

Large scale potential of green H₂ in the Hydrogen Delta

Smart Delta Resources Hydrogen plant study

External report

July 2020



Disclaimer

Introduction

Arthur D. Little was commissioned by the SDR consortium to conduct a study into the system integration of a 1 GW electrolyzer in the SDR region. Arthur D. Little accept no responsibility for information other than that contained in this report.

The conclusions in this report are the results of the exercise of our best professional judgment, based in part upon materials and information provided to us by SDR and their subject matter experts and advisers, and others at the date of writing. Any person seeking to rely on this report should consult with their own professional advisors to provide an opinion as to the appropriateness of the statements and opinions set out in the light of the conditions which operate on the date at which such reliance is to occur and in the light of the Qualifications and Disclaimers set out below.

Qualifications and Disclaimers

The statements and opinions set out in this report are based on economic, market, regulatory, technical and other conditions prevailing at the date of this report. The conditions in the renewable energy space and technologies may change significantly over a period of time.

Arthur D. Little has prepared this report on the basis of information provided to it, which it believes to be reliable, complete and not misleading.

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This document contains the results of the study into a IGW electrolyzer in the SDR region in the period Sept 2019 to May 2020

Project timing & available data

Project timing	Start of project	September 23 rd , 2019
	End of project and report delivery	End of project May, 2020 Final report delivery July 3 rd , 2020
Project duration	Seven months	
Interaction with SDR consortium	<ul style="list-style-type: none"> ■ 5 workshops with SDR Consortium; SDR and ArcelorMittal, Dow, ENGIE, North Sea Port, Ørsted, PZEM, Yara and Zeeland Refinery ■ In-depth interviews and site visits to all Consortium members' facilities as well as many different others (e.g. Gasunie, ISPT, TenneT, Elia, Air Products, Evides, Hydrogen Delta Day) 	
Quality & completeness of data and other observations	<ul style="list-style-type: none"> ■ Arthur D. Little has collected a high quantity of data for this study, which have not been independently assessed for robustness 	

Note to the reader

- Findings in this document are based on:
 1. Interviews with all SDR members and other stakeholders
 2. Independent ADL research, incl. e.g. phone interviews with electrolyzer suppliers
 3. External reports, e.g. CUST study, CE Delft reports
- Zoning and environmental contexts have only been assessed at high level
- Detailed possible construction layouts, including electrical connections and BoP details have been outside the scope of this study
- This project has been facilitated through subsidies from the Province of Zeeland

Glossary

AEL electrolysis	Alkaline (water) Electrolysis
BE	Belgium
Blue hydrogen	Hydrogen produced from fossil sources but capturing and either storing or using the resultant CO ₂
CAGR	Compound Annual Growth Rate
CCU	Carbon Capture & Usage
CCS	Carbon Capture & Storage
Green hydrogen	Hydrogen produced through electrolysis powered by a renewable energy source
Grey hydrogen	Hydrogen produced from fossil sources producing CO ₂ in the process
Hydrogen Backbone	NL-wide network of pipelines, owned and managed by Gasunie, that currently transports gas (CH ₄) and might in future transport H ₂
NL	The Netherlands
Orange hydrogen	Hydrogen produced through electrolysis powered by nuclear energy
Oxyfuel combustion	Oxyfuel combustion is the process of burning a fuel using pure oxygen instead of air as the primary oxidant
PEM electrolysis	Proton Exchange Membrane electrolysis
Salt cavern	Artificial cavity in an underground salt formation, created by the controlled dissolution of rock salt by the injection of water
SDE++	Stimuleringsregeling Duurzame Energietransitie, NL subsidy for stimulating renewable energy, awarded based on avoided CO ₂ emissions
SDR	Smart Delta Resources, a group of thirteen energy- and feedstock companies in South West NL and East Flanders BE searching for a reduction in their use of energy and feedstock through industrial symbiosis
SMR	Steam Methane Reformer
Yellow hydrogen	Hydrogen produced through electrolysis powered by imported green energy

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Executive summary (1/3)



- **Smart Delta Resources** (SDR) is an initiative taken by thirteen energy- and feedstock intensive industrial companies in South West NL and East Flanders BE to investigate significant reductions in their use of energy and feedstocks
- SDR has developed a **roadmap** towards a **CO₂-neutral** industry in their region by 2050. Key to this is the production of **green H₂** (electrolysis powered by CO₂-neutral electricity)¹
- The SDR region is **well positioned** for large scale and fast implementation of electrolyzer-based green H₂ production:
 - Large current **H₂ demand** (~ 400 kt/a) that is forecasted to **double** by **2050** through significant planned green H₂/CCU projects; large scale **O₂ outlet**
 - Proximity to ample **renewable energy** supply (and possibly nuclear energy)
 - Existing gas / 380kV electricity **infrastructure**
 - Excellent opportunities for (connection to) a **H₂ backbone**
 - **Electricity balancing** options in BE/NL
 - Specific **SMR H₂ production** setups allow rapid deployment of electrolyzers

For many of the Consortium members, **lowering CO₂** emissions is **mission critical** for long term survival in the region

1) SDR foresees this to be supported by **blue** H₂ (CCS), **yellow** H₂ (import) and possible **orange** H₂ (nuclear)

Executive summary (2/3)



- Arthur D. Little has evaluated the **system integration** of **GW scale** electrolysis with existing production processes, gas/electric infrastructure (and expected developments) and possible locations in the region in detail, resulting in a **roadmap** to enable an **immediate start** of green H₂ production, starting with two decentralized projects of 100 MW electrolyzers each, building to ~1 GW by 2030 and ~10 GW by 2050:
 - **2022 – 2023** 2X 100 MW **decentralized** electrolyzer plants at Yara/Zeeland Refinery, resulting in **CO₂ reduction of ~140 kt/a**
 - **2024 – 2027** Additional 490 MW **centralized** electrolyzer capacity planned in **Vlissingen-Oost** providing 690 MW total capacity in SDR region, resulting in **CO₂ reduction of ~ 500 kt/a** (4000 load hrs/year; producing 55 kt/a H₂)
 - **2028 – 2030:** After connection to the NL H₂ backbone, electrolyzer capacity can be expanded to **1 GW**, resulting in **CO₂ reduction of ~ 740 kt/a** (4000 load hours/yr; producing 80 kt/a H₂)

In Rodenhuize, requirements of 190 kt/a electrolytic H₂ at ArcelorMittal and CCU Hub Ghent necessitate additional 2.4 GW capacity. Connections to the NL H₂ backbone, using cross-border pipelines, are required
 - **2050** ~ **10 GW** electrolyzer capacity is feasible, provided enough wind energy is landed near Vlissingen-Oost / Rodenhuize (possibly combined with blue, yellow (orange) H₂). The SDR region is **CO₂ neutral**

Executive summary (3/3)



- Lowest unsubsidized green **H₂** costs in 2030 are **€ 2.90/kg** (at 4000 electrolyzer load hours and provided existing transmission tariff reductions are applicable; without these tariff reductions lowest price is **€ 3.22/kg**), still **~7%** higher than conventional H₂ in 2030, which is expected to increase to **€ 2.71/kg** by then (impact of ETS/CO₂ tax)
 - An unsubsidized business case is therefore still negative in 2030. At 4000 load hours, losses are minimized, at € 42 mln/a; subsidies (most notably SDE++ under enhanced conditions with respect to load hours) can make this business case positive in 2030
- Key requirements to realize the SDR electrolyzer project are:
 - **Immediate** initiation of the **decentral projects** at Yara and Zeeland Refinery (i.e. initiate planning on both sites, assess site infrastructure updates required, (jointly) engage with electrolyzer suppliers, ..)
 - **Discount** for electricity **transport** tariffs
 - Connection to the **H₂ backbone**
 - **SDE++** subsidy increase to **4000 load hours**. Options to combine with other (NL/BE/EU) subsidies
 - **Sufficient** offshore **wind** landing in SDR region short term (e.g. IJmuiden Ver) and long term (>2030)
 - **Enhanced 380kV** electricity grid in Zeeuws-Vlaanderen to enable multi-GW scale electrolyzers in the long run (> 2030)

