstly, it can be done by installing hydrogen-run peak boilers in heating networks. Secondly, hybrid heat pumps with hydrogen-run boilers can be installed in individual houses.
- **Transport:** Long distance transportation has little alternatives, since electrical solutions are less obvious. Therefore, public transportation, truck transport, shipping and aviation are interesting market segments for hydrogen.

Hydrogen is not the holy grail for the energy transition, but a large market is foreseen where hydrogen is a likely solution.

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3 Components for oxygen synergy

Chapter 3: Components for oxygen synergy

Chapter 2 – Role of hydrogen → **Chapter 3 – Components for oxygen synergy** → Chapter 4 – Cases: oxygen synergy applied → Chapter 5 – Demonstration program → Chapter 6 – Institutional framework → Chapter 7 – Conclusions and spin-off

Research objectives:

- Investigate the workings of the components

Main conclusions:

- All components are known in enough detail in order to model oxygen synergy

Components

Oxygen synergy needs several components each with their own particularities.

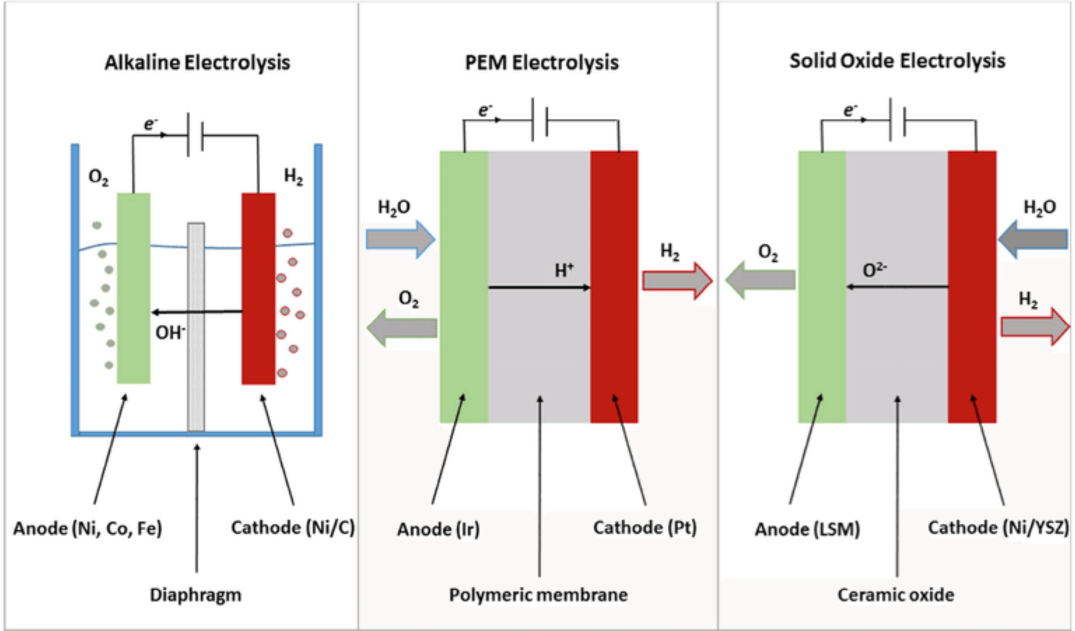
These components are important, because of the role they play in our study:

- Electrolyzers: produce both H_2 and O_2 and are therefore the start of the hydrogen accelerator and other possible oxygen synergies.
- Cryogenic Air Separation Units (ASU): the industry standard for oxygen production.
- O_2 transport by pipelines: to let the oxygen flow from electrolyzer or ASU to the ATR.
- O_2 compression: the oxygen needs to be compressed in order to feed the ATR process.
- Liquid O_2 storage: to maximize the possibilities of oxygen synergy buffering of oxygen in liquid form is essential.
- Auto-Thermal Reforming (ATR): one of the techniques to produce blue hydrogen, this process needs oxygen typically produced by an ASU but possibly by using oxygen from an electrolyzer; we call oxygen synergy with an ATR: the hydrogen accelerator.
- O_2 integration considerations: in the combination of components some considerations arise.

Each component is discussed in further detail in the rest of this chapter.

H_2 & O_2 production by electrolysis (1/3)

- Electrolysis is the process through which (high purity) hydrogen is produced from water and electricity.
- There are several electrolysis options available. Find below the most mature technologies:
  - Alkaline electrolysis (most mature)
  - Proton exchange membrane electrolysis
  - Solid oxide membrane electrolysis
- While operating with different fundamental principles and under different conditions, all three co-produce H_2 and O_2.



	Alkaline	PEM	Solid Oxide
Anode	$4OH^- \rightarrow 2H_2O + 4e^- + \mathbf{O_2}$	$2H_2O \rightarrow 4H^+ + 4e^- + \mathbf{O_2}$	$O^{2-} \rightarrow ½\,\mathbf{O_2} + 2e^-$
Cathode	$4H_2O + 4e^- \rightarrow 4OH^- + \mathbf{2H_2}$	$4H^+ + 4e^- \rightarrow \mathbf{2H_2}$	$H_2O + 2e^- \rightarrow \mathbf{H_2} + O^{2-}$

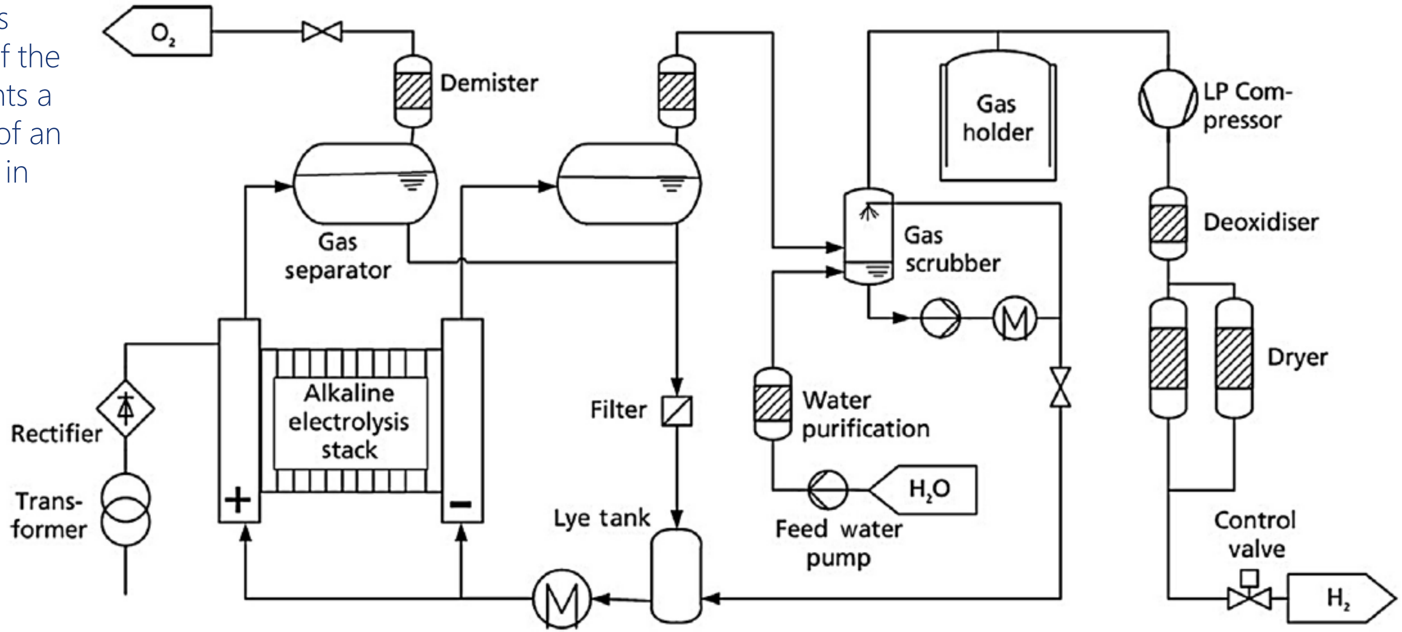
P. Millet, S. Grigoriev, *Water Electrolysis Technologies*, in Renewable Hydrogen Technologies, 2013

H_2 & O_2 production by electrolysis (2/3)

- Simplified process flow diagram for an alkaline electrolysis plant that delivers both H_2 and O_2:

- Although the electrolysis stack itself is the heart of the process, it only represents a relatively small fraction of an entire production plant, in terms of footprint.

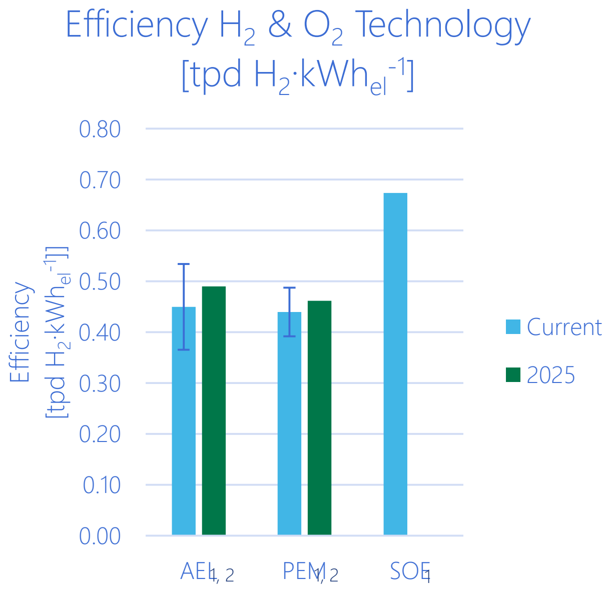
- On volume basis electrolyzers produce half as much O_2 as H_2, but on mass basis O_2 production is eight times higher.

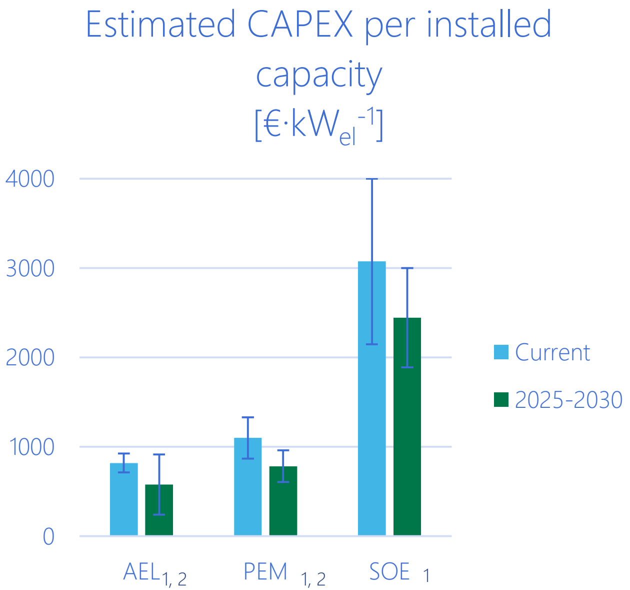


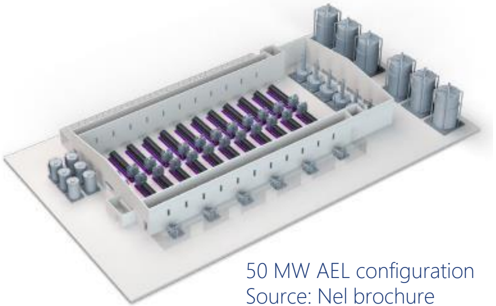
Tom Smolinka, Emile Tabu Ojong and Jürgen Garche, Electrochemical Energy Storage for Renewable Sources and Grid Balancing, 2015, Chapter 8 - Hydrogen Production from Renewable Energies Electrolyzer Technologies

H_2 & O_2 production by electrolysis (3/3)

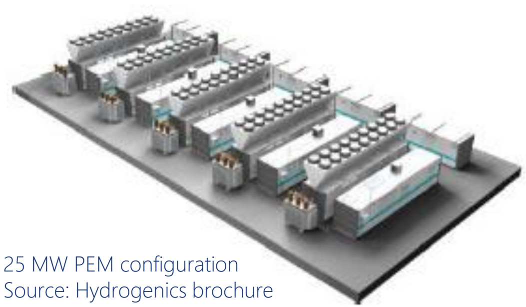
- A substantial decrease in associated CAPEX for all three technologies is expected for the next decade.
- Efficiency per installed MW_{el} will not vary much for mature technologies (SOE is still demo scale).
- Footprint (rough indication) of large scale electrolysis plants: 30-100 MW/ha (including utilities, substations, compressors etc.)







50 MW AEL configuration
Source: Nel brochure



25 MW PEM configuration
Source: Hydrogenics brochure

(1) Schmidt, O. et al (2017). Future cost and performance of water electrolysis: An expert elicitation study. In *International Journal of Hydrogen Energy* 42, 30470-30492
(2) IRENA. (2018). *Hydrogen From Renewable Power*: Technology outlook for the energy transition. Retrieved from www.irena.org

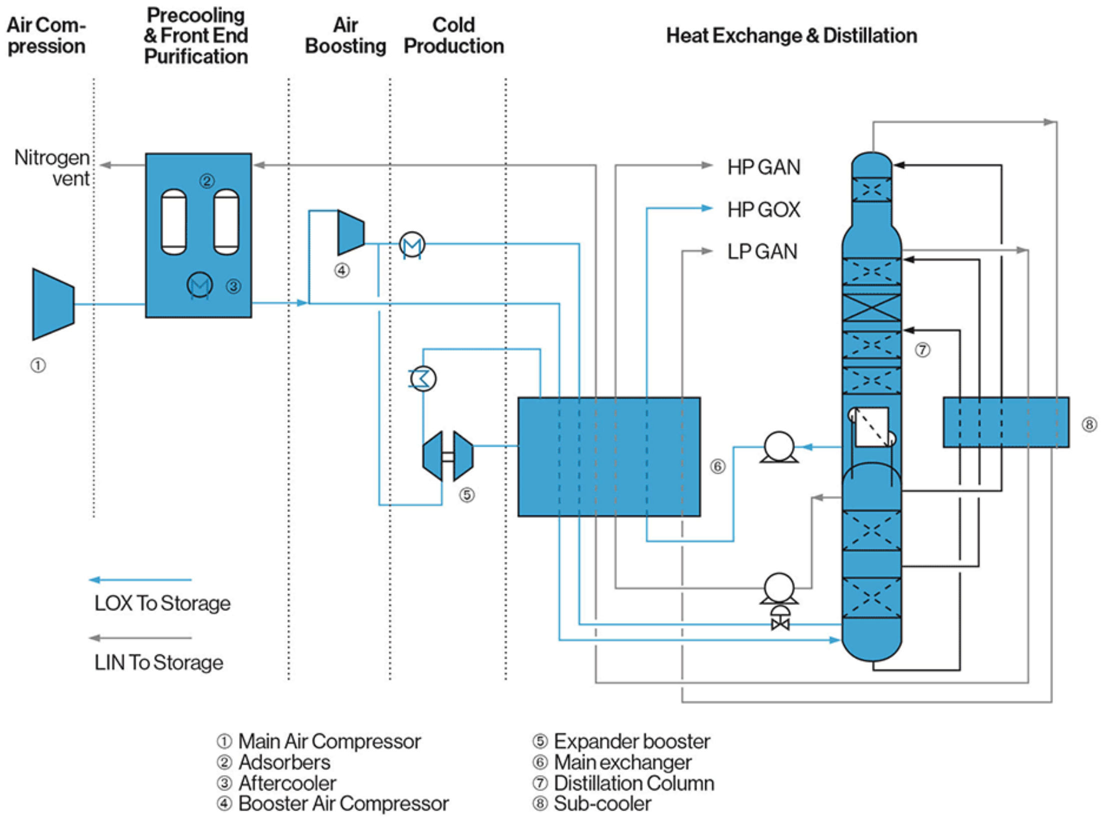
Increasing the load hours of the electrolyzer is beneficial to oxygen synergy, but in future electricity markets it might not be for the electrolyzer business case.