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Chapter summary

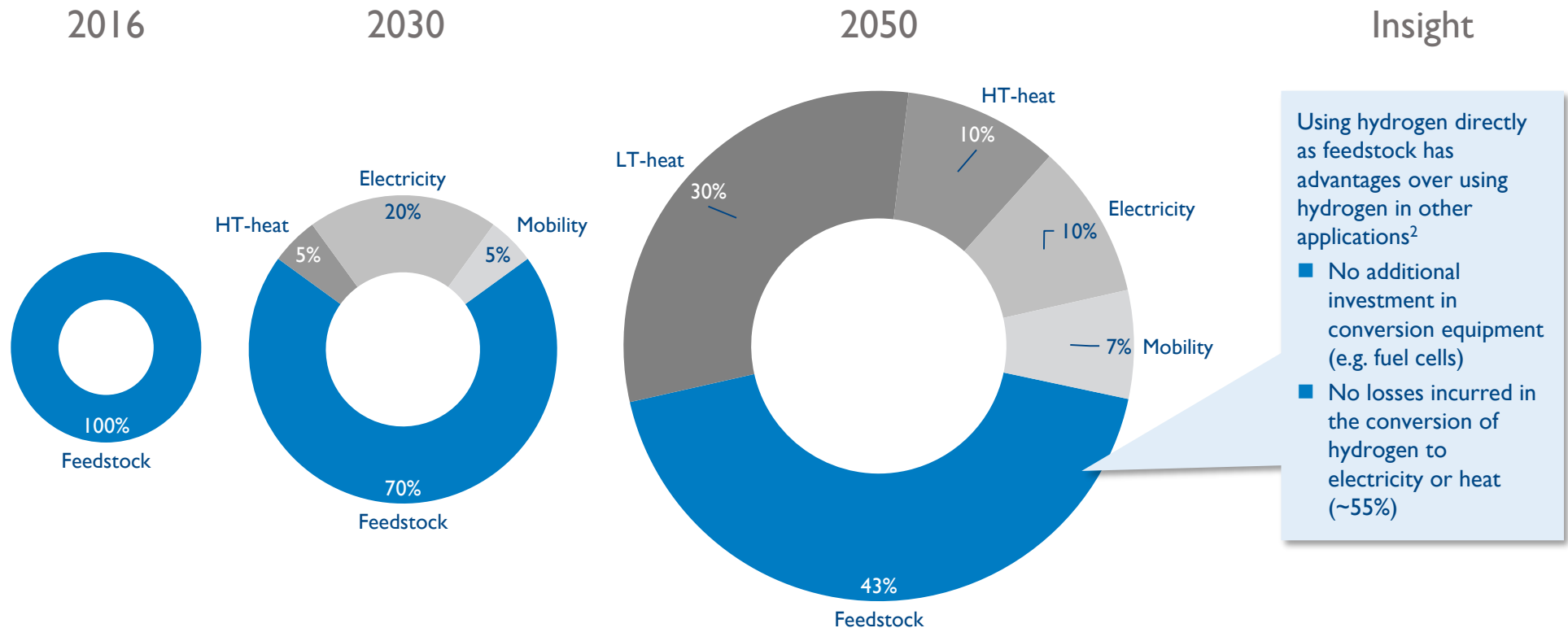
Hydrogen demand in SDR region

- **Hydrogen** is currently used predominantly as industrial **feedstock**, with other uses by 2030 still no more than 30%. **Mobility** applications are expected to be **5%** in **2030** and **7%** by **2050**
- **Steam Methane Reforming** (SMR) is the dominant technology to produce hydrogen (73% of total volume). This uses a **fossil** source and generates CO₂. **Electrolysis** currently accounts for **~1%** of **H₂ production**
- In the SDR region, current H₂ **demand** is **~ 400 kt/a**, exclusively located in NL. Developments in BE make it a significant H₂ usage area in the long run, if all current green H₂ projects implemented¹
 - The SDR region's total feedstock **demand** increases from **402 kt/a** in **2019** (grey) to **832 kt** in **2050** (green)
 - The biggest increase in demand is at **ArcelorMittal** in BE SDR and depends on various novel technologies
- Current total H₂ **production** in the **NL** SDR region is **~ 521 kt/a**, of which **~ 400 kt/a** is on-purpose production using SMR technology, at Yara and Zeeland Refinery (the remainder is produced as by-product of various production processes)
 - In the **BE** SDR region, there is **no** on-purpose **production**, and **~ 55 kt/a** of by-product production
- In the NL SDR all on-demand hydrogen is currently produced using SMRs, emitting **~4 Mton CO₂** per year
- With respect to **oxygen** demand, **ArcelorMittal** is the largest consumer of oxygen in the NL/BE SDR region with **~1000 kt/a**, accounting for **97%** of the region's oxygen demand. This is expected to decrease by **~ 10%** by 2050 to **~ 900 kt/a**

¹) The NL H₂ demand is assumed to be static

The vast majority of hydrogen is currently used as feedstock for (the chemical) industry, with other uses by 2030 still no more than 30%

Hydrogen applications In NL



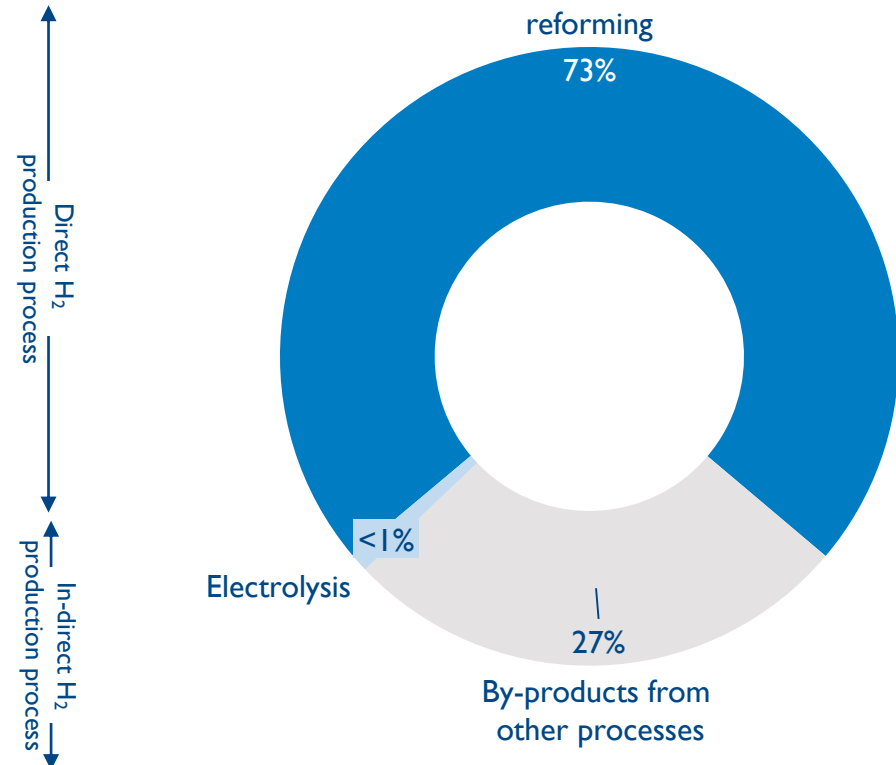
Source: 1) Waterstofroutes Nederland (CE Delft, 2018); 2) US Department of Energy

Steam Methane Reforming (SMR) is currently the dominant technology to produce hydrogen, currently using fossil inputs and generating CO₂

Hydrogen production processes

Process	Description
Steam methane reforming 	Steam-methane reforming, a mature production process in which high-temperature steam (700 – 1000°C) is used to produce hydrogen from a methane source, producing either ‘Grey H ₂ ’, ‘Blue H ₂ ’ or ‘Green H ₂ ’ (using biogas)
Electrolysis 	Electrolysis is the process of splitting water into Hydrogen and oxygen, by passing a direct current through two electrodes that are submerged in water using electricity, producing either ‘Grey H ₂ ’ (using e.g. coal-fired powerplant electricity) or ‘Green H ₂ ’ (using e.g. wind or solar energy) ¹
By-products from other processes	Hydrogen is also produced as a by-product of several industrial processes, e.g. crude cracking, production of chlorine, caustic soda, cokes (for steelmaking)

Hydrogen production volume by source (Volume%, 2017)



1) When using imported green energy ‘yellow’ H₂ results, nuclear energy will provide ‘orange’ H₂
 Source: Shell Hydrogen study (2017), Arthur D. Little

Electrolytic H₂ demand in SDR region is expected to grow significantly, if all current electrolytic H₂ projects are implemented according to plan

Electrolytic H₂ demand outlook

SDR, 2020,2030,2050, H₂ kt/a

Grey

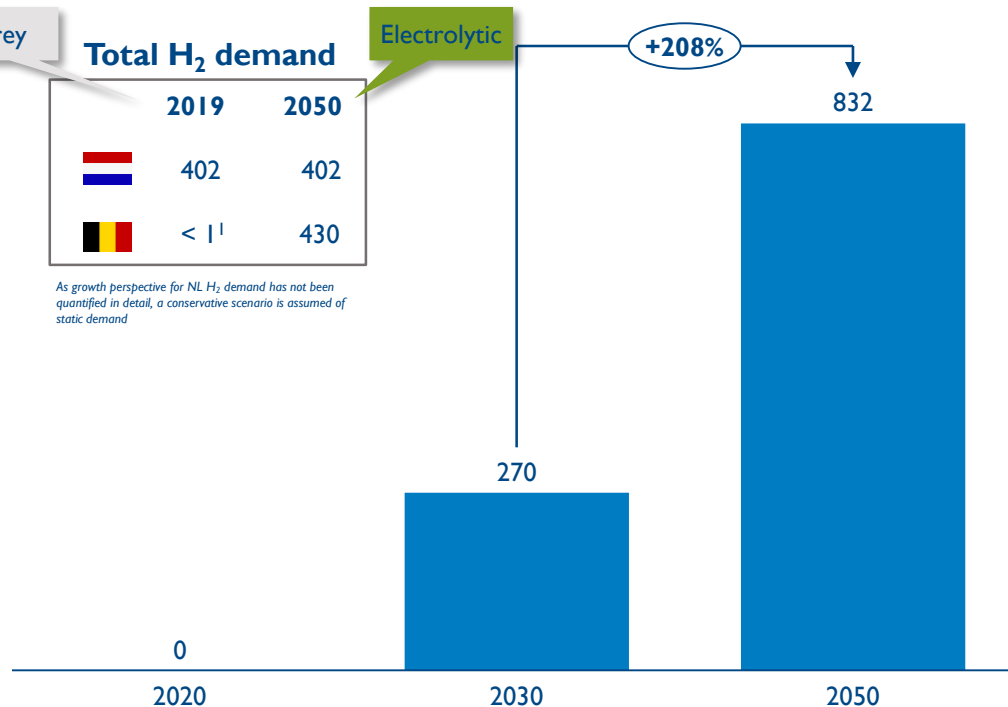
Total H₂ demand

	2019	2050
	402	402
	< 1 ¹	430

As growth perspective for NL H₂ demand has not been quantified in detail, a conservative scenario is assumed of static demand

Electrolytic

+208%



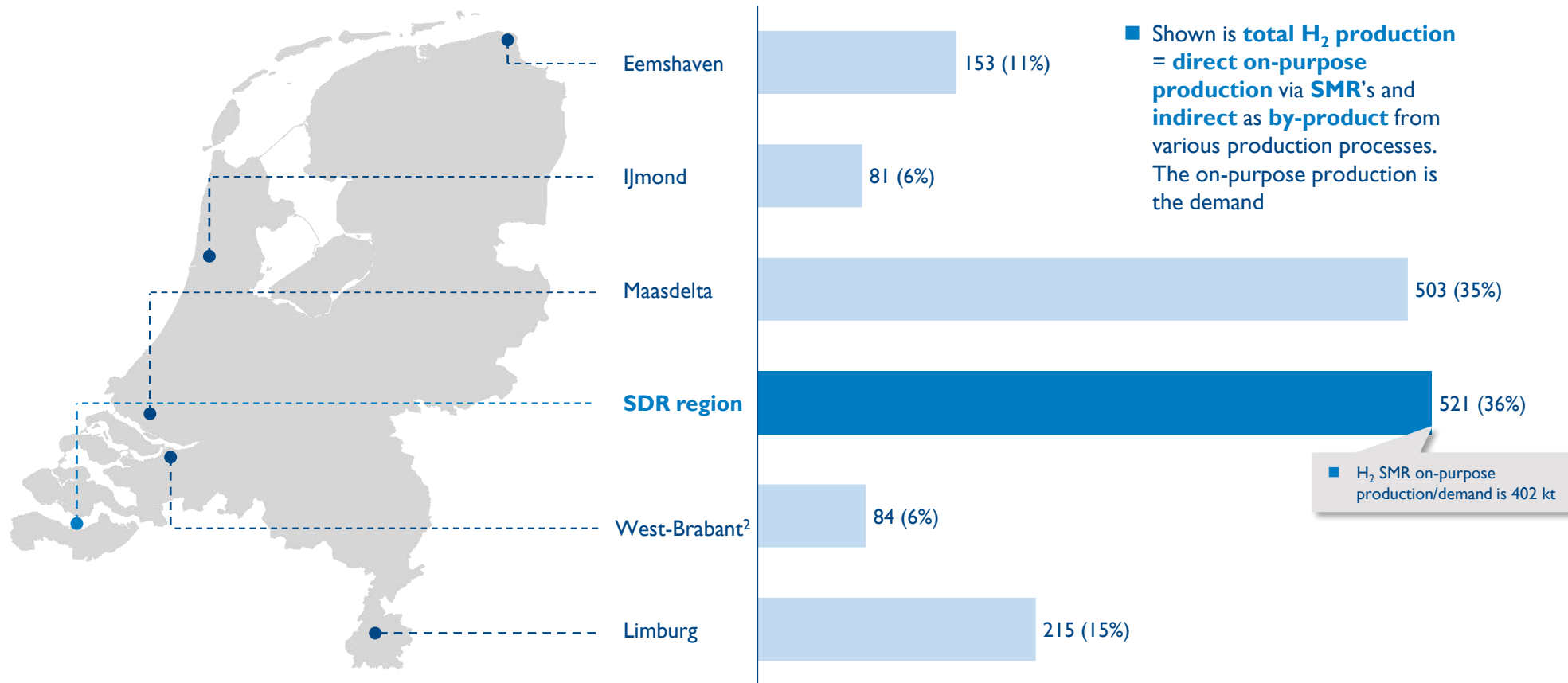
- Various projects in Ghent will create **H₂ demand of ~190 kt/a** in the BE SDR region by 2030²
- **Hydrogen** in the **NL SDR** region is currently produced by a number of **in-house SMR** units, each of which is flexible to reduce production with 20-35% of capacity³
 - Utilizing this flexibility of the SMR units will create an “short term” opportunity for an annual electrolytic hydrogen demand of **~80 kt/a** in the NL SDR region by 2030
- Full scale deployment of the Steel2Chemicals technology, and various other projects in Ghent will increase H₂ demand to **~430 kton/year** in the BE SDR region by 2050
- By **2050**, the industrial **H₂ demand** from existing industrial processes is assumed to be 100% electrolytic, primarily driven by regulatory demands. Coupled with new demand, the total **H₂ demand** in the SR region is **832 kt/a**

1) Only ArcelorMittal uses < 1 kt/a in current processes; 2) Total demand based on interviews with SDR partners and not visualizing individual demand for relatively small quantities of <5kt/year (e.g. for processes at DOW, ICL-IP, Eastman); 3) Depending on SMR unit and operator

2) Source: Stakeholder interviews, Arthur D. Little

Total current production of H₂ in the NL SDR region is ~ 520 kt/a, with ~ 400 kt/a being produced on-purpose

Hydrogen production in NL By industrial cluster, 2019, kt/a¹



1) Source: DNV-GL; 2) Includes Moerdijk, value is estimated

Note: In 2017, DNV-GL published an analysis of hydrogen production in 2017, based on data from the Roads2Hy project (2007). Figures have been corrected for 2020 situation

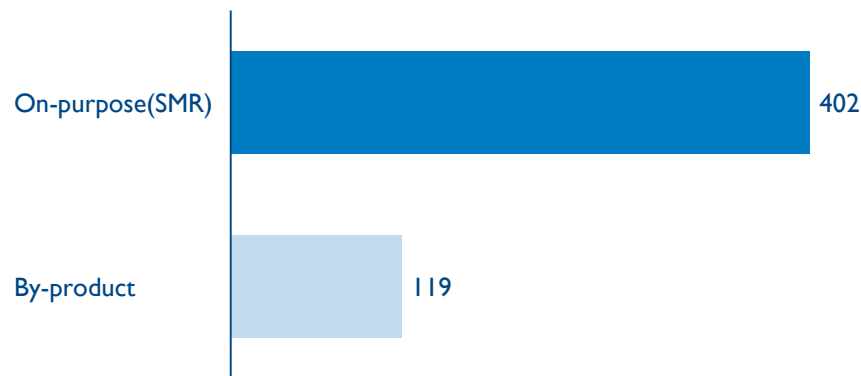
In the NL SDR region all on-purpose hydrogen is currently produced using Steam Methane Reformers, emitting ~4 Mton CO₂ per year