- The synergy becomes higher when the electrolyzer is operating with more load hours, because the production of (green) oxygen is increased. Load hours can be increased in two ways compared to the current configuration, where there is an offshore wind park with 3500 full load hours.
  - Option 1: adding solar energy to the supply mix.
  - Option 2: connecting the electrolyzer to grid electricity, which consists of also fossil energy.
- In reality the business case of the electrolyzer improves up to a certain point. Running the electrolyzer for an entire year, which comes down to 8760 load hours, results in paying a higher energy bill, because more expensive electricity prices are also included. With a dedicated wind park there are about 3500 load hours. The sweet spot is somewhere in between 3500 – 8760 load hours.
- The business case for the entire electrolyzer depends on the current energy system and the associated market conditions, such as electricity prices. A study showed that with 2018 market conditions, minimal costs occur at 8050 load hours. With 2025 market conditions, this figure lies at 7500 load hours. In 2040, the load hours are even lower at 6710 (Enpuls, DNV GL and TNO).
  - The major assumption is that there will be more volatility in the future energy system. The price curve will be steeper. So there will be times when electricity is a lot cheaper, but also where it is much more expensive. These more expensive prices drive down the load hours of the electrolyzer, because these deteriorate the business case.

https://www.enpuls.nl/media/2345/eindrapport-module-1-_-technologiebeoordeling-groene-waterstof-_-enpuls.pdf

Cryogenic air separation units (1/2)

- Cryogenic air separation is a very well known and widely deployed technology and the industry standard for large volume oxygen production.
- Single train ASUs can have capacities of up to 6,000 tons per day of O_2.
- Fundamentally, air separation units operate on the principle of cooling based on compression and expansion cycles, combined with distillation.
- The specific power demand is approx. 175-245 kWh/t O_2, depending on plant CAPEX, O_2 purity, O_2 delivery pressure and co-products.

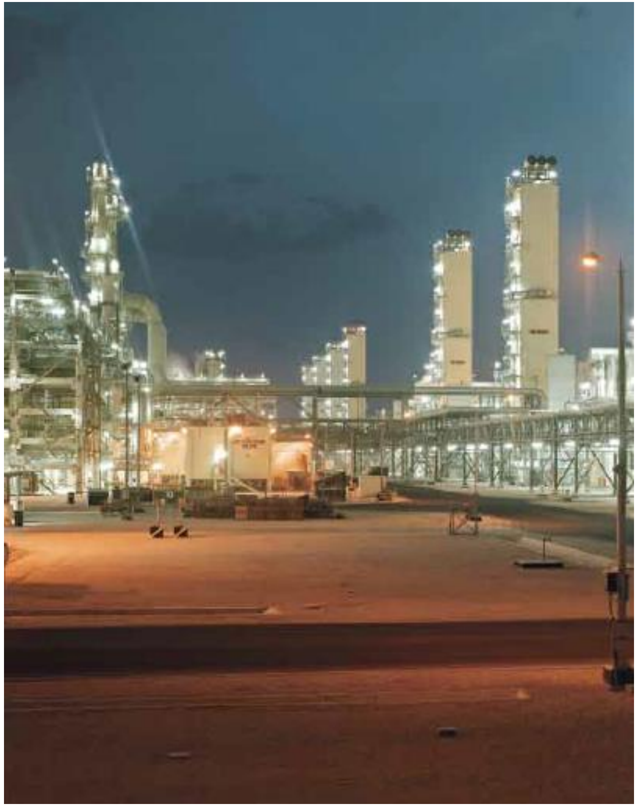


Source: Air Liquide website

Cryogenic air separation units (2/2)

- Conventional ASU designs have typical operating ranges between 70-105% of their nominal capacity.
  - Cold boxes are designed for 50% turn-down, but operating below 70% leads to a higher specific energy use due to inefficient air compressor operation.
- Within that range, ASUs can be operated flexibly with ramp-up / ramp-down rates of 2-3% / min. Together with liquid oxygen storage, this flexibility enables combining co-produced O_2 from an electrolyzer with O_2 produced by an ASU.

- The following ASU parameters were used for this study:
  - 200 M€ CAPEX for a 240 t/h O_2 plant (H-vision reference) and a scale-up factor of 0.65
  - Specific power required: 210 kWh / metric ton O_2
  - LOX production: 10% of total capacity



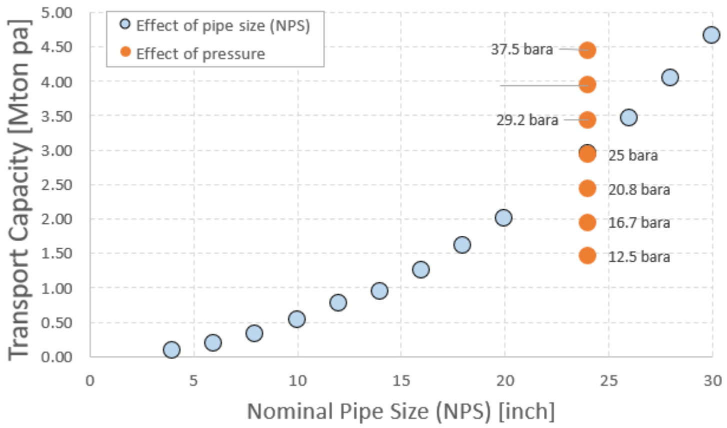
ASUs at the Pearl GTL plant in Qatar (source: Linde)

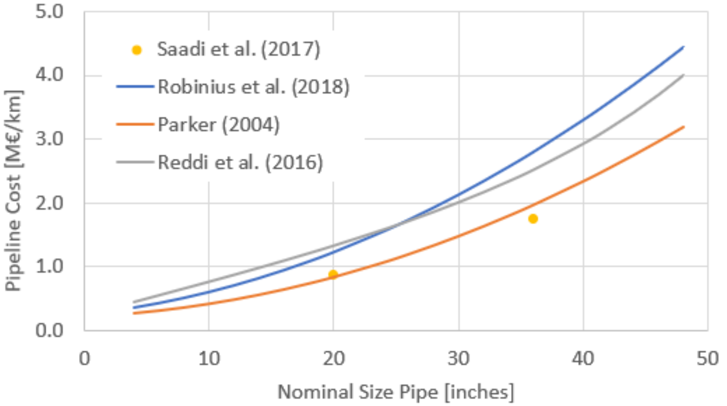
O_2 transport by pipeline

- There are no special requirements for transporting O_2. Carbon steel pipelines can be used.
- In the Benelux region there is already a pipeline network in place for the long distance transport of O_2.

- Several authors have reported cost models as a function of diameter for natural gas, CO_2 and H_2 pipelines (three models from literature are compared in the chart on the right).
- For short lines some models expect higher costs, but there is no overall agreement that this is the case. Therefore we did not take this into account in our model. For further research pipeline costs for short distances should be looked into, perhaps by contacting pipeline constructors.

- O_2 Pipeline costs estimates were calculated on a cost per km basis, using the Robinius correlation (most recent and considered a conservative approach for this study).
- The pipeline diameter was estimated using a TNO tool and the following parameters:
  - Pipeline inlet pressure: 25 barg (DP 70 bar)
  - Fluid velocity: 5 m/s for D < 16″ and 10 m/s for D > 16″
  - Maximum pressure drop: 0.5 bar/km
  - Average temperature: 15 °C





O_2 compression

- Supplying oxygen for a high pressure (60-65 barg) ATR from an electrolyzer operating at 20-30 barg requires a compression step.
- This is standard for industry and there are several O_2 compressor vendors available. A margin was added to the compressor outlet pressure to account for pipeline / control valve pressure losses in the ATR unit.
- The compressor duty for each case was calculated using Aspen Plus.

- Compressor CAPEX was estimated for two different capacities, assuming the same operating conditions.
- An equipment vendor confirmed that the cost estimate of the 1.3MW machine is in the right order.
- That company doesn't supply machines larger than 2 MW. The estimated CAPEX for the 8.3 MW machine assumes such large compressors are available and takes economy of scale into account, so the costs could therefore be underestimated.

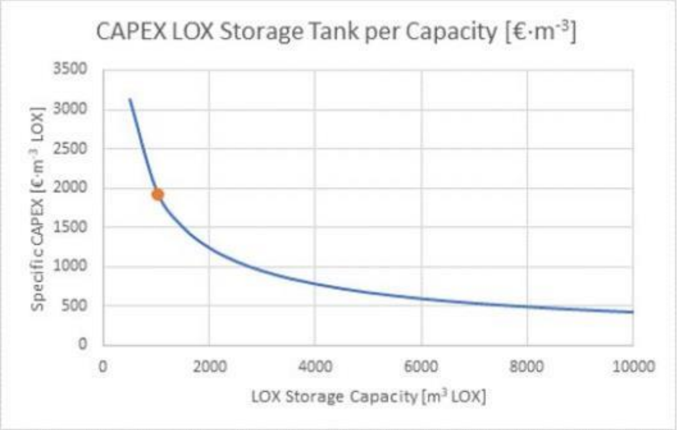
O_2 compression			
Electrolyzer capacity	[MW]	250	1650
Mass flow O_2	[tph]	38.4	253.4
Compressor inlet pressure	[barg]	25	
Compressor outlet pressure	[barg]	70	
Compressor inlet temperature	[°C]	30	
Required compression duty	[MW]	1.3	8.3
Estimated compressor CAPEX	[M€]	3.5	11.6

Compressor cost estimates were calculated based on a 2014 article by Amin Almasi
www.chemicalprocessing.com/articles/2014/how-much-will-your-compressor-installation-cost/

Liquid O_2 storage

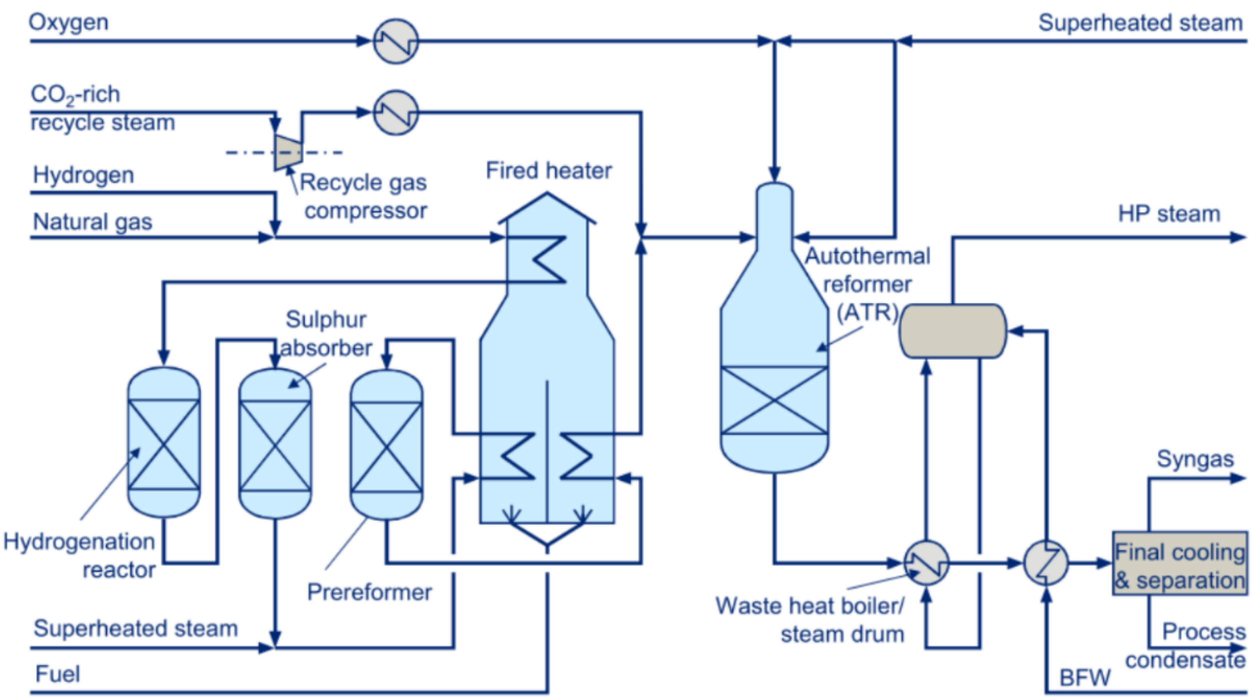
- Depending on the ASU design, gaseous O_2 units can have a side stream of liquid oxygen (LOX).
- Such designs frequently include liquid oxygen (LOX) tanks, either to enable the sale of liquid O_2 as a secondary product or to add buffer capacity to the unit.

- Literature reference available for LOX tanks with a capacity of 6,500 m^3. Liquid N_2 tanks can reportedly have capacities of up to 17,000 m^3.
- The estimative cost curve is based on a CAPEX reference 1.9 M€ for a 1,000 m^3 tank and a scale-up factor of 0.66.
  - Ballpark cost indication from a major air separation technology licensor: 1500 €/m^3 for LOX storage (presumably for tanks in the 1,000-2,000 m^3 range)
- Typical LOX storage tank pressure is 18 barg. O_2 boil-off from LOX tanks only significant for long periods (>1 week) of the ASU being out of operation.



ATR (Auto-Thermal Reforming)

- ATRs are reforming units in which (partial) oxidation reactions also take place, providing the heat required to produce syngas from methane and other light hydrocarbons.
- These units typically produce syngas for the production methanol or for Fischer-Tropsch synthesis.
- Pure or nearly pure O_2 is used instead of air because
  - Separating N_2 and CO is extremely difficult
  - Having N_2 in the system as an inert increases unit size



Example of a syngas production plant using Haldor Topsøe ATR stand-alone reforming. Reproduced from (Dahl, Christensen, Winter-Madsen, & King, 2014).

O_2 integration chain

- For this study the electrolyzer is assumed to be situated nearby the ATR plant (5 km pipeline length). O_2 is produced by the electrolyzer at 25 barg, compressed to 70 barg and then transported by pipeline to the site where the ATR is.
  - Some ASU designs for gaseous O_2 production already include a compressor for O_2. There is potential to achieve additional cost savings by using the same machine to also compress O_2 from the electrolyzer, instead of having an additional compressor.
    - This would be partially offset by the need to have a larger diameter pipeline because of the lower transport pressure.
    - This option is not applicable for high pressure ASUs, which have high pressure main heat exchangers and use a liquid O_2 pump instead of a compressor.
- The possible uplift of higher purity O_2 from the electrolyzer (100% instead of 95% from the ASU) was not taken into account in the economic evaluation.

Berenschot

4 Cases – oxygen synergy applied

Chapter 4: Cases - oxygen synergy applied

Chapter 2 Role of hydrogen → Chapter 3 Components for oxygen synergy → **Chapter 4 Cases: oxygen synergy applied** → Chapter 5 Demonstration program → Chapter 6 Institutional framework → Chapter 7 Conclusions and spin-off

Research objectives:

- Determining the techno-economic feasibility of oxygen synergy.
- Testing the techno-economic feasibility in different market conditions (retrofit/greenfield) and stages of the hydrogen economy.

Main conclusions:

- Oxygen synergy results in a cost-beneficial way to increase cost- and energy-efficiency. It should therefore be considered in developing hydrogen production projects. It is scalable to the size of green H_2 projects which are currently planned and possibly larger installations.
- It is beneficial in both a retrofit and greenfield situation, due to reduced operational expenses. A greenfield situation leads to further advantages, due to the opportunity to reduce the size of an Air Separation Unit (ASU).
- Oxygen accounts for only a small part of the hydrogen production costs. The acquired cost reduction is therefore insufficient to directly enable green hydrogen.

The techno-economic feasibility was examined using 3 cases, based on different markets and sizes of green hydrogen production

	*Size Green H_2	*Size blue H_2	Market blue hydrogen
Case 1 Retrofit adaptation	250 MW	1000 MW	Retrofit
Case 2 Current greenfield initiatives	250 MW	1000 MW	Greenfield
Case 3 Future greenfield initiatives	1650 MW	1000 MW	Greenfield

Considering a retrofit or a greenfield situation is a fundamental difference:

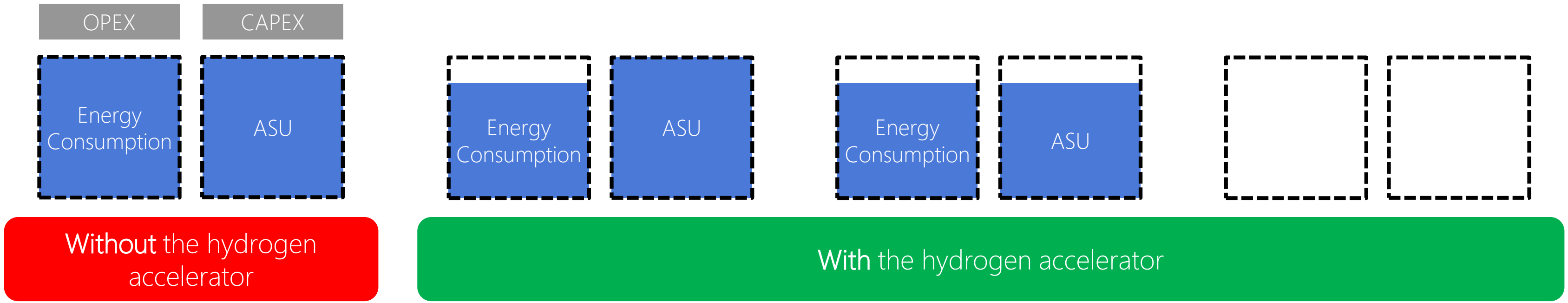
- **Retrofit** considers the situation in which oxygen from an existing ASU is being replaced.
- **Greenfield** considers the situation in which oxygen from a new-built ASU is being replaced.

Realistic sizes for hydrogen production were chosen, using initiatives currently being deployed by the market:

- The **blue hydrogen** size was tuned to H-vision. H-vision is the initiative of refineries, power plants and the hydrogen industry to build an ATR in the Rotterdam harbor area, which can be realized before 2025.
- The **current green hydrogen size** was tuned to an initiative of BP, Nouryon and Port of Rotterdam. They are planning to build a 250 MW electrolyzer, with a final investment decision in 2022.
- The **future green hydrogen size** was tuned to match the oxygen demand of H-vision. This size is distant, because currently there is not enough renewable energy and electrolyzer capacity. Though, in future situations it seems realistic: the Dutch climate agreement mentions a total of 3-4 GW electrolyzer capacity in the Netherlands in 2030, and the GW-electrolyzer project aims to scale electrolyzers to the size of at least 1 GW.

*Size of the green hydrogen plant is expressed in MW of electrical input. Whereas the size of the blue hydrogen plant is expressed in MW of output (H_2 rich fuel).

3 cases based on savings in ASU size (CAPEX) and energy consumption (OPEX)



Reference ASU size and energy consumption

- In the reference case the green oxygen from the electrolyzer is not linked to the ATR, which uses oxygen in its process to make blue hydrogen. We assume the oxygen is vented into the air.

Case 1: Retrofit adaptation

- ASU has the same size to match peak O_2-demand, but has reduced energy consumption. The ASU can reduce its energy consumption, because it does not have to produce the oxygen the electrolyzer is supplying.

- *Case 2: Current greenfield initiatives*
- The ASU's size is decreased and there is less energy consumption. Additional liquid oxygen buffer tanks are used to store oxygen when there is oversupply from the electrolyzer and allows us to match peak O_2-demand when there is little supply.

- *Case 3: Future greenfield initiatives*
- No ASU is required or input electricity is required, because the size of the electrolyzer matches the O_2-demand from the ATR. To build flexibility into this system, a large liquefaction plant and liquid oxygen storage tank are necessary.

Model limitations and assumptions

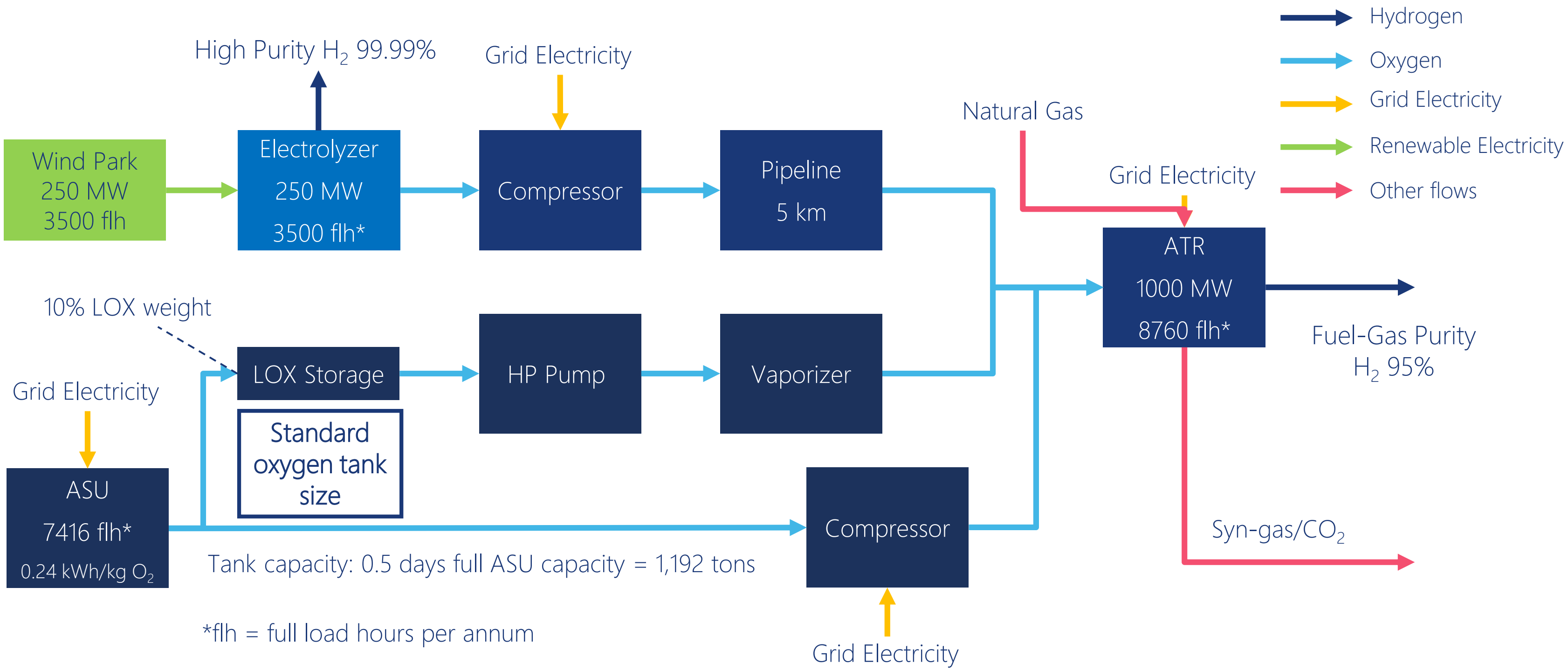
- Limitations, and suggestions for future research:
  - We use the hourly wind profile for one year (2015). The wind profile varies each year. Further study could look at the variation in wind profiles over many years, and use an average profile.
  - Next to the offshore wind that we connect to the electrolyzer, solar farms can also be connected. It would be interesting to see how this would change the storage requirements in for instance case 3.
  - We use one electricity price throughout the year. Future work could study different future electricity price scenarios, and study the effect on the business case.
  - The specific energy consumption of an oxygen liquefaction plant is determined by taking the delta of a gaseous oxygen ASU plant (10% LOX) and a liquid oxygen ASU plant (100% LOX), of which the liquefaction process is a subpart. Assuming that the difference accounts for the energy necessary to fully liquefy oxygen. The plant CAPEX is assumed to be 50% of an ASU, which is a number we estimated based on a brief discussion with an engineering company. To our knowledge there are no commercial oxygen liquefaction facilities today, therefore the numbers used are a first estimate. Future research should try to increase the certainty around these numbers.
- Assumptions:
  - Operational expenses are calculated on a yearly basis (OPEX). Some operational expenses are calculated using specific energy consumption, others are calculated as a percentage of CAPEX.
  - Capital expenditures are converted to a yearly figure using the WACC, which is the interest that has to be paid over the investment. We assume a WACC of 5%.
  - The electricity price assumed for running compressors, the ASU, the liquefaction plant et cetera is 44 €/MWh. This is the transaction price in 2015 for large electricity consumers (150,000+ MWh), excluding VAT and including energy taxes.
  - See the appendix for an extensive list of assumptions per technology component.

Case 1 – 250 MW Electrolyzer

- *Case 1 considers a retrofit situation, where there is an existing 250 MW green hydrogen site (Electrolyzer) and an existing 1000 MW blue hydrogen site (Autothermal Reformer). Since the two sites already exist, large adaptations to the configurations of both sites are not possible. This case therefore only considers using the (otherwise vented) oxygen from the green hydrogen site by connecting a compressor and pipeline to the blue hydrogen site.*
- *Case 1 results only in energy savings from the ASU.*

<u>Case 1 ASU</u> has the same size to match peak O_2-demand, but has reduced energy consumption

- This process scheme is implemented to model case 1 of the "hydrogen accelerator". Using energetic and financial inputs from various sources (desk research and interviews) results in a business case evaluation of green hydrogen production.



*flh = full load hours per annum

In case 1 the electrolyzer provides a small amount of the ATR's required oxygen input

- The electrolyzer (250 MW) provides 15% of the oxygen demand, see figure 4.1.1, from the ATR (1000 MW). Hence, the ASU can reduce load hours, energy consumption and hence operating costs (OPEX).
- Green hydrogen from the electrolyzer accounts for 11% of total hydrogen production, see figure 4.1.1, which is a relatively small part compared to the ATR. However, this makes sense when you consider that they have a different size (250 MW electrolyzer versus 1000 MW ATR).
- The total amount of hydrogen produced is 154 kilotons per year, which expressed in energy units is roughly 22 PJ (based on a HHV of 39.4 kWh/kg).
- Electrolyzer full load hours: 3500.

Figure 4.1.1. Relative distribution of hydrogen and oxygen production.

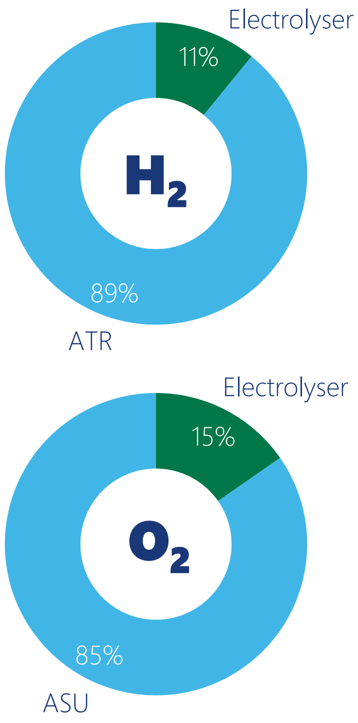
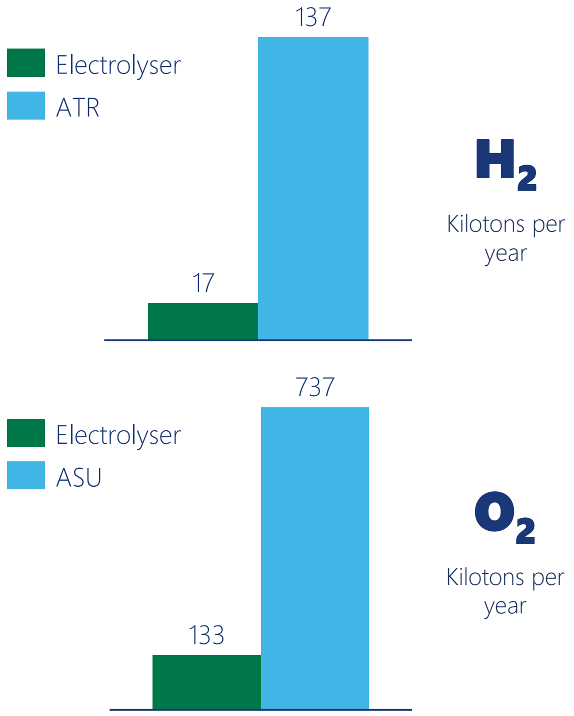


Figure 4.1.2. Absolute production of hydrogen and oxygen.

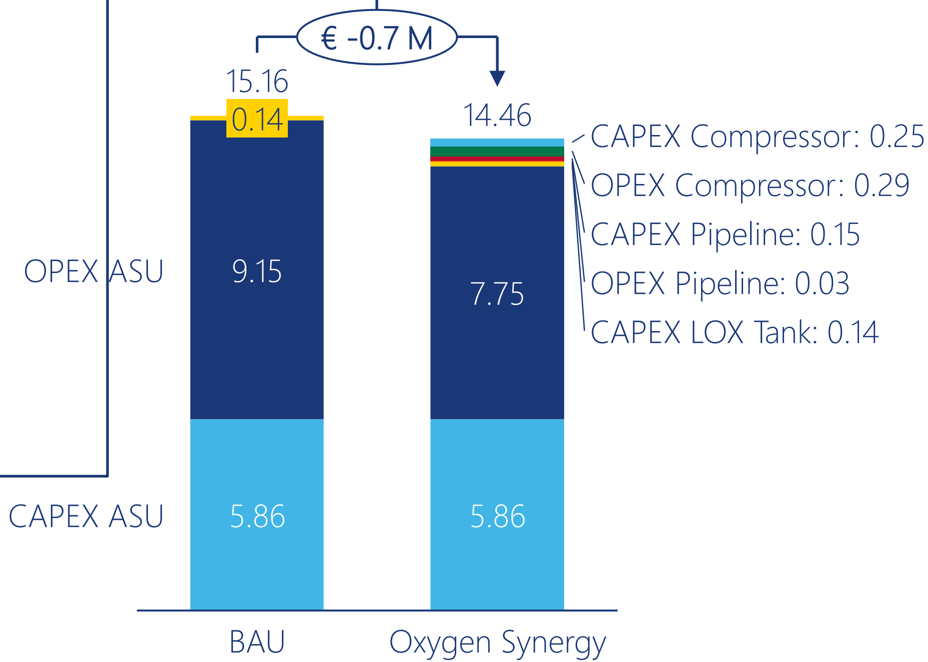


Case 1 results only in ASU OPEX savings, and some additional CAPEX and OPEX components

- Case 1 results in yearly total savings of € 0.7 million.
- The main driver of this saving is a reduction in ASU energy consumption of € 1.4 million (OPEX), which has been made possible by the electrolyzer providing oxygen to the ATR.
- A few extra cost elements are added, namely a compressor and pipeline to get the oxygen from the electrolyzer site to the ATR site at the required operating pressure. These extra costs amount to € 0.7 million per year.
- The LOX tank (CAPEX), which is also present in the BAU scenario, has the same size in the oxygen synergy case.