Hydrogen production in NL SDR

2019, kt/a¹



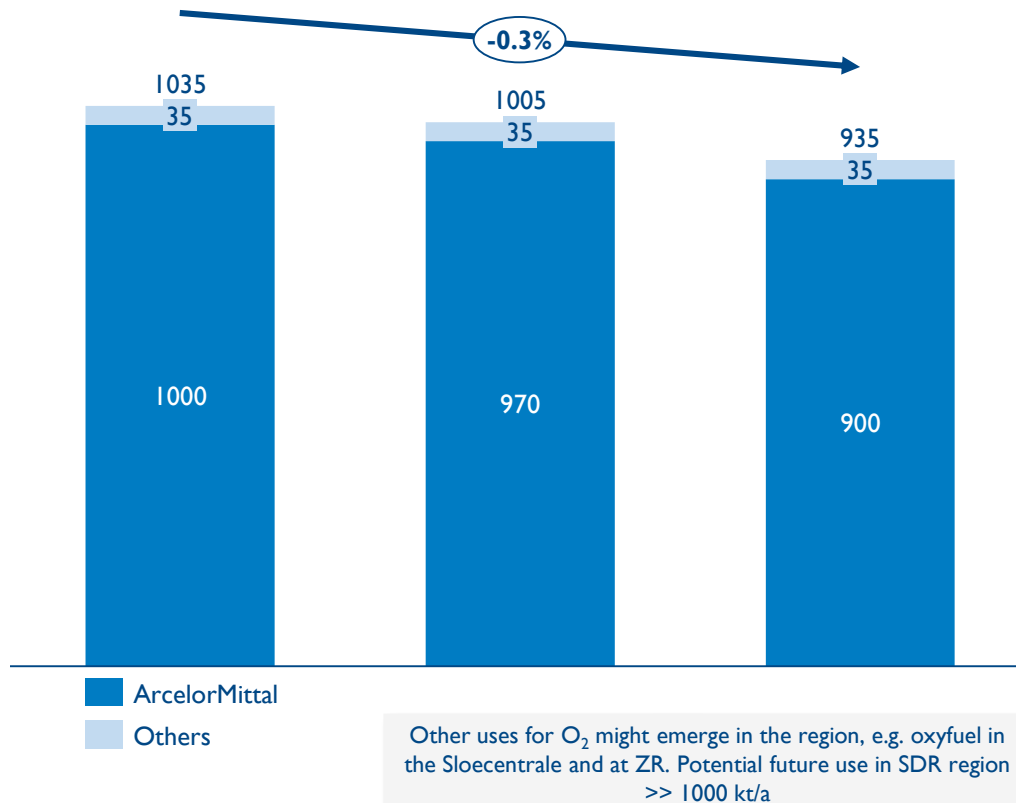
- Most hydrogen in the NL SDR region is produced by Steam Methane Reforming (SMR)
- Steam methane reformers (SMRs) use steam to convert natural gas into hydrogen and CO₂
- SMRs emit ~9 ton CO₂ per ton hydrogen produced
 - For NL SDR, this amounts to ~4 Mton CO₂ per year
 - Part of the CO₂ is used for indoor horticulture



¹) Based on interviews with SDR partners. Any CO₂ possibly produced through H₂ production as by-product is not taken into account, CO₂ production mentioned concerns CO₂ generated from SMRs only

ArcelorMittal is the largest consumer of oxygen in the NL/BE SDR region with ~1000 kt/a

Demand outlook for oxygen 2020-2050, kt/a



- Current demand for O₂ by SDR partners is ~1035 kt/a and originates almost entirely from ArcelorMittal (97%)
 - Current on-site production of O₂ (Air Products) for AM requires 30 MW of (grey) electricity
 - This accounts for 50% of Arcelor Mittal's need, the rest comes through Air Liquide pipeline
- ArcelorMittal expects O₂ consumption to decrease with ~10% by 2050, driven by the need to lower CO₂ emissions

Industrial Oxygen

- Air Liquide & Air Products are the main suppliers of industrial O₂ in the SDR region
- Oxygen is currently mostly produced via air separation. Selling prices are ~€ 20-30/t O₂
- Price is largely driven by electricity, transport and depreciation costs
- O₂ is transported by pipeline or truck, depending on individual demand

1) Estimated electrolyzer capacity for the production of total oxygen demand (assuming 100% capacity factor and efficiency of 6.25 kWh/kg oxygen) is; Source: Stakeholder interviews, Arthur D. Little

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Chapter summary

SDR ambition

- The **NL climate agreement** sets out ambitious goals for GHG emission reductions and foresees an important role for **green H₂**, just as the **Flanders¹ governmental policy** does
 - **Electrolysis**, splitting water into H₂ and O₂, allows production of **green H₂** using **renewable energy**
- Several companies from **Smart Delta Resources (SDR)** region have joined forces to study the **system integration** of a large scale **electrolyzer**. SDR's vision for H₂ is based on a mixture of blue, green, yellow (import) and possibly orange hydrogen (nuclear)
 - The study focuses on the area between **Vlissingen-Oost (NL)** and **Rodenhuijze (BE)** to identify the most suitable location(s), powered by **renewable energy** (possibly nuclear energy may also be considered); by 2030 ~ 7.5 GW offshore wind will be landed in the region
- While the supply of renewable (wind) energy fluctuates over time, H₂ demand in the SDR region is constant; to supply all **SMR H₂** from fluctuating **renewable** energy would require a **~5 GW** electrolyzer and **50 kt storage**
- **Salt caverns** are the only feasible option to **store** 50 kt of hydrogen, accessible via the **H₂ backbone** from **2028**
 - Until the backbone can be accessed in 2028, existing **SMRs** can serve as **back-up** to even-out fluctuations in renewable energy supply
- Replacing **Yara** and **Zeeland Refinery's** SMR hydrogen will result in an **electrolytic hydrogen demand** of **55 kt/a** in **2027** and **402 kt/a** in **2050**
- **New CCU processes** in **BE SDR** are expected to generate an **additional** electrolytic hydrogen **demand** of **190 kt/a** in **2030** and **430 kt/a** in **2050**

1) Flanders' ambitions are more limited than NL

The NL climate agreement¹ sets out ambitious goals for fossil GHG emission reductions and foresees an important role for green hydrogen

Climate agreement¹

- The NL climate agreement is a set of policy measures to significantly reduce GHG emissions in NL compared to 1990
 - 2030: by 49%
 - 2050: by 95%
- In the agreement, each of 5 sectors (Industry, Electricity, Mobility and Transport, Built environment and Agriculture) has an individual CO₂ reduction target
- The agreement contains an ambitious H₂ program applicable to all above sectors, and aimed at
 - Research and pilot & demonstration projects
 - Infrastructure
 - Broad hydrogen applications
- In addition, the NL government published its 'Kamerbrief waterstof' in March 2020, highlighting the importance of H₂ and the availability subsidies for the H₂ economy
- The Flanders climate policy is less ambitious than the NL agreement, targeting CO₂ reduction in 2030 by 35%. Also here, H₂ will play a key role

Hydrogen targets per sector²

Sector	Role of hydrogen	Objective	Approach
Industry	<ul style="list-style-type: none"> ■ For the process industry, hydrogen will act as a CO₂-free feedstock and energy carrier for high temperature heat 	<ul style="list-style-type: none"> ■ Installation of 3-4GW electrolysis capacity in 2030 (500MW in 2025) ■ Reduction of 65% of investment cost for electrolyzers between today and 2030 	<ul style="list-style-type: none"> ■ €30-40 million for demonstration and kick-start projects ■ Potential inclusion into SDE+(+) program, utilization EU funds, involvement of financial sector ■ Timely adjustment and construction of hydrogen infrastructure between industry clusters
Electricity generation	<ul style="list-style-type: none"> ■ Use hydrogen as a carbon-neutral dispatchable source of energy 	<ul style="list-style-type: none"> ■ Up to 17 TWh hydrogen-based electricity production in 2030 ■ Development of North sea green powerhouse, 60 GW in 2050 	<ul style="list-style-type: none"> ■ National vision and adjustment of legislation ■ Development of (EU) H₂ certificates
Mobility and transport	<ul style="list-style-type: none"> ■ Hydrogen vehicles are especially suitable for long distance passenger and heavy road transport 	<ul style="list-style-type: none"> ■ 50 gas stations, 15,000 cars, 3,000 heavy vehicles in 2025 ■ Reduction of gas stations investment costs 10% per yr. ■ 150 inland barges in 2030 	<ul style="list-style-type: none"> ■ Covenant stimulation ■ Fiscal stimulation and use of EU funds ■ Govt. as launching customer ■ Zero emission zones for city logistics in 30-40 largest municipalities ■ CO₂ neutral transport agreements
Built environment	<ul style="list-style-type: none"> ■ Use of hydrogen to decarbonize heating of buildings 	<ul style="list-style-type: none"> ■ Determine by 2030 how hydrogen can contribute to the reduction goal of 2050 	<ul style="list-style-type: none"> ■ Change legislation and regulation ■ In neighborhood-oriented approaches for kick-start projects