The yearly saving of € 0.7 million is allocated to the production of green hydrogen. Divided by the amount of green hydrogen produced (17 kilotons), the saving is € 0,04 per kg of H_2.

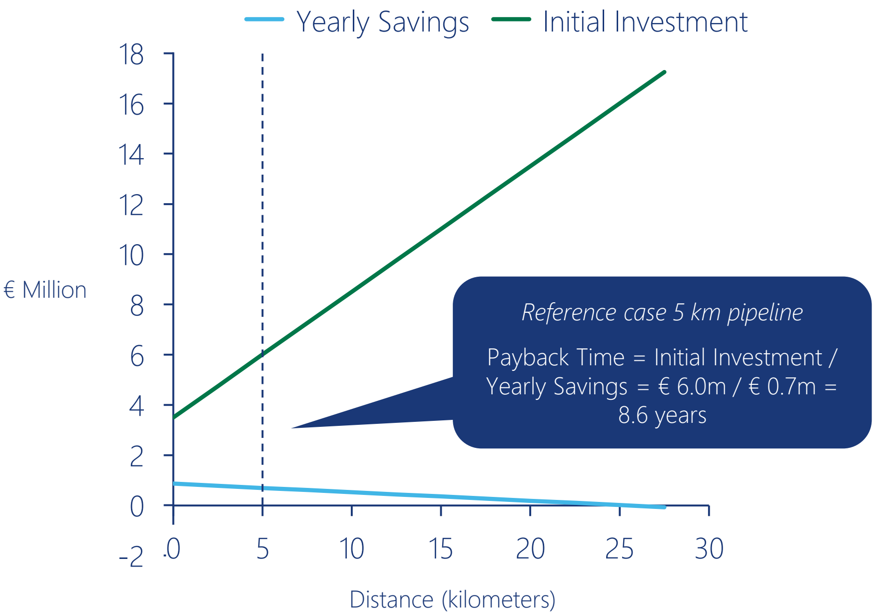
Figure 4.1.3. Yearly CAPEX and OPEX for green hydrogen production from electrolysis with or without the "Hydrogen Accelerator" (€ million).



Pipeline Distance: Sensitivity Analysis (Pipeline length is significant)

- Ideally the electrolyzer location is as close as possible to the ATR. Project revenues will appear until a distance of 25 km between the supply of green oxygen and the demand. The payback period increases with the distance between supply and demand.
- The amount of additional investment in the oxygen synergy case starts at € 3.5 million, consisting only of an oxygen compressor, and increases to € 17.3 million when the distance between the two sites reaches 27.5 km.
- Our reference assumption is a 5 km pipeline, which results in total yearly CAPEX and OPEX savings of € 0.7 million. When the pipeline distance reaches 27.5 km, a yearly loss occurs of € 0.1 million.
- A significant improvement to the business case would arise if one can make use of an existing oxygen pipeline network. In that case no additional investment is required, and the distance between the two sites can become larger.
- A final note is that we now assume a linear relation between pipeline distance and cost. However, shorter pipeline projects generally have higher costs per kilometer, relative to longer pipelines. This observation is something for future study.

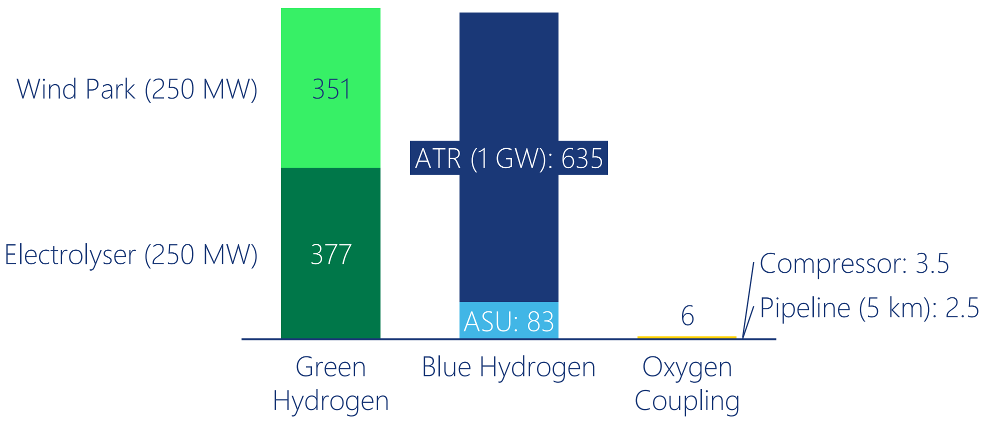
Figure 4.1.4. Yearly, CAPEX and OPEX, savings and the initial investment for different pipeline lengths (€ million).



Additional costs to couple oxygen from green hydrogen to blue hydrogen are relatively low compared to other cost components

- Compared to other technical components in the green and blue hydrogen value chain, the additional investments to couple green oxygen to the ATR are small, i.e. less than 1% of the total integral costs.
- Building a green hydrogen site requires a wind park and an electrolyzer, which both are significant cost items. When it comes to a blue hydrogen site the ATR is by far the most expensive component, followed by the ASU.
  - The electrolyzer in this comparison is an alkaline electrolyzer, which has an estimated CAPEX of 1150 €/kW.

Figure 4.1.5. Comparison of investment costs for various components of the total value chain: green hydrogen, blue hydrogen and oxygen synergy (€ million).

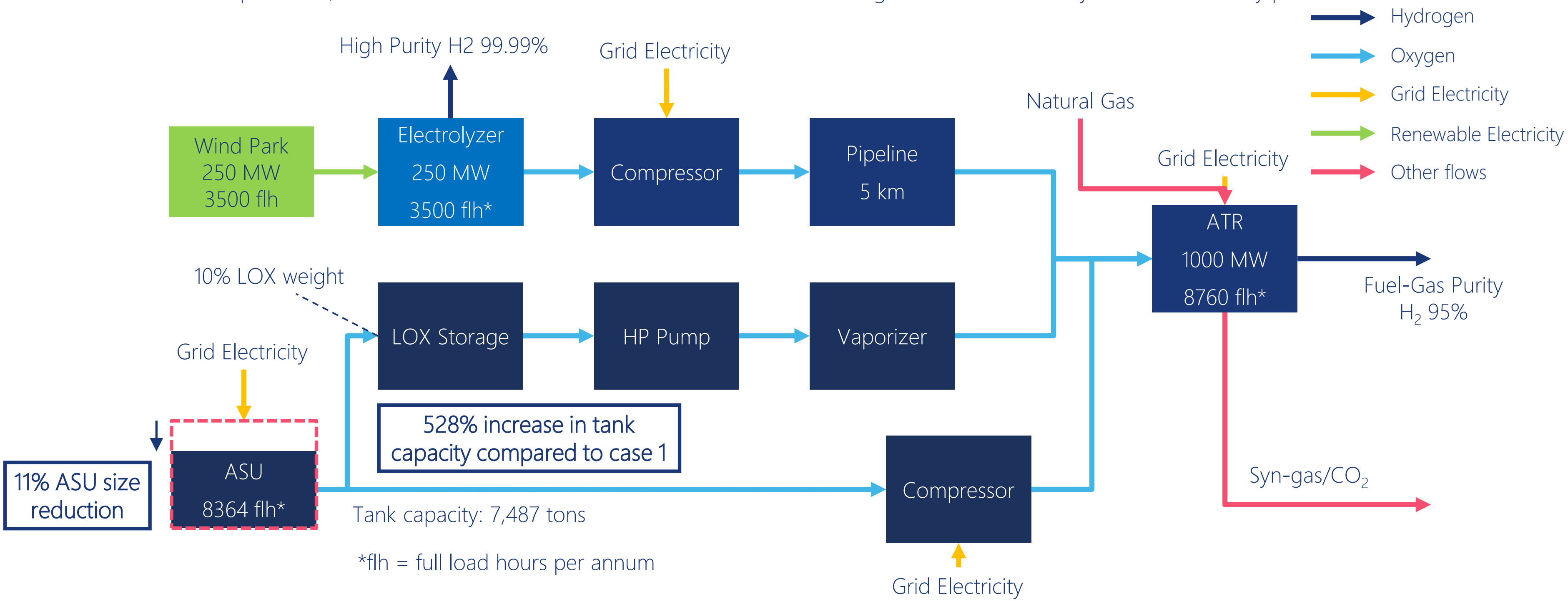


Case 2 – 250 MW Electrolyzer and LOX storage

- *Case 2 considers a greenfield situation, where a new 250 MW green hydrogen site (Electrolyzer) and a new 1000 MW blue hydrogen site (Autothermal Reformer) are built. Since the two sites are now engineered from scratch, large adaptations to the configurations of both sites are possible. This case considers a further optimization of the ASU system, by downsizing it in combination with installing a larger liquid oxygen storage tank.*
- *Case 2 results in both energy savings from the ASU, as well as investment savings related to a smaller ASU.*

Case 2 - Smaller ASU using a LOX buffer tank to match peak O_2 demand

- This process scheme is implemented to model case 2 of the "hydrogen accelerator". In this case the ASU size is reduced, and the peak O-demand from the ATR is met by buffering significant amounts of O_2 in a LOX storage tank. Moreover, there is also a saving in ASU load hours. If we could flex the amount of LOX produced, then we could make the ASU even smaller. Further investigation is needed to say if this is technically possible.



In case 2 the electrolyzer provides a small amount of the ATR's required oxygen input

- Similar to case 1 the electrolyzer (250 MW) provides 15% of the oxygen demand, see figure 4.2.1, from the ATR (1000 MW). Compared to case 1 the ASU smaller and the liquid oxygen is stored when there is no demand, and supplied when there is actual demand. This configuration allows us to downsize the ASU and reduce ASU energy consumption.
- Similar to case 1 green hydrogen from the electrolyzer accounts for 11% of total hydrogen production, see figure 4.2.1, which is a relatively small part compared to the ATR.
- The total amount of hydrogen produced is 154 kilotons per year, which is roughly 22 PJ (based on a HHV of 39.4 kWh/kg).
- Electrolyzer full load hours: 3500.

Figure 4.2.1. Distribution of hydrogen production from ATR and electrolyzer

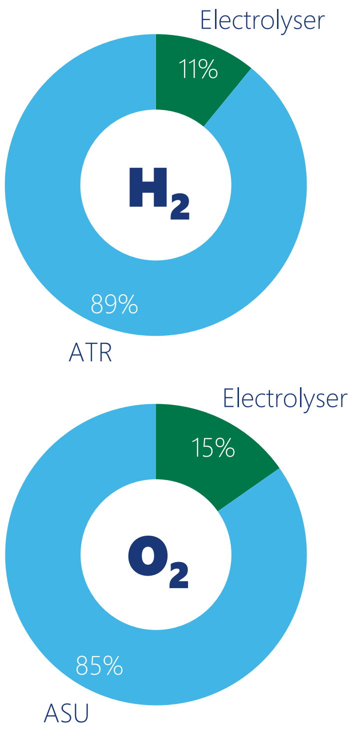
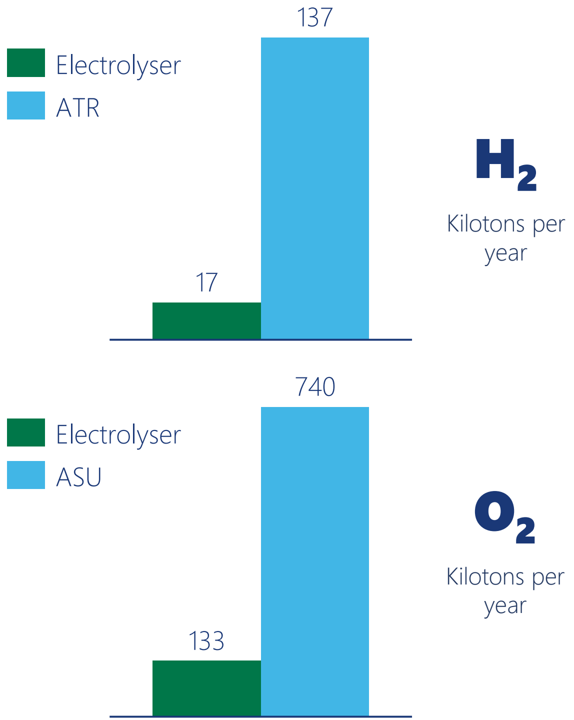


Figure 4.2.2. Distribution of oxygen production from ASU and electrolyzer

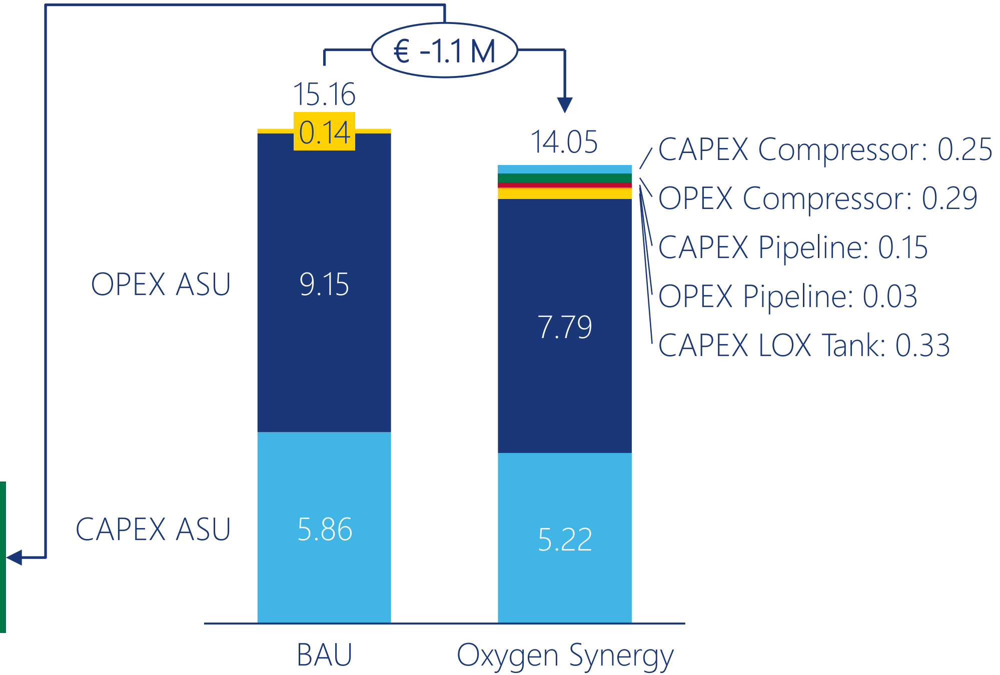


Case 2 results in both ASU CAPEX and OPEX savings, and some additional CAPEX and OPEX components

- Case 2 results in yearly total savings of € 1.1 million.
- The primary driver of this saving remains the reduction in ASU energy consumption of € 1.4 million (OPEX), which has been made possible by the electrolyzer providing oxygen to the ATR. The secondary driver is a reduction in ASU size. A bigger LOX storage tank is used to buffer oxygen to match peak O_2-demand, otherwise supplied by a larger ASU. The ASU's size is 11% smaller compared to BAU, and results in yearly savings of € 0.6 million.
- Similar to case 1 a number of cost elements are added, namely a compressor and pipeline to get the oxygen from the electrolyzer site to the ATR site at the required operating pressure. These extra costs amount to € 0.7 million per year.
- The LOX tank, which is also present in the BAU scenario, is significantly larger in the oxygen synergy case. The tank's yearly CAPEX is approximately 136% larger to buffer oxygen when there is too much production, and to provide oxygen when there is too little production (i.e. Dunkelflaute).

The yearly saving of € 1.1 million is allocated to the production of green hydrogen. Divided by the amount of green hydrogen produced (17 kilotons), the saving is € 0,07 per kg of H_2.

Figure 4.2.3. Yearly CAPEX and OPEX for green hydrogen production from electrolysis with or without the "hydrogen accelerator" (€ million).

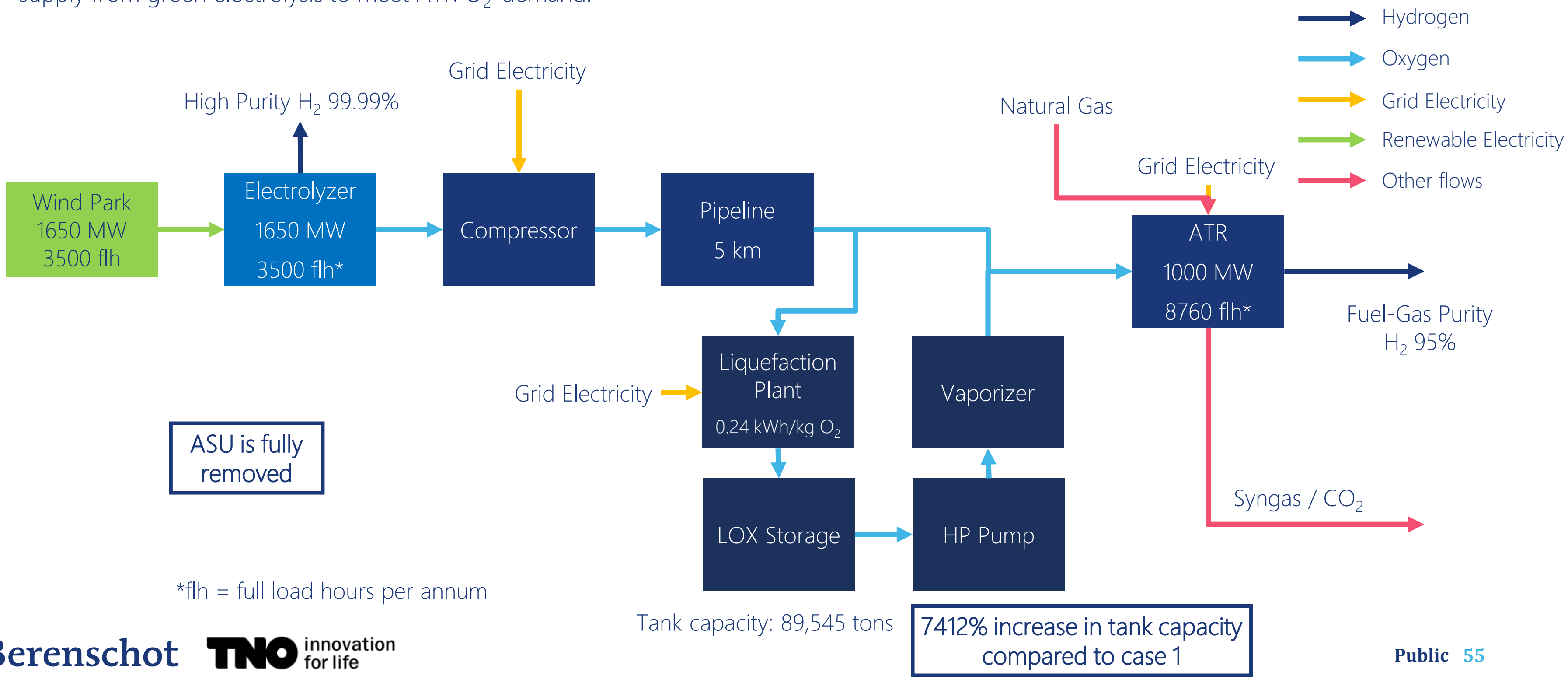


Case 3 – 1650 MW Electrolyzer and LOX storage

- *Case 3 considers a greenfield situation, where a new 1650 MW green hydrogen site (Electrolyzer) and a new 1000 MW blue hydrogen site (Autothermal Reformer) are built. This situation occurs when the energy transition is fully underway, with significant green and blue hydrogen production capacity installed. Similar to case 2 the two sites are engineered from scratch, which allows a significant adaptation in the technical configuration. The electrolyzer is now able to fully cover the oxygen demand from the autothermal reformer, which means the ASU becomes obsolete. To mitigate the intermittency of green hydrogen production, a liquefaction plant and a large liquid oxygen tank are installed.*
- *Case 3 results in the complete elimination of the ASU, but requires a considerable investment in a liquefaction plant and liquid oxygen tank.*

Case 3 - Eliminating the ASU by sizing the electrolyzer to meet the full amount of ATR O_2-demand

- This process scheme is implemented to model case 3 of the "hydrogen accelerator". In this case the ASU is eliminated, and the O_2-demand is met by increasing the electrolyzer capacity. A liquefaction plant and LOX storage tank is used to buffer O_2, and will supply oxygen when there is little supply from green electrolysis to meet ATR O_2-demand.



*flh = full load hours per annum

In case 3 the electrolyzer provides all of the ATR's required oxygen input

- In case 3 the electrolyzer (1650 MW) is sized to meet all the oxygen demand from the ATR (1000 MW). This is reflected in figure 4.2.2, where 100% of the oxygen demand is supplied by the electrolyzer. The ASU is completely eliminated, which saves significant amounts of ASU CAPEX & OPEX. To compensate for the intermittent nature of green oxygen supply, a liquefaction plant and LOX storage tank is added to the system configuration.
- The electrolyzer is now significantly larger, 1650 MW, compared to case 1 and 2, 250 MW. Therefore, the share of hydrogen production compared to the ATR is much larger, namely 44%, see figure 4.3.1.
- The total amount of hydrogen produced is 247 kilotons per year, which roughly 35 PJ (based on a HHV of 39.4 kWh/kg).
- Electrolyzer full load hours: 3500.

Figure 4.3.1. Distribution of hydrogen production from ATR and electrolyzer

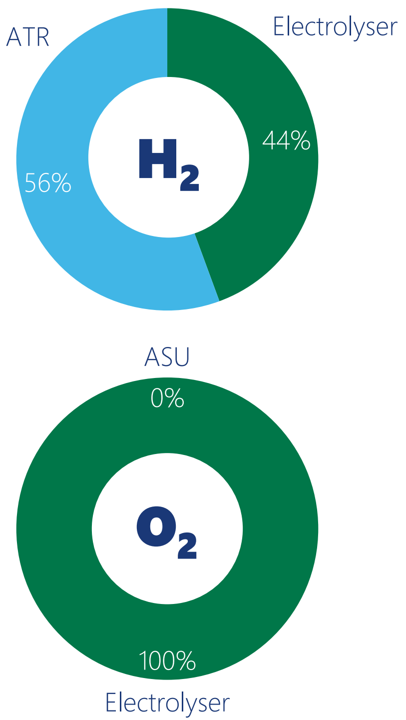
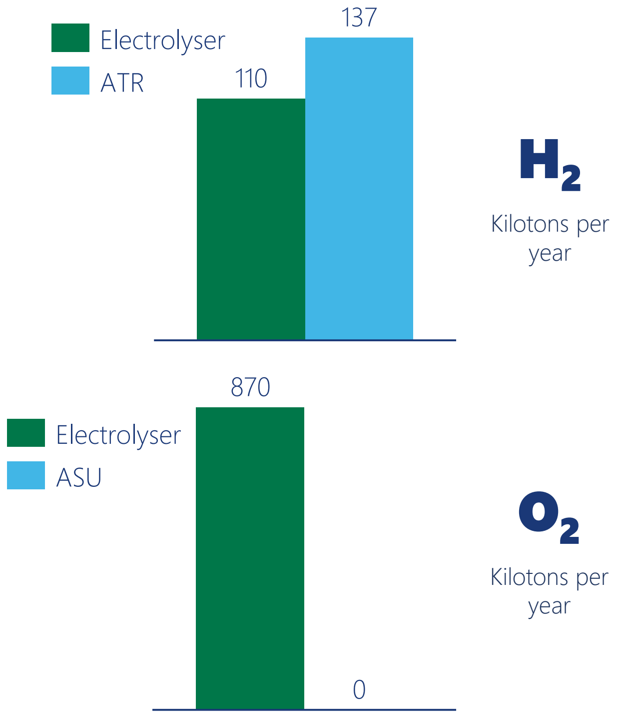


Figure 4.3.2. Distribution of oxygen production from ASU and electrolyzer

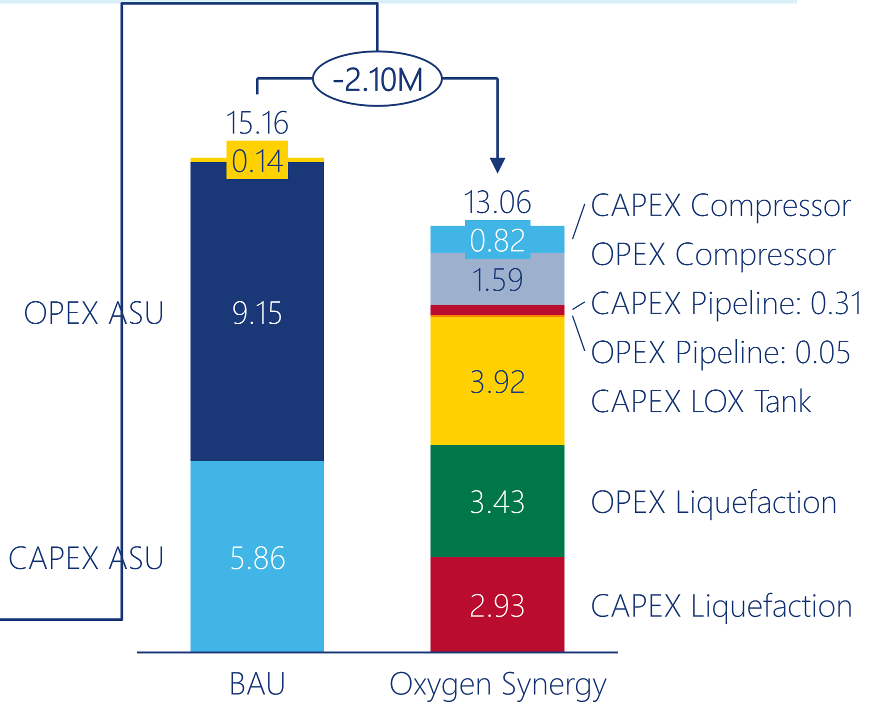


Case 3 results in the complete removal of the ASU, and adds significant CAPEX and OPEX components to create system flexibility

- Case 3 results in yearly total savings of € 2.1 million.
- The main driver of this saving is the complete removal of the ASU, and thereby saving € 9.2 million in OPEX and € 5.9 million in CAPEX.
- In case 3 all the oxygen is produced by the electrolyzer, which is powered by a wind park. Since the wind park is intermittent, gaseous oxygen from the electrolyzer needs to be buffered in a tank. The gaseous oxygen needs to be liquefied if there is overproduction of green oxygen. The liquefaction process adds approximately € 3.4 million in OPEX and € 2.9 million in CAPEX.
- Similar to case 1 and 2 a number of cost elements are added, namely a compressor and pipeline to get the oxygen from the electrolyzer site to the ATR site at the required operating pressure. These extra costs amount to € 2.8 million per year.
- The LOX tank, which is also present in the non-synergy case, is significantly larger in the synergy case. The tank's yearly CAPEX is approximately 2700% larger to buffer oxygen when there is too much production, and to provide oxygen when there is too little production (i.e. Dunkelflaute).

The yearly saving of € 2,1 million is allocated to the production of **green** hydrogen. Divided by the amount of **green** hydrogen produced (110 kilotons), the saving is € 0,02 per kg of H_2.

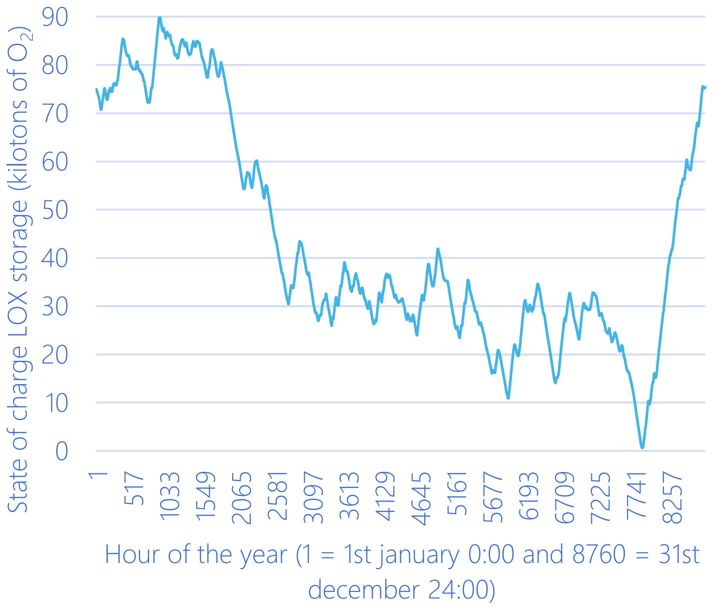
Figure 4.3.3. Yearly CAPEX and OPEX for green hydrogen production from electrolysis with or without the "hydrogen accelerator" (€ million).



Storage profile

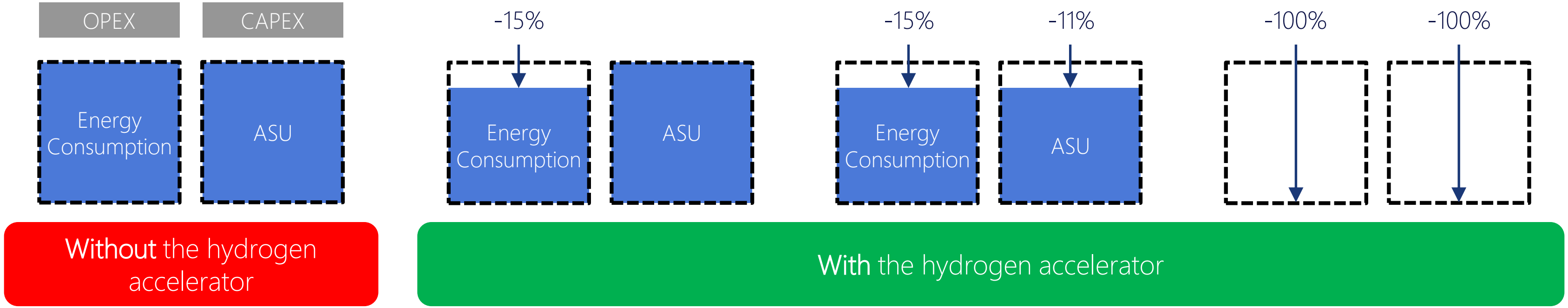
- The use of a wind park to supply green electricity also has implications for the storage requirement, which is a significant cost component in case 3, as we have seen in the slides above.
- Figure 4.2.4 shows the yearly storage profile for case 3 and essentially reflects load profile of the wind park. The storage profile shows that during winter oxygen is added to the LOX tank, and that during summer oxygen is drawn from the tank. The wind blows harder and more often during winter compared to summer. Connecting the electrolyzer to solar and/or grid electricity, reduces the need for storage, because the energy supply is more diversified.
- The storage factor is defined as followed: total LOX volume that travels through the tank/LOX tank capacity. The total LOX volume that travels through the tank equals the amount of oxygen that comes into the tank (=input). The input is the same as the amount of oxygen that leaves the tank (=output). In case 3 the storage factor is 3.6, which is relatively low. The tank can provide storage for 100 days. Tanks usually have a lot less provision in terms of days. To improve the business case for LOX storage, a much higher storage factor is necessary. This can be done by connecting the electrolyzer to solar and/or grid electricity.