1) As NL is more ambitious than BE in its climate ambitions, the NL perspective is chosen to be leading

2) Source: TKI, "Hydrogen for the energy transition"

Several companies in NL/BE from the Smart Delta Resources consortium joined forces to study the system integration of a large scale electrolyzer

Smart Delta Resources

- Smart Delta Resources (SDR) is an initiative of 13 energy- and feedstock intensive industrial companies in South West NL and East Flanders BE investigating significant reductions in their use of energy and feedstock through industrial symbiosis
- SDR ambition is to achieve a CO₂-neutral industry by 2050
- Power2Hydrogen (P2H2) has been identified as one of eight pillars to significantly reduce CO₂ emissions
- The main objective of the P2H2 project is the realization of a regional facility that provides hydrogen produced from **renewable energy** to the local Hydrogen users by 2025
 - While this report's focus is on **green H₂**, SDR also views **blue H₂** (grey + CCU/CCS), **yellow H₂** (using imported green energy) and **orange H₂** (using nuclear energy) possible routes in their vision for H₂ in the region
- An exploratory study on the system integration of a large-scale electrolyzer has been commissioned by SDR, together with North Sea port, Yara, Zeeland Refinery, Dow Benelux, ArcelorMittal, Engie Electrabel, PZEM, and Ørsted¹



Initiators of the study



North Sea Port is a cross-border harbor on both sides of the Westerschelde, stretching from Vlissingen-Oost (NL) to Ghent (BE)



Yara Sluiskil is a producer of nitrogenous fertilizers and industrial chemicals, located along the Ghent-Terneuzen canal-zone



Zeeland Refinery is a processor of petroleum into the fuels LPG, gasoline, kerosene and diesel oil, located in eastern Vlissingen



Dow Benelux operates three large Naphtha crackers in Terneuzen that produce basic chemicals for the chemicals and plastics industry



ArcelorMittal is an integrated steel company that processes raw material (coal and ore) into sheets of steel, located in the Port of Ghent



Engie Electrabel is an electric utility company that operates a power plant in Knippegroen on blast furnace gas and one in Rodenhuize on biomass



PZEM purchases wind energy from Gemini park and operates various power plants: nuclear in Borssele, biomass in Moerdijk and gas in Vlissingen (Sloe)



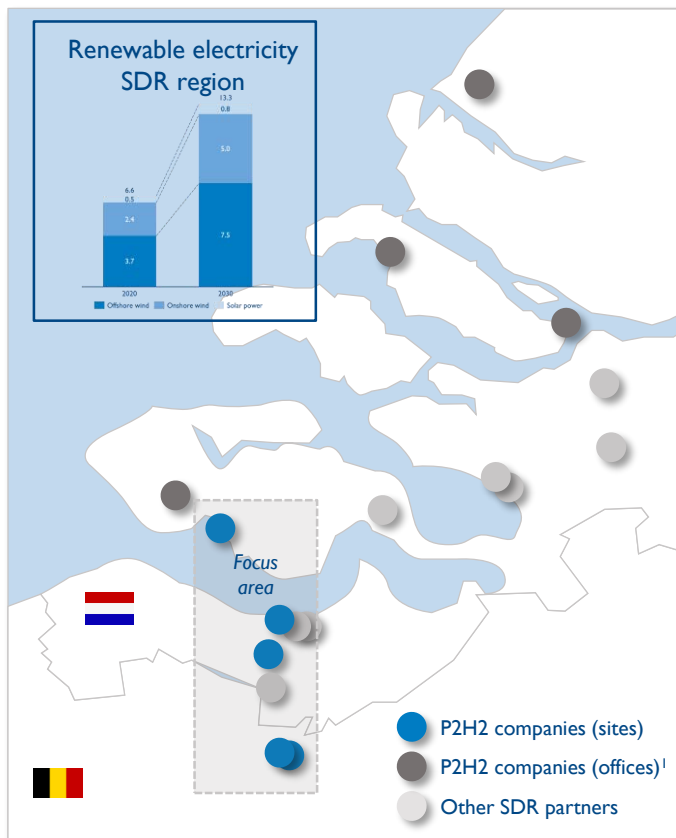
Ørsted develops, builds and exploits offshore wind parks and is currently building Wind Park Borssele 1+2 off the coast of Westkapelle

1) The port of Ghent plans to realize a Carbon Capture and Use (CCUG) hub. While not a Consortium member, their interests are also represented in this report

2) Other members of SDR include i.a. Gasunie, Fluxys, provinces Zeeland (NL)  and East Flanders (BE)

The SDR electrolyzer study focuses on the area between Vlissingen-Oost (NL) and Rodenhuize (BE) to identify the most suitable location(s)

SDR company area



Focus area

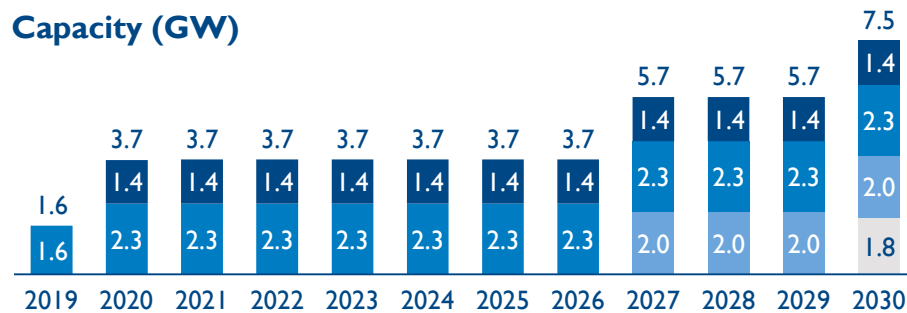


- Production sites of the SDR consortium companies, that are or will be using green H₂, are located in the North Sea Port: North of the Westerschelde in Vlissingen-Oost and South of the Westerschelde along the Ghent –Terneuzen Canal
- The electricity to power the electrolyzer will be provided by offshore-wind turbines, the largest category of renewable electricity in the SDR region, now and in the future
 - An alternative electricity source would be nuclear energy, with nuclear energy plants located at Borssele (NL) and Doel (BE). See appendix for a short assessment of the potential use of nuclear energy
- This system integration study will focus on the area mapped on the left to identify the most suitable electrolyzer location(s)

In this area, up to 7.5 GW of offshore wind energy capacity will be landed by 2030 (Borssele and Zeebrugge)

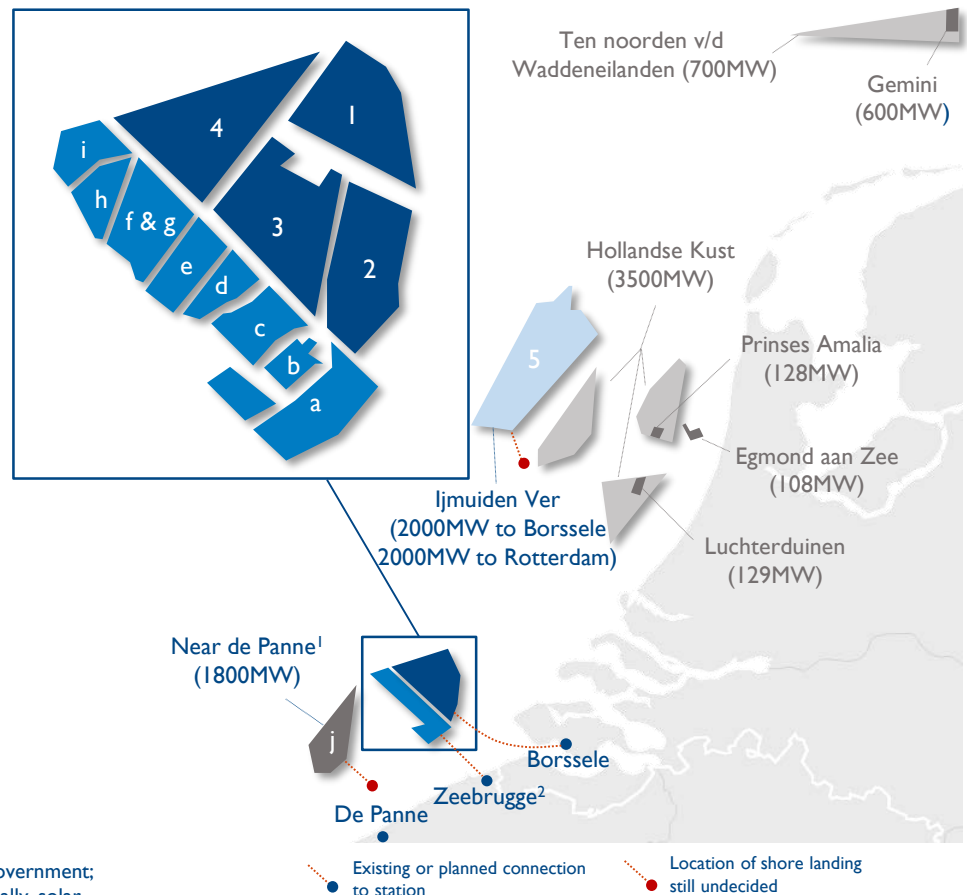
Offshore wind projects near SDR until 2030