Figure 4.3.4. Yearly storage profile



Comparison of 3 cases

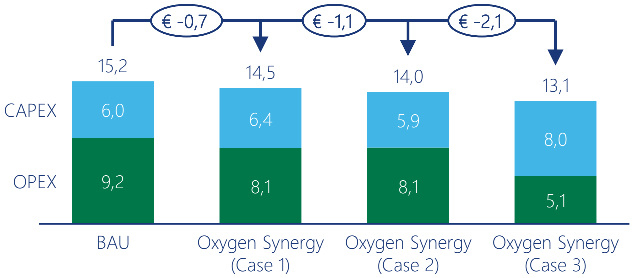
Three cases based on savings in ASU size (CAPEX) and energy consumption (OPEX)



- *Reference ASU size and energy consumption*
- *Case 1: 250 MW Electrolyzer*
- *Case 2: 250 MW Electrolyzer and LOX storage*
- *Case 3: 1650 MW Electrolyzer and LOX storage*

- Removing the ASU is financially the most attractive option, followed by downsizing the ASU and reducing the load hours (i.e energy consumption).
- Case 3 results in the highest (possible) financial savings, because there is no ASU necessary in this case. However, this case is somewhat uncertain. The economics currently show that blue hydrogen is significantly cheaper than green hydrogen. This is why most hydrogen outlooks expect blue hydrogen production to be ramped up quicker than green hydrogen. In case 3 we assume the ATR is 1 GW and the electrolyzer is 1.6 GW, which recalling the ramp-up rate seems like an illogical ratio.
- Case 2 outperforms case 1, because of the additional reduction in ASU CAPEX.

Figure 4.4.1. Comparison of yearly CAPEX and OPEX for the 3 different cases.*



*with fixed electricity prices

Correcting the total yearly savings in each case by the green hydrogen produced, gives us an idea of the savings per kg of H_2 produced

- Figure 4.4.2 shows yearly CAPEX and OPEX savings compared to BAU, which are corrected for the amount of green hydrogen that is produced by the electrolyzer. In case 1 and 2 the electrolyzer is 250 MW, with a corresponding amount of green hydrogen production. In case 3 the electrolyzer is 1650 MW, resulting in a significant increase in the amount of green hydrogen produced. The correction is performed to put the savings of each case into perspective, based on the amount of green hydrogen produced.
- The best performer in this analysis is case 2, with savings of € 0.07 per kg of green H_2. In case 2 yearly CAPEX and OPEX for the green hydrogen site, i.e. electrolyzer and wind park, are € 73 million per year. Dividing the yearly synergy related savings by the total yearly CAPEX and OPEX for the green hydrogen site results in a saving of 1.5%.
- The significant step change in oxygen production in case 3 results in a low amount of corrected savings, € 0.02 per kg of H_2. We can observe that although the absolute savings in case 3 are the highest, the relative savings are the lowest.
- Finally, we calculate the CO_2 abatement cost by dividing the yearly savings by the avoided CO_2 emissions. Case 2 clearly outperforms the other two cases.

Figure 4.4.2. Yearly total CAPEX and OPEX savings corrected by the amount of green hydrogen production (€ / kg of H_2).*

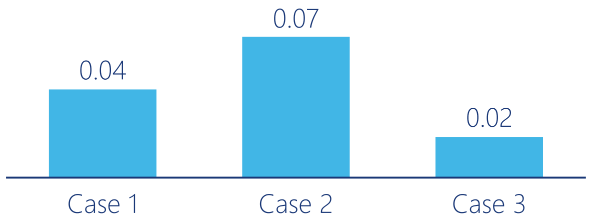


Figure 4.4.3. CO_2 abatement costs (€ / ton of CO_2).*

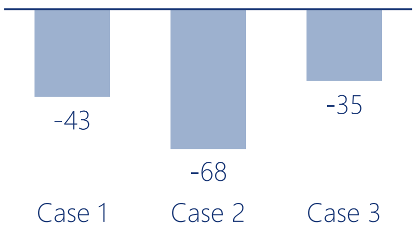
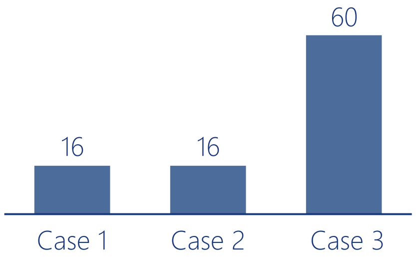


Figure 4.4.4. Absolute CO_2 avoided (kilotons CO_2).



*with fixed electricity prices

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5 Demonstration program

Chapter 5: Demonstration program

Chapter 2
Role of hydrogen
→
Chapter 3
Components for oxygen synergy
→
Chapter 4
Cases: oxygen synergy applied
→
Chapter 5
Demonstration program
→
Chapter 6
Institutional framework
→
Chapter 7
Conclusions and spin-off

Research objectives:

- Identify first demonstration case to put oxygen synergy in practice.
- Identify points of attention for such a demonstration case.

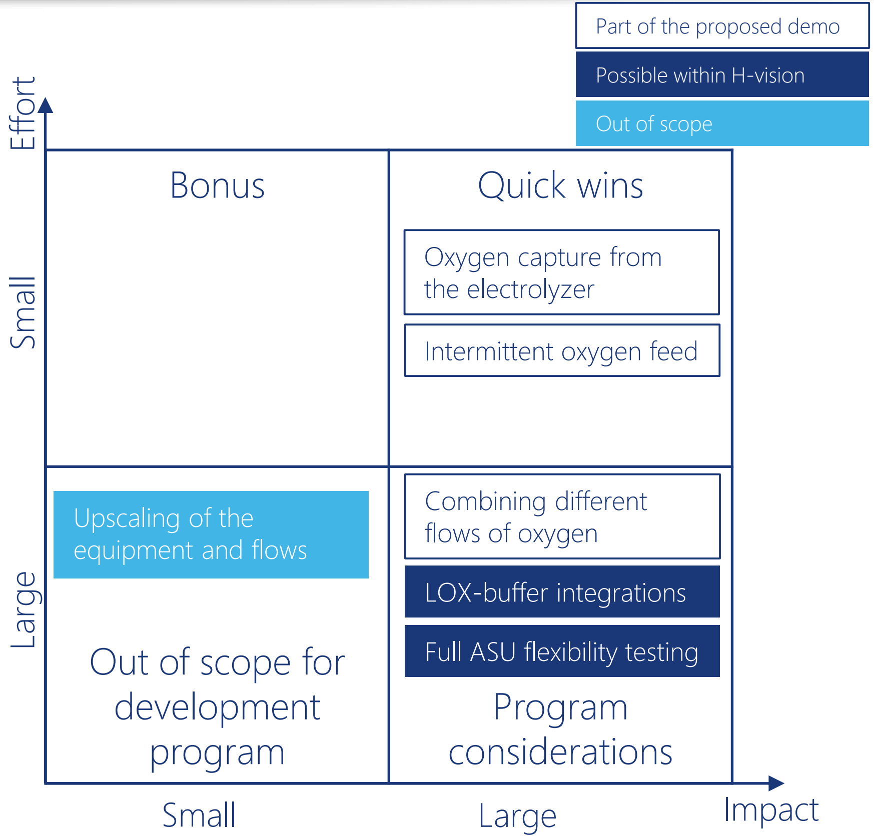
Main conclusions:

- A demonstration project was identified for oxygen synergy, where an intermittent flow of oxygen from an electrolyzer is integrated within an existing industrial process.
- The demonstration of large LOX-buffers combined with the flexible operation of an ASU would need to be addressed within other demonstration projects.

Oxygen synergy can be demonstrated in different processes: the proposed demo case and within H-vision

All sub-components for oxygen synergy are available in the market. The integration of these components is where the developmental challenges lie. Oxygen synergy could be integrated into the test-program of H-vision. But oxygen synergy could also be tested in other demos, since oxygen synergy from electrolyzers could be tested within all processes that require oxygen. In the following chapter such a demonstration case is looked at in more detail. It is based on a case that is currently under consideration.

The demonstration case presented in this chapter, focuses on the integration of intermittent oxygen supply by an electrolyzer within an industrial process. This is considered as the most vital part of the demonstration program. Thorough testing is necessary to make this an accepted industrial application. Out of scope for this demonstration case are the large LOX-buffers and the flexible operation of an ASU. These parts could be tested in projects like H-vision where an ASU is part of the demonstration facility. Also larger LOX buffers could be integrated within such a project.



Demonstration project for O_2 integration

- A possible demonstration case for the O_2 integration concept was found* in the Rotterdam industrial harbor, connecting two industrial companies:
  - Company A generates power on site and is currently evaluating the opportunity to convert part of this electricity into hydrogen via electrolysis.

    There is ample demand for H_2 from nearby industrial sites, in addition to the possibility of distributing the H_2 to refueling stations in the future for mobility.
  - Company B is located in the vicinity of company A, and uses pure O_2 in its production process. This company currently imports high-purity O_2, produced by a nearby cryogenic air separation unit, by pipeline. Their annual demand for O_2 could absorb co-produced O_2 from a 50 MW electrolyzer plant (rough estimate, assuming 6000 full-load hours).

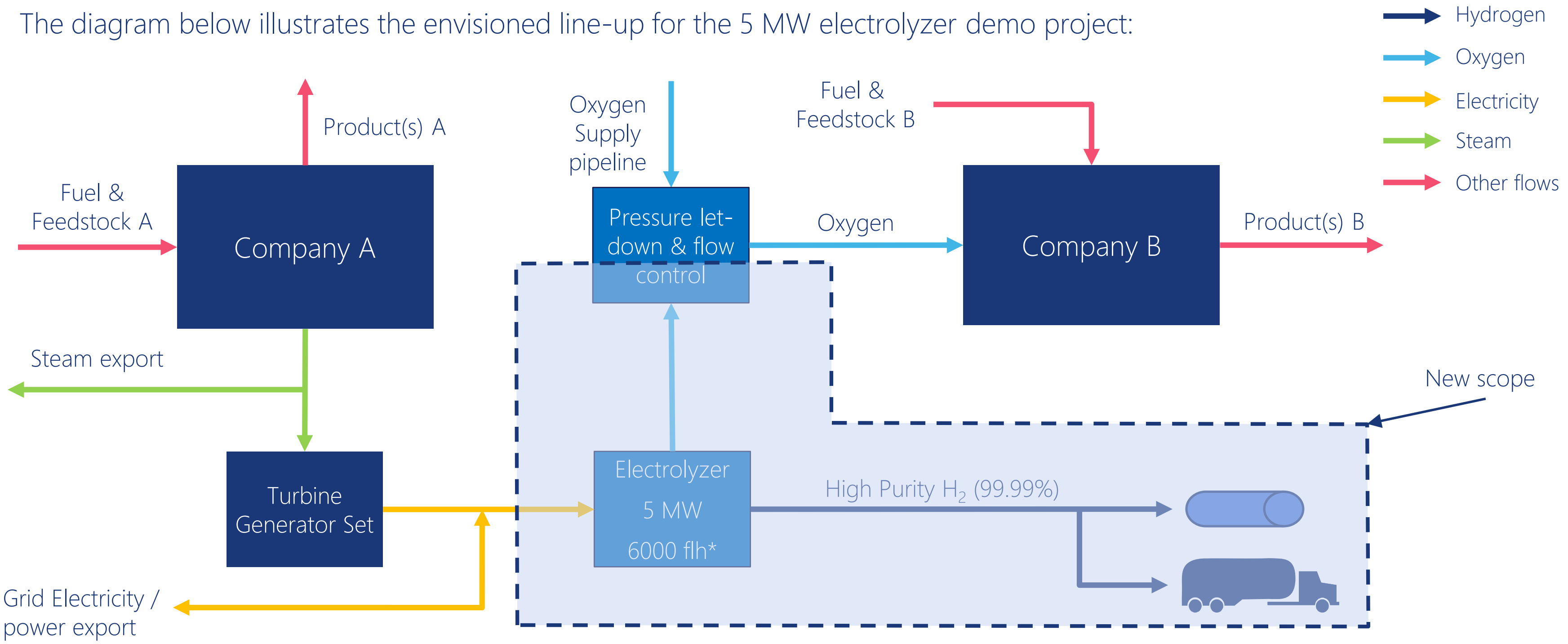
- To demonstrate the concept, a demo project is proposed to build and operate a flexible 5MW electrolyzer unit.
- Several possible outlets will be evaluated for the H_2 product. Co-produced O_2 from this unit will be supplied to Company B and integrated within the existing O_2 supply system.

* Together with Deltalinqs and two industrial partners, TNO identified the opportunity and submitted a project proposal to evaluate the integration of their existing processes, making use of O_2 co-produced by electrolysis.

The proposal was approved, work started in November 2019 and the study will run until May 2020.

Demonstration project: proposal

- The diagram below illustrates the envisioned line-up for the 5 MW electrolyzer demo project:



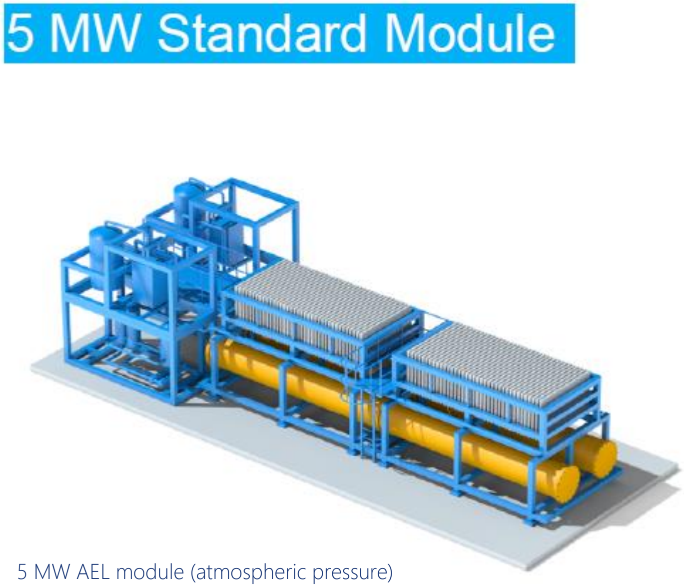
*flh = full load hours (per annum)

H_2 can be delivered to customers by pipeline or truck tanker

Demonstration project for O_2 integration

- Several electrolyzer technology suppliers have developed standard designs for 5MW (power input) systems and it is expected that the demo project will be based on one of these already available solutions.

- Objectives of the 5 MW demo project:
  - The primary aim will be to demonstrate that technical issues related to integration and balancing an intermittent supply of O_2 from the electrolyzer can be overcome.
  - The demo project would provide a clear overview of O_2 integration costs at this scale, helping pave the way for future integration concepts for other green H_2 projects.
  - The partners involved will have a much clearer picture of what the envisioned full-scale project entails in terms of technical complexity and costs. There is potential for further expansion beyond the 5MW demonstration scale in the future.



5 MW AEL module (atmospheric pressure)
Source: Thyssenkrupp brochure

Demonstration project for O_2 integration

Technical background and challenges:

- Electrolyzer technology is already available commercially at this scale, from multiple experienced vendors, for both AEL and PEM technologies. As such, there is no technology demonstration scope for the water electrolysis part.
- The largest electrolyzer installed in the Netherlands is the 1.2 MW HyStock unit, a 20 MW plant is currently being designed by Nouryon and several feasibility studies are in progress for larger systems.
- Project examples of dedicated hydrogen production plants:
    - A 6 MW PEM demo system is in operation in Austria at the Voestalpine plant in Linz.
    - A 10 MW PEM system is under construction in Germany at the Rheinland refinery.
    - A 10 MW AEL system is under construction in Japan at Fukushima.
- Oxygen integration itself is a relatively new concept, especially the aspect of combining the steady supply of O_2 by pipeline from an ASU with intermittently available (green) O_2 from an electrolyzer. From our point of view this is the key technological aspect to be demonstrated. Hence, it should be the focus of the test program.

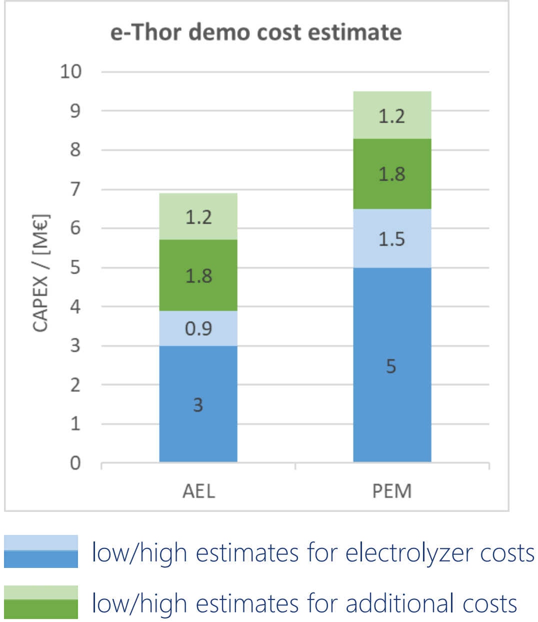
Demo project – preliminary cost estimate

To have a first indication of the costs for such a demo unit, a preliminary (rough order of magnitude) cost estimate was made in this study and summarized in the table below, covering:

- The electrolyzer unit itself, including auxiliary equipment (power supply, water purification, cooling etc.)
- Engineering, commissioning and installation costs + integration costs on site for O_2 transport (assumed equal for AEL & PEM)

	Electrolyzer system ("factory gate" cost)	EPCM, tie-ins, installation & commissioning
Low estimates, [M€]	3.0 + 30%* (AEL)	1.8
High estimates, [M€]	5.0 + 30%* (PEM)	3.0
Pilot CAPEX, [M€]	4.8 (LL) - 9.5 (HH)	

* 30% margin for preliminary cost indications and differences between suppliers



- These estimates **exclude** downstream costs (e.g. H_2 compression or liquefaction for transport using LH_2 tankers), as the intended use is not known at this stage.
- The indicative cost estimate will be revisited and improved as part of the demonstration study, after the conceptual design is defined in more detail.

Demo project – timeline

A preliminary timeline was made based on the following proposed test plan, divided in three main sections:

1. Field acceptance/commissioning tests + operator training
2. Demonstrate safe and reliable operation
3. System flexibility testing and long term monitoring

After technology selection, it can take up to two years or longer to have the demo system up and running. The timeline below gives a preliminary indication of the expected duration for all the phases of the overall demo project:

Phase 1
Scope definition

The exact scope of the demo project will be defined in detail during the demonstration study, covering:

- Electrolyzer technology selection
- Utilization of the H_2 product

4-6 months

Phase 2
Engineering and procurement

- Basic engineering
- Tendering process / ordering long-lead items
- Detailed engineering for site modifications and connections

4-12 months engineering
12-18 months lead time

Phase 3
Operation and testing

- Pre-commissioning and testing
- Installation, commissioning, operator training
- Demonstrate flexible operation of integrated O_2 supply

3-6 months installation and commissioning

4-6 additional months could be required for funding, new contracts, permits etc.

Demo project – test program

The three phases can be broken down further into more specific lists of tasks to be carried out:

1. Field acceptance/commissioning tests + operator training

- These are standard tests, required to verify that equipment installed on site operates in conformity with vendor specifications.
  - H_2 and O_2 leak tightness checks at max operating pressure for the system, downstream equipment and transport pipelines.
  - Demonstrate rated H_2 production at full power load for the electrolyzer.
  - Demonstrate design stack and system efficiency at full load and stable operating conditions .
- The operating envelope of the system should be validated using guarantee points provided by the equipment vendors.

2. Demonstrate safe and reliable operation + operator training

- After commissioning, the unit should be subjected to a rigorous series of tests. These ensure correct functioning of controls and logic blocks, and adequate system responses to emergency situations (as defined by the site owner):
  - Cold start-up testing to verify the full start-up control sequence.
  - Testing to demonstrate rapid & safe shutdown in case of malfunction or emergency scenarios.
  - Hot restart testing (criteria/cut-off conditions for hot restart to be provided by equipment vendors). In case of short duration power interruptions, the system should be able to autonomously perform an automatic hot restart procedure.

Demo project – test program

3. System flexibility testing and long term monitoring

- A key aspect of the demonstration project is to prove that intermittently produced O_2 from an electrolyzer can be supplied to an existing industrial process, without causing undesired process disturbances.
  - Demonstrate electrolyzer system flexibility, i.e. that the entire system adequately responds to demand fluctuation and/or an intermittent power supply profile. Performance at different power loads will be recorded and compared to vendor data.

    KPIs: system response time, stability, ramp-up rate, efficiency curve.
  - The flexibility of the modified O_2 supply control loop also needs to be demonstrated.
- In addition to flexibility testing, other long term monitoring objectives can also be defined for the demonstration project:
  - The overall efficiency will be monitored to track loss of performance due to stack degradation.
  - The decline in stack performance over the cumulative number of run-hours will be evaluated relative to the system baseline.
- Lastly, standard equipment monitoring should also be carried out for the demo unit (these requirements are typically covered by existing procedures of the site owners), such as:
  - Corrosion monitoring program for critical equipment.
  - Rotating equipment monitoring program.

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6 Institutional framework

Chapter 6: Institutional framework

Chapter 2 Role of hydrogen → Chapter 3 Components for oxygen synergy → Chapter 4 Cases: oxygen synergy applied → Chapter 5 Demonstration program → **Chapter 6 Institutional framework** → Chapter 7 Conclusions and spin-off

Research objectives:

- Identify institutional limitations to realize oxygen synergy
- Identify institutional limitations to realize carbon neutral hydrogen production

Main conclusions:

- Oxygen is a well-known industrial gas, which is handled in large scale at this moment. Therefore, no institutions are limiting oxygen synergy.
- The production of carbon neutral hydrogen is new, and therefore ample limitations exist. The government plays an important role in the adoption of hydrogen economy. It should fulfill four different roles in the adoption of hydrogen as an energy carrier.

There are no stringent institutional limitations for oxygen synergy, other barriers do exist

There are no institutional limitations for oxygen synergy or the use and storage of oxygen in general.

Although permits and safety requirements have to be met according to legislation (for example the REACH regulation), there are no show stoppers for oxygen synergy.

- Oxygen can be transported through pipelines.
- Oxygen can be stored on location.
- Venting is currently common practice for electrolyzers, the concentration of oxygen is kept low by mixing with air.

Oxygen synergy leads to a complex project

Since it couples renewable electricity production, electrolyzers and an oxygen requiring process. In the case of the hydrogen accelerator, the investments double compared to just a blue hydrogen project (see slide 42). Reaching an agreement for the exchange of oxygen can be challenging, if the project is a collaboration between several parties.

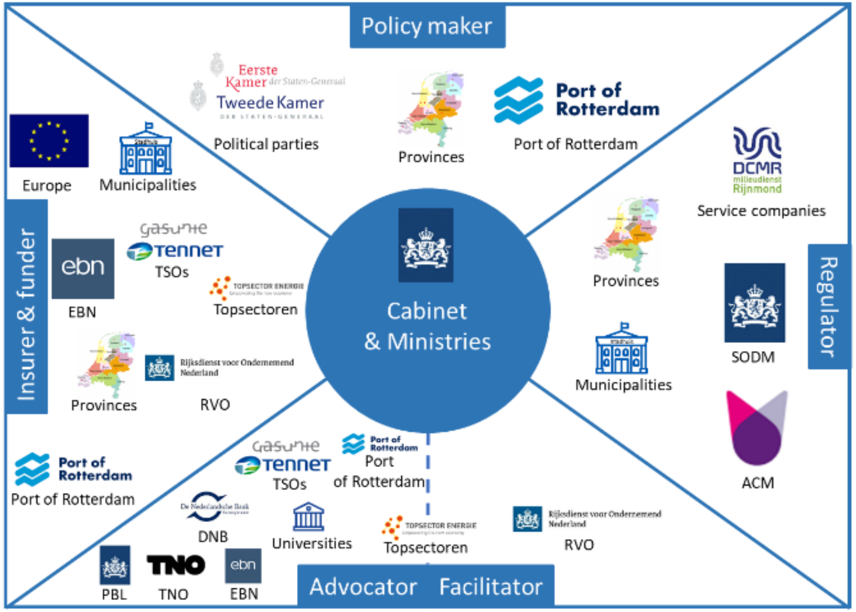
Furthermore the hydrogen accelerator currently is in a situation where it has to compete with the simplicity of the planned ASU. The ASU is normally designed to fit a new plant, therefore the hydrogen accelerator has to be considered at the start of a project.

The government has four vital roles in the hydrogen economy

Governmental organizations can play four roles in the adoption of hydrogen as an energy carrier

- Policy maker: as was stated in H-vision, there is not a dedicated policy for hydrogen. One of the solutions posed is to include hydrogen in the Dutch Gas Act, in order to regulate third party access to hydrogen infrastructure against reasonable terms and conditions.
- Regulator: these policies should be transformed in regulations, guidelines, boundary conditions and licensing and permit systems in order to be able to enforce the policies
- Advocator and facilitator: the government can also enable better uptake of the hydrogen economy by connecting parties, providing information and enabling societal support.
- Insurer and funder: the governmental role as insurer and funder of projects within the energy transition by subsidies, contracts of difference, shareholder/partner and loans. One of the main instruments in this category is the SDE+ and the future SDE++. These are discussed on slide 78.

Governmental organizations and their roles



Source: Adapted from H-vision

The governmental role as advocator and facilitator

The governmental role as advocator and facilitator

- Several parts of the government are involved in hydrogen. Investigative research and development is for example carried on and commissioned by the Topsectoren/RVO, EBN, Gasunie, Tennet and universities.
- Some examples of the role of advocator and facilitator:
  - Topsector Energie is developing a "programmatic approach to hydrogen";
  - Gasunie is investing in a pilot project called HyStock a power to gas and hydrogen storage facility in the North of the Netherlands;
  - Port of Rotterdam and the Port of Amsterdam are looking at green hydrogen plants in collaboration with other parties.

The governmental role as policy maker

- Currently, there is not yet a dedicated policy for hydrogen. One of the solutions posed in H-vision is to include hydrogen in the Dutch Gas Act. This would regulate third party access to hydrogen infrastructure, against reasonable terms and conditions. Furthermore, it could regulate standards for hydrogen quality and socialization of infrastructure costs over the end-users.
- An European Hydrogen strategy is a priority for the new European Commission, but common standards, guarantees of origin and market regulations are not yet in place.[1]

The governmental role as regulator

Regulation of hydrogen is clear in some cases and unclear in others:

- Regulation of storage of hydrogen and storage of CO2 is the responsibility of SodM, as is high pressure transport of hydrogen[2]
- Safe industrial use of hydrogen is regulated by the Dutch "Inspectie SZW" and by the European "Echa".
- Conditions on usage, safety and market conditions for "domestic use" are not yet transformed in regulations (see governmental role as policy maker). If this would be incorporated in the Dutch Gas Act, ACM would be responsible for regulation of the hydrogen market.

1. Hydrogen market in the Netherlands, Hydrogen Envoy The Netherlands, 2019
2. SODM.nl and https://magazines.sodm.nl/jaarplan-sodm/2019/01/netbeheer

The governmental role as insurer and funder is essential in order to meet the ambitions for hydrogen

The governmental role as insurer and funder

Currently, the main energy transition subsidy does not accommodate for many hydrogen projects:

- The SDE+ is currently the main subsidy for projects within the energy transition. In the latest subsidy round € 5 billion is available for projects that produce renewable energy.[1] The SDE+ will be followed up by the SDE++ in 2020, where the project base will expand to projects that reduce CO_2 emissions and subsidies will be based on the non-economically viable part of these projects. PBL (Planbureau voor de Leefomgeving) calculates the amount of subsidy that is available for different types of projects.
- PBL recently calculated electrolyzers are not reducing CO_2 emissions, because of preconditions set by the ministry of EZK. The main condition is 8000 full load hours and grid electricity with high CO_2 emissions. Therefore electrolyzers are considered to emit even more CO_2 than current grey hydrogen production.[2]
- Therefore it looks as if electrolyzers will not be eligible for the SDE++.
- The H-vision parties state that the subsidy for blue hydrogen project in the SDE++ will be too low as well to make the H-vision project feasible. The reason being that PBL has calculated the subsidy for blue hydrogen projects with steam methane reforming in mind and with use of the hydrogen as feedstock.[3]
- The SDE++ subsidy could be a welcome stimulus for hydrogen projects, currently it seems that the ambitions for hydrogen projects are not directly met by this subsidy.

1. https://www.rvo.nl/subsidies-regelingen/stimulering-duurzame-energieproductie
2. https://energeia.nl/energeia-artikel/40084218/industrie-vreest-streep-door-waterstofambities-klimaatakkoord
3. https://energeia.nl/energeia-artikel/40084320/waterstofproject-met-ccs-in-de-knel-bij-nieuwe-opzet-sde

For hydrogen the government acts as advocator and facilitator, but its other roles are still under development

The Dutch government in all its facets, plays an instrumental role for the development of a hydrogen economy in the Netherlands.

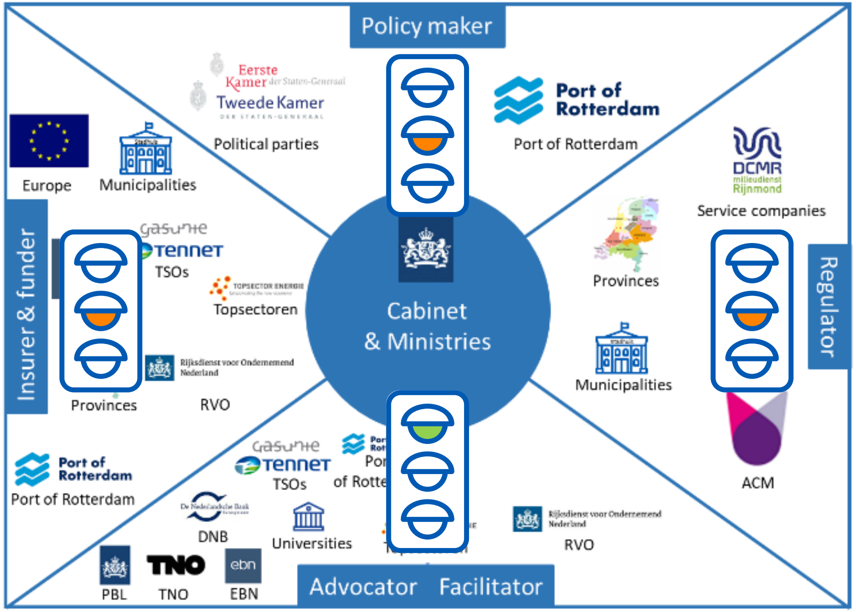
In the institutional framework, the government acts as advocator and facilitator of hydrogen via development and research projects initiated and performed by a variety of governmental organizations.