Capacity (GW)



#	Project	Capacity (MW)	Status
1-2	Borssele I & II	700	Planned for 2020
3-4	Borssele III & IV	700	Planned for 2020
5	Ijmuiden Ver	2000	Planned for 2027 & 2029
a	Norther	370	Operational since 2019
b	C-Power	325	Operational since 2009
c	Rentel	309	Operational since 2018
d	Northwind	216	Operational since 2014
e	Seastar	252	Planned for 2020
f	Nobelwind	165	Operational since 2017
g	Belwind	171	Operational since 2010
h	Northwester 2	219	Planned for 2020
i	Mermaid	235	Planned for 2020
j	Near de Panne	1800	Ambition 2030

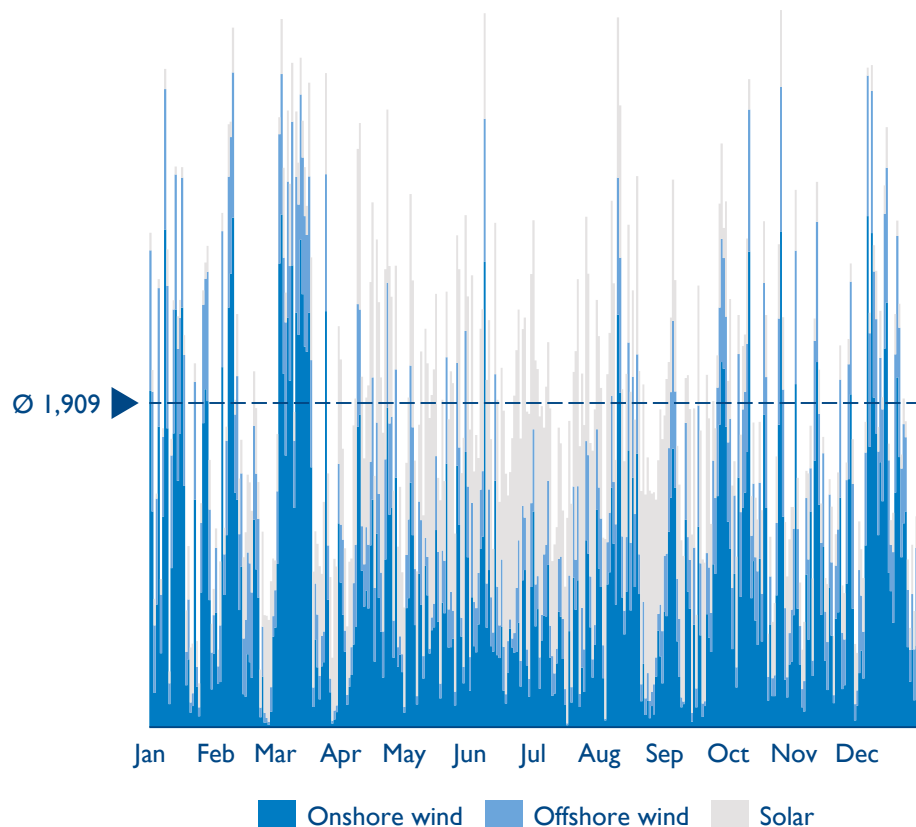
Legend
 ■ NL landing point determined ■ BE landing point determined
 ■ NL landing point to be determined ■ BE Landing point to be determined



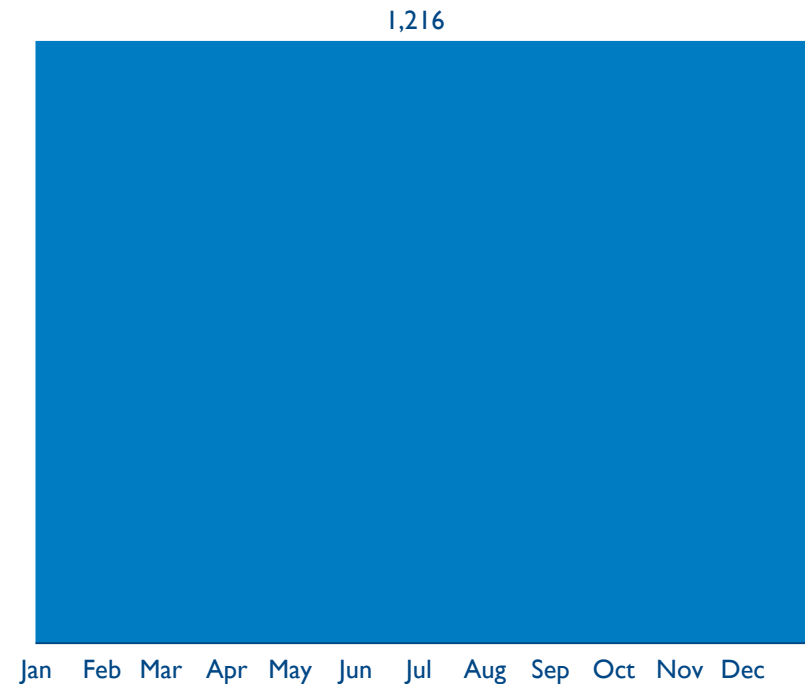
1) Potential new location for Belgium offshore wind parks by 2030, based on early stage plans of the Belgium government;
 2) Includes all shore landings at the Slijkens (Ostende), Zeebrugge and Stevin (Zeebrugge) stations; 3) Additionally, solar energy could also be available (Appendix). Source: 4C Offshore, Belgium Offshore Platform (BOP), Hoogspanningsnet.com, Net op Zee, Rijksoverheid, Van Oord company website, VRT, Arthur D. Little

While the supply of renewable (wind) energy fluctuates over time, the demand for hydrogen in the SDR region is constant

Variable renewable energy supply
NL, 2019, daily average production, MW



Constant hydrogen demand
SDR region, 2019, daily demand, ton/day



Source: Energieopwek.nl; Arthur D. Little analysis

Replacing all SMR-produced hydrogen with H₂ made via electrolysis using renewable energy requires a ~5 GW electrolyzer & 50 kt H₂ storage

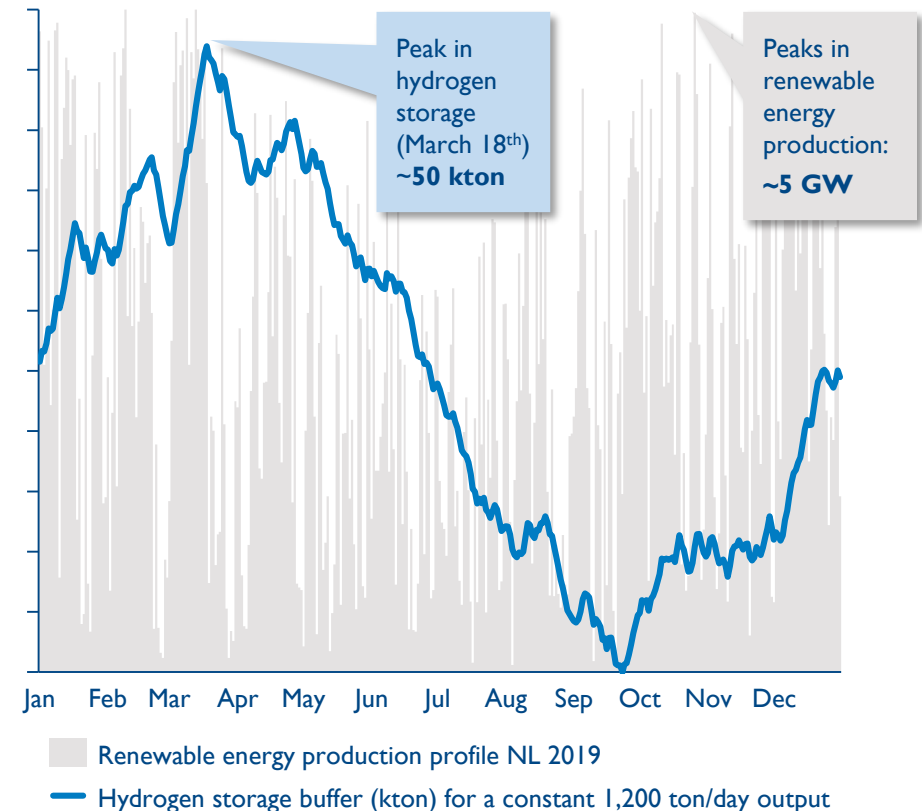
Required hydrogen storage buffer (kt)