However, for hydrogen to come out of the experimental and developmental phase as an energy carrier, focus should also be given on the other roles of government in the institutional framework.

Clear policy making will pave the way for easier use of hydrogen by interested parties. This would also structure the role as regulator.

Limitations still lie in getting an economically viable hydrogen project. Realizing stand-alone economically viable CO_2-neutral hydrogen projects is still a distant reality. Making better use of the role as insurer and funder could help parties adopt hydrogen today.

The fulfillment of the governmental roles for the use of hydrogen as an energy carrier



Source: Adapted from H-vision

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7 Conclusions and spin-off

Chapter 7: Conclusions and spin-off

Chapter 2	Chapter 3	Chapter 4	Chapter 5	Chapter 6	Chapter 7
Role of hydrogen	Components for oxygen synergy	Cases: oxygen synergy applied	Demonstration program	Institutional framework	Conclusions and spin-off

Main conclusions:

- Oxygen synergy leads to a reduced CO_2 footprint and costs and therefore deserves to be taken into account in hydrogen projects.
- Hydrogen initiatives can apply oxygen synergy together with other parties; focusing on the flexible integration of oxygen flows.
- Oxygen synergy contributes to the adoption of green hydrogen, but the upsides are insufficient to be the big breakthrough technology.

Discussion

Oxygen synergy is a way to use the now untapped flow of oxygen from electrolyzers. However, this research has also led us to some points of discussion for oxygen synergy:

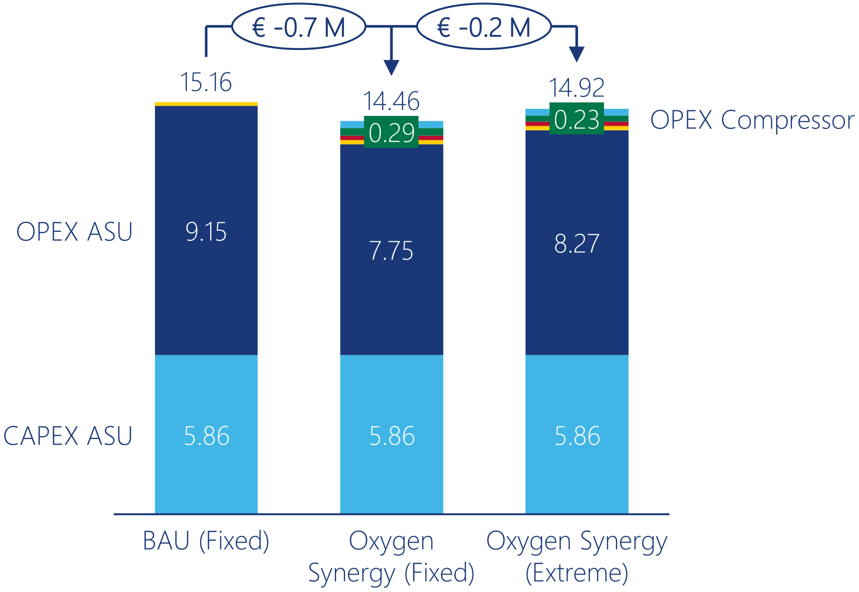
- Variable electricity prices
- Different oxygen synergies
- Transporting oxygen
- Seasonality and storage

These points will be discussed below.

Discussion: a variable electricity price correlated with low prices for the electrolyzer has negative impact on case 1, but positive impact on case 2 and 3

- In the future electricity prices could show more variation, for example when there is a lot of wind energy, electricity prices could come down and vice versa. What effect does this have on the cases?
- We have recalculated case 1 using the average electricity price of the 3500 cheapest hours for the oxygen compressor and the average electricity price of the 5260 most expensive hours for the ASU. This is an extreme situation, because the correlation of price and wind power production is unlikely to be this strong.
- The impact is different for each case:
  - Case 1: negative impact; since the ASU runs at lower capacity when electricity prices are low; therefore the savings are lower (see figure 7.1). The OPEX of the ASU is higher compared to the fixed case and the OPEX of the oxygen compressor (green) becomes smaller.
  - Case 2: small positive impact; since the ASU runs year round and flexibility of the oxygen supply comes from a larger LOX-tank the OPEX of the ASU will not be affected, the compressor will benefit from lower electricity prices.
  - Case 3: positive impact; since the liquefaction plant will run at hours where electricity price are low, the total OPEX will be lower.

Figure 7.1. Yearly CAPEX and OPEX for green hydrogen production from electrolysis under various electricity prices (€ million).



Discussion: variable electricity prices (2), other oxygen synergies, transporting oxygen and seasonality and storage

Variable electricity prices (2)

- Electrolyzers could also be operated via the electricity grid, with which they can choose a certain threshold price point. This could lead to the same effects as we have seen above. However DNV GL and TNO estimated that until 2040 the minimal cost for hydrogen production lies above 6000 full load hours.[1] This would dampen the effect of variable electricity prices on the business cases. On the other hand, far more oxygen would be produced and this would lead to the possibility of using even smaller ASUs.

Oxygen synergy in general

- In this study we have focused on the use of oxygen in blue hydrogen production. In the proposed demo case we have shown that oxygen synergy could also be used in different industrial processes that require oxygen. Other uses for oxygen such as in making steel, as oxyfuel or in other industrial processes are all possible and should be considered.

Transporting oxygen

- Pipelines are the best choice of transporting oxygen, however long pipelines have a detrimental effect on the business case of oxygen synergy. Therefore, the electrolyzer should be placed as close as possible to the oxygen consumer. Another possibility exists if the industrial gas suppliers also produce oxygen with electrolyzers and feed that into their existing pipelines. This will make the total oxygen production more sustainable.

Seasonality and storage

- In order to make most of oxygen synergy a large buffer tank is needed in order to overcome the seasonality of renewable electricity supply. Typically liquid oxygen is stored, however if gaseous oxygen could be stored effectively the energy consumption for liquefaction could also be saved. When storing gaseous oxygen the large volumes should be taken into account as well as the reactive nature of oxygen.

1. Technologiebeoordeling van groene waterstofproductie, DNV GL, 2018

Oxygen synergy leads to a reduced CO_2 footprint and costs and therefore deserves to be taken into account in hydrogen projects

Green hydrogen is produced by splitting water molecules in hydrogen and oxygen, using surplus renewable electricity. Therefore, oxygen is a byproduct of this process. This project researched the economic potential of using this in the production of blue hydrogen, in order to further decarbonize this process.

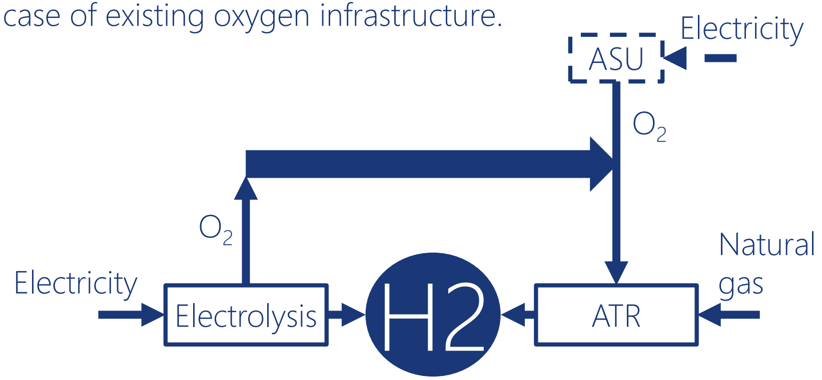
The effects were studied by comparing the execution of both a green and blue hydrogen project with and without oxygen synergy. Overall, the use of oxygen was found to be a cost-effective decarbonization measure. This result is found in multiple cases, differing in both scale and market conditions.

Market condition	Capacity green hydrogen	Payback period	Added cost (- is a saving)*
Retrofit	250 MW	8.6 years	-0.7 M€/year
Greenfield	250 MW	-0.3 years	-1.1 M€/year
Greenfield	1650 MW	13.8 years	-2.1 M€/year

*with fixed electricity prices

The following observations were made:

- In all cases, less grid electricity was needed to produce oxygen. This leads to both a reduction in carbon emissions and costs.
- A greenfield situation has an additional advantage. The size of the Air Separation Unit (ASU) can be reduced. This leads to an even better financial result.
- The cost-effectiveness is dependent on the distance between supply and demand of oxygen. Project revenues are witnessed up-to a distance of 25 km. Therefore, a synergy is especially interesting within large industrial clusters and in case of existing oxygen infrastructure.



Hydrogen initiatives can apply oxygen synergy together with other parties; focusing on the flexible integration of oxygen flows

Oxygen is a well-known industrial gas, and therefore institutions do not limit the application of oxygen synergy. Initiatives involving the production of green hydrogen can directly apply this synergy. Among others, this project could be of interest of the following initiatives:

- Initiatives of large industrials: BP, TATA Steel, RWE, Innogy and Nouryon announced large green hydrogen projects lately.
- H-vision: development of a blue hydrogen plant in the Rotterdam harbor area with a large demand for oxygen.
- Magnum power plant: development of a hydrogen power plant in the Groningen area with blue hydrogen from Norway.
- The GW-project: focuses on developing a GW-size electrolyzer in the large industrial clusters in the Netherlands.

Though, applicability does not equal simplicity. Realizing oxygen synergy demands collaboration between different industries within one project. Mutual trust and coordination is key in projects involving industrial symbiosis.

A demonstration and test program is developed in order to test the integration of an intermittent flow of oxygen from an electrolyzer within an industrial process. The following is key in developing such projects:

1. Field acceptance/commissioning tests + operator training
2. Demonstrate safe and reliable operation
3. System flexibility testing and long term monitoring

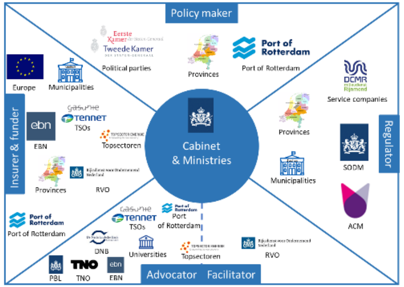
Other demonstration projects could focus on integration of a large LOX buffer storage facility and/or the flexible operation of a modified ASU.

Oxygen synergy contributes to the adoption of green hydrogen, but the upsides are insufficient to be a breakthrough technology

The adoption of green hydrogen is limited by high production costs at this moment. The production costs of green hydrogen is 5-6 €/kg (equivalent to 8-9 times the natural gas price). For example, this leads to significantly higher costs than estimated production costs of grey hydrogen (~1.1 €/kg), blue hydrogen (1.5 €/kg) and natural gas. At this point, green hydrogen is only possible if it is subsidized substantially: comparison between natural gas and green hydrogen leads to abatement costs of 543 - 668 €/ton CO_2.

Oxygen synergy is cost-effective, but only accounts for a modest cost reduction per kilogram of green hydrogen.

A coherent stimulation program is required to kick-start the hydrogen economy. The government should take an active role. The H-vision project suggested four roles the government could take to stimulate hydrogen. Recent discussions concerning the SDE+/SDE++ subsidies indicate the urgency to do so.



Market condition	Capacity green hydrogen	Effect on CAPEX (+ is a cost, - saving)	Effect on OPEX (- is a saving)	Effect on price green hydrogen	Abatement costs
Retrofit	250 MW	6.0 M€ & 0.4 M€/year	-1.1 M€/year	€ -0.04	-43 €/tonCO_2
Greenfield	250 MW	-0.3 M€ & -0.1 M€/year	-1.0 M€/year	€ -0.07	-68 €/tonCO_2
Greenfield	1650 MW	28.9 M€ & 2.0 M€/year	-4.1 M€/year	€ -0.02	-35 €/tonCO_2

*with fixed electricity prices

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Appendix

Appendix

A Model assumptions per technology component

B Project execution

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A Model assumptions per technology component

Model assumptions per technology component

Wind Farm		
Item	Sub-Item	Value
Lifetime		20 years
O&M costs	Maintenance costs	6.00 €/MWh
	Infrastructure	0.56 €/MWh
Investment costs	Turbine	1112 €/kW
	Foundation	90 €/kW
	One-time connection fee	Depends on the installed capacity (€ 31,000 - € 240,000)
	Cable costs	Depends on the installed capacity (95 €/m – 150 €/m)
Insurance		0.5 €/MWh

Model assumptions per technology component

Green Hydrogen Production: Electrolysis

Item	Value
Lifetime	25 years
O&M costs	1.5% of investment costs
Investment costs	1150 €/kW* (alkaline electrolyzer)
Replacement costs cell stacks	30% of investment costs
Insurance	0.5% of investment costs
Energetic efficiency (based on HHV of hydrogen)	76%

* This is a somewhat conservative estimate (compared to recent publications and electrolyzer cost forecasts). This value represents full system costs, including engineering, installation etc. This is why the stack replacement cost is a smaller percentage than what is typically indicated (i.e. as a percentage relative to system costs, excluding installation).

Model assumptions per technology component

Air Separation Unit

Item	Value
Lifetime	25 years
Investment costs	832 €/(kg of O_2/h)
Specific energy (including compression)	0.24 kWh/kg O_2

Compressor

Lifetime	25 years
Investment costs	250 MW case: € 3,500,000 1650 MW case: € 11,600,000
O&M costs	2.75% of investment costs
Specific compression energy	0.033 MWh/t of O_2

Model assumptions per technology component

Pipeline

Item	Value
Lifetime	40 years
Investment costs	250 MW case: 500,000 €/km 1650 MW case: 1,080,000 €/km
O&M costs	1% of investment costs

Liquid Oxygen Storage Tank

Item	Value
Tank size	= Difference between the maximum state of charge (SOC) and the minimum SOC
Lifetime	25 years
Investment costs	X €/ton of O_2 • X is extracted from a function, where the input is the tank size • X = 188,207 * (Tank size)^(-2/3) • Valid between a tank size of 0 – 7,417 tons • If more than 1 tank is necessary, a CAPEX multiplication factor of 1.25 is applied, to correct for extra interconnecting lines, the larger required plot space and the higher project complexity of using multiple tanks

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B

Project execution

Project execution and dissemination

Project execution

The project did not experience major problems and was executed by Berenschot and TNO in close cooperation. Additional to the project proposal, several interviews with industry parties were organized, as well as a workshop with experts from green and blue hydrogen projects.

For the demonstration case we have pursued two different paths. One: defining the set-up of the hydrogen accelerator. Two: defining a demonstration project for oxygen synergy that could be carried out soon.

A first demonstration project was identified, with two industrial parties located next to each other in the Rotterdam area. TNO and Deltalinqs are working together with the two companies to further define the scope and proceed with technology selection.

Due to the early stage of this relevant demonstration case, detailed engineering was therefore not part of the current project.

Budget

The project was performed within budget.

Dissemination

- Dissemination will be done via the website of the parties involved.
- The final report will be made freely and publicly available and will be announced in a press statement.
- Organizations that were involved in the workshop will be emailed directly with the final results of the project.
- Another possibility for dissemination is to present the outcome of our results at an industry conference.

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