Assumptions of illustrative example

- An electrolyzer is powered by renewable energy, following the production profile of NL 2019
 - The energy production profile is indexed to 2.5 GW annual average, which would be exactly enough to satisfy the SDR region's constant H₂ demand in 2019 (1200 ton/day, 402 kt/a)
- The electrolyzer is over-dimensioned to absorb the highest peaks in energy supply
 - Daily above-average power production is stored as hydrogen, which is used on below average production days (cumulative storage displayed on the right in blue)

Conclusions

- Producing a constant 1200 ton/day electrolytic hydrogen supply, based on fluctuating renewable energy would require:
 - **~5 GW** over-dimensioned electrolyzer capacity to process the peaks in renewable energy supply, even though average annual power consumption is 2.5 GW
 - **~50 kt** storage capacity to bridge shortages in renewable energy in spring and summer



Note: For CCU hub Ghent, no H₂ storage has been included. A PPA for renewable energy for the necessary operating hours will be negotiated; Source: Energieopwek.nl; Arthur D. Little analysis

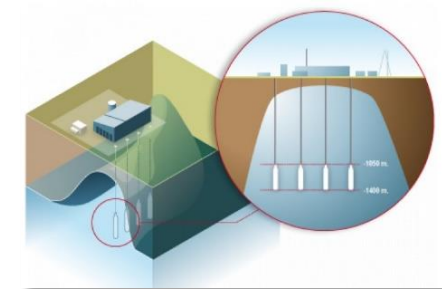
Underground salt caverns are the only feasible option to store 50 kt of H₂, which will be accessible via the NL hydrogen backbone from 2028

Hydrogen storage methods overview

Principle	Method & feasibility	Feasibility GW scale
Compression	Salt caverns	Only feasible form of large scale storage, proven on industrial scale. Lowest cost, requires access to salt caverns ^{1,2,3}
	Above ground tanks	Compression to 300 bar requires ~1 40ft container per ton, which is unfeasible and unviable for large scale storage ^{1,2,3,4,8}
	Depleted gas field	Depleted gas fields contain gasses and bacteria that affect H ₂ purity, making them unsuitable for storage of feedstock ⁵
	Line packing	The capacity for line packing is very limited for a GW scale electrolyzer (~15 MWh/km) ⁶
Liquefaction	Cryogenic tanks	Liquefying H ₂ is energy intensive and the investments associated with a liquefaction plant are high ¹
Materials	Ammonia	The Haber Bosh process needs to run continuously ^{2,7} and cannot be used to manage flexibility
	Methane & Formic acid	No high volume methane or formic acid is used in the SDR region and processes require a constant supply of hydrogen ⁷
Other	Liquid organic HC & Metal hydrides	Limited large scale experience with the application of adsorbent-based H ₂ storage ¹

Salt cavern storage in NL

- Salt caverns are located in the northern NL, in Zuidwending near Veendam^{5,9}
- There are 6 natural gas storage salt caverns in operation at Zuidwending. Plans are being developed for 4 salt caverns dedicated for hydrogen⁵
- Each cavern is 300 meters tall and has a diameter of 70 meters. Calculated work quantity is ~ 6kt (excl. cushion gas)⁵
- Caverns are currently used for natural gas storage, Gasunie is assessing possibility to make (some) available for H₂ storage
- Caverns are planned to be accessible from Zeeland via the 'H₂ back bone' from 2028⁵

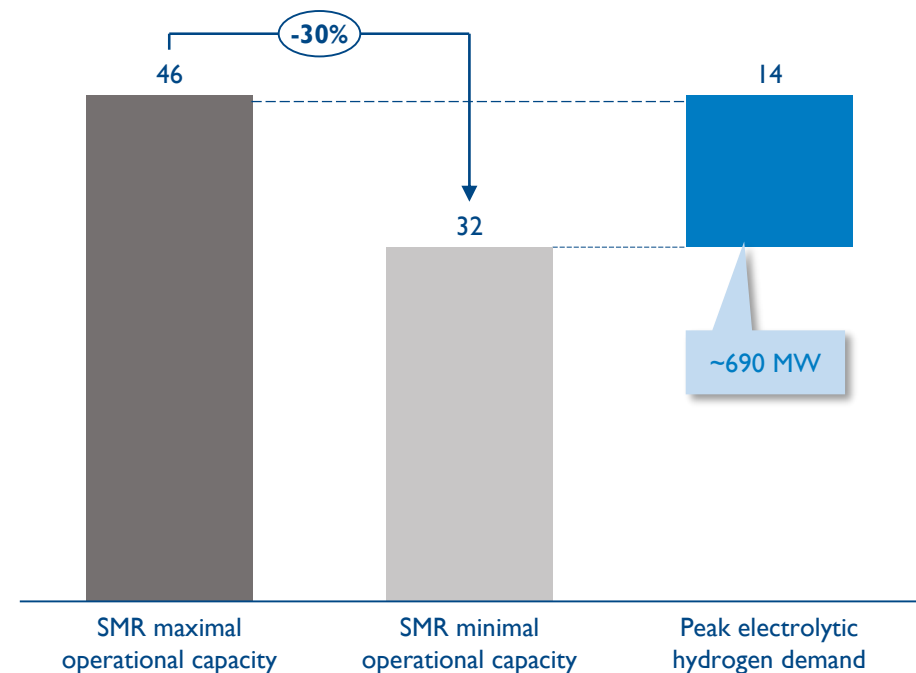


Sources: 1) Large scale storage of hydrogen (International journal of hydrogen energy, 2019); 2) National Hydrogen Roadmap Australia (2018); 3) Smart Port position paper Rotterdam hydrogen hub (2019); 4) Energy stock presentation (2017); 5) Gasunie reports, meeting, call (2019), email (June 2020); 6) HyNet North West, From Vision to Reality (Cadent, 2018); 7) CCU hub Gent research; 8) These investment costs are not tolerable for an GW-scale electrolyzer, or an intermediary solution awaiting accessibility to salt caverns; 9) 1) Fluxys operates an underground natural gas storage facility in Loenhout (Belgium), but this is a rock formation and not a salt cavern and is therefore assumed to be unsuitable for hydrogen storage

The region's existing SMRs serve as back-up to even-out fluctuations in renewable energy supply¹, until the H₂ backbone can be accessed in 2028

SMR back-up and its effect on peak electrolytic hydrogen demand (ton/hr)

- In 2019, Yara and Zeeland Refinery's H₂ demand was 402 kt/a
- The demand was met by SMRs producing a constant supply of ~46 ton/hour
 - The processes using H₂ do not allow for (significant) fluctuations in supply
- In contrast, electrolytic hydrogen supply quantity will vary from hour to hour
 - Electrolytic hydrogen will be produced from renewable energy, the availability of which is variable (4000 load hours per year)¹
- Since large scale hydrogen storage will not be available (until the salt caverns can be accessed via the hydrogen backbone) till 2028², the existing SMRs can serve as a back-up source of H₂ to ensure constant supply
- While SMRs serve as back-up, peak electrolytic hydrogen demand is 30% of the SMRs' production capacity (or ~14 ton/hr)³
 - SMRs can operate flexibly between 70% and 100% of capacity, quickly scaling up and down. Utilization below 70% however results in unacceptably inefficient operation; fully shutting down and then restarting an SMR takes several days during which time the SMR cannot serve as back-up



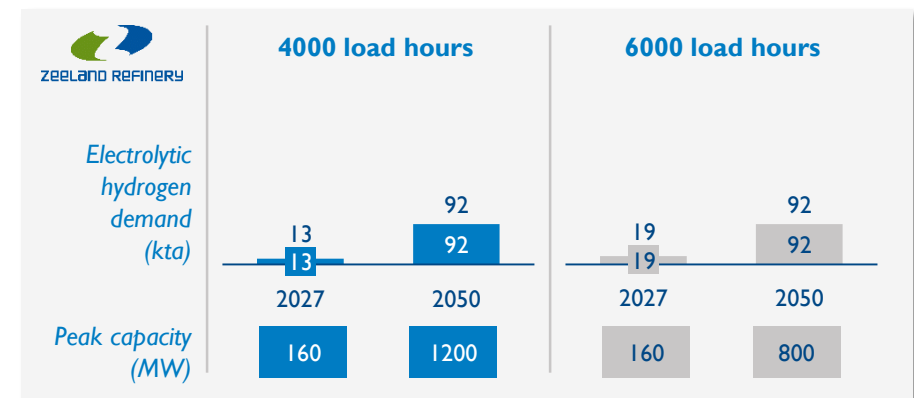
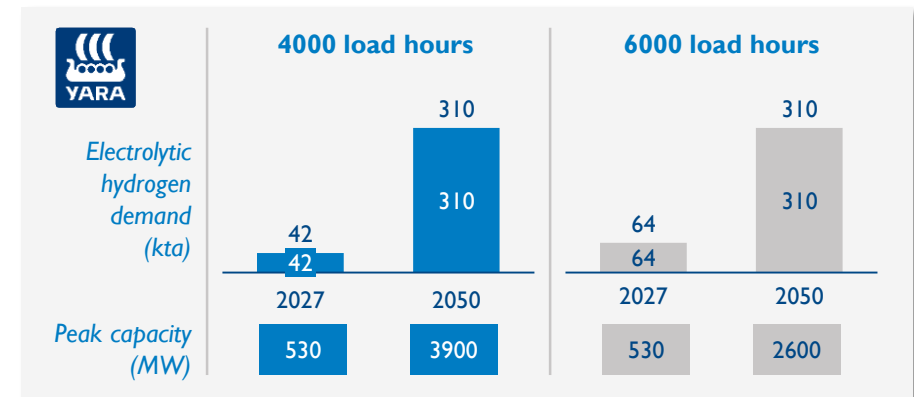
The SDR region's existing SMR's offer a great opportunity to even-out fluctuations in renewable electrolytic hydrogen supply

¹) Based on SMR capacity. Other possible routes would be to use grey electricity or nuclear energy, allowing for a larger electrolyzer
Source: Company interviews, 1) Business plan, 2) Gasunie reports, meeting, and call; 3) Arthur D. Little analysis

As existing SMR's at Yara/Zeeland Refinery will gradually scale down, their electrolytic H₂ demand is 55 kt/a in 2027² and 402 kt/a in 2050

Yara and Zeeland Refinery electrolytic hydrogen demand (2027 & 2050)

- Yara and Zeeland Refinery will use electrolytic hydrogen to increasingly replace SMR hydrogen in existing processes¹
 - Electrolytic hydrogen should therefore meet the same specifications (~25 bar, 99.99% pure)
- The growth in electrolytic hydrogen demand is restricted until the hydrogen backbone can be accessed in 2028
 - While SMRs serve as back-up, peak electrolytic hydrogen demand is 30% of the SMRs' production capacity (or ~14 ton/hr)
- Before 2028 (e.g. 2027), peak electrolytic hydrogen demand is limited to ~14 ton/hr, corresponding to:
 - ~690 MW electrolyzer capacity (regardless of load hours)
 - ~55 kt/a hydrogen production (at 4000 load hours)
 - ~83 kt/a hydrogen production (at 6000 load hours)
- From 2028 onwards, electrolysis can be scaled up to eventually serve the total hydrogen demand in 2050, corresponding to:
 - ~5100 MW electrolyzer capacity (at 4000 load hours)
 - ~3400 MW electrolyzer capacity (at 6000 load hours)
 - ~402 kt/a hydrogen production (regardless of load hours)



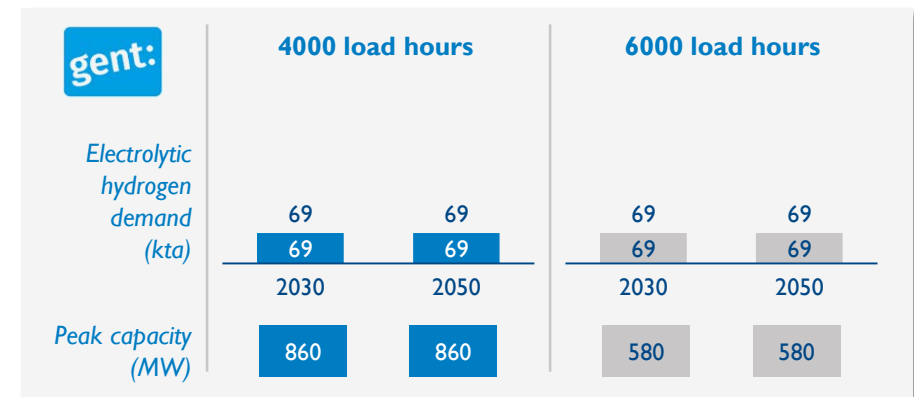
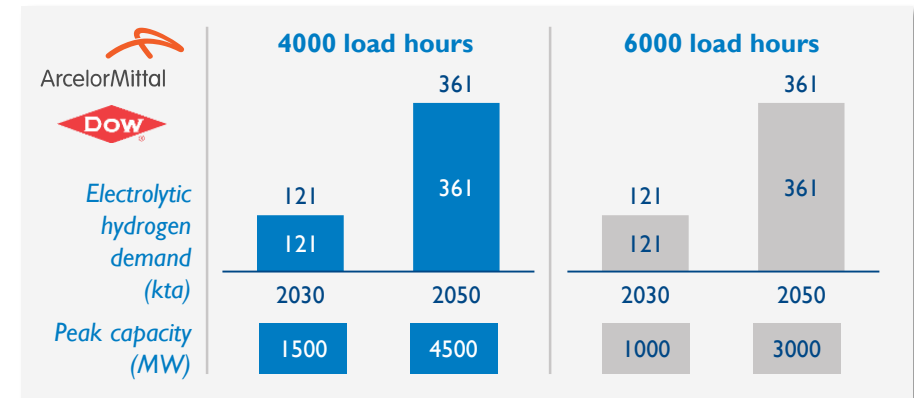
1) Total H₂ demand of Yara and Zeeland Refinery (regardless of production method) assumed to be roughly stable until 2050; 2) Assuming that the electrolyzer is operational for 4000 load hours (due to the fluctuating nature of renewable energy) at an efficiency of 50 kWh/kgH₂, yielding 80 tton/GW

Sources: Company interviews; Arthur D. Little analysis

New CCU processes in BE SDR are expected to generate an additional electrolytic hydrogen demand of 190 kt/a in 2030 and 430 kt/a in 2050

ArcelorMittal/Dow and CCU Hub Ghent electrolytic hydrogen demand (2030 & 2050, kt/a)

- **ArcelorMittal** and **Dow** co-develop several projects to mitigate CO₂ emissions from steel making with hydrogen
 - **Steel2Chemicals** (converting CO from steel production to synthetic naphtha using innovative Fischer Tropsch catalyst developed by **Dow**) forecasted electrolytic H₂ demand of 10 kt/a in 2030 and 250 kt/a in 2050¹
 - **Direct injection** (of H₂ in blast furnace to reduce CO₂ emissions) forecasted demand of 70 kt/a from 2030 onward
 - **Steelanol** (converting carbon-rich industrial waste gas into bio-ethanol via gas-fermentation) forecasted demand 40 kt/a from 2030 onwards
 - ArcelorMittal now uses 0.6 kt/a H₂ for **annealing** (heat treatment of steel)
- Within the BE part of North Sea Port at Rodenhuis a consortium plans to realize a CCU hub by 2030, for synthesis of chemicals with CO₂ and H₂³:
 - **Methanol**: 54 kt/a; **Ammonia** : 8 kt/a; **Formates** : 7 kt/a
- AM/CCU have total electrolytic H₂ demand of 190 kt/a in 2030 and 430 kt/a in 2050. This requires electrolyzer capacity of 2.4 GW in 2030 and 5.4 GW in 2050 at 4000 load hours (1.6 GW and 3.6 GW at 8000 load hours)
- **H₂ demand** depends on successful implementation of **new processes**
- AM/CCUG do not have access to SMRs that can serve back-up, so the H₂ demand must be met by electrolytic H₂
 - Furthermore, the H₂ demand is constant and AM/CCUG should therefore be connected to H₂ storage buffers via the hydrogen backbone⁴



1) The total hydrogen demand of Steel2Chemicals is 80 kt/a in 2030 and 320 kt/a in 2050 (all CO converted), of which 70 kt/a will be provided as a by-product from Dow's cracker processes; 2) Assuming that the electrolyzer is operational for 4,000 load hours (due to the fluctuating nature of renewable energy) at an efficiency of 50 kWh/kgH₂, yielding 80 kton/GW; 3) Currently, 350 kt/a methanol is used for production of methylamines, biodiesel and ureumformaldehyde. For this methanol volume, 450 MW of electrolyser capacity is needed; 4) Assuming that the electrolyzer(s) will be powered by renewable energy at <100% capacity factor; Sources: Company interviews; Arthur D. Little analysis

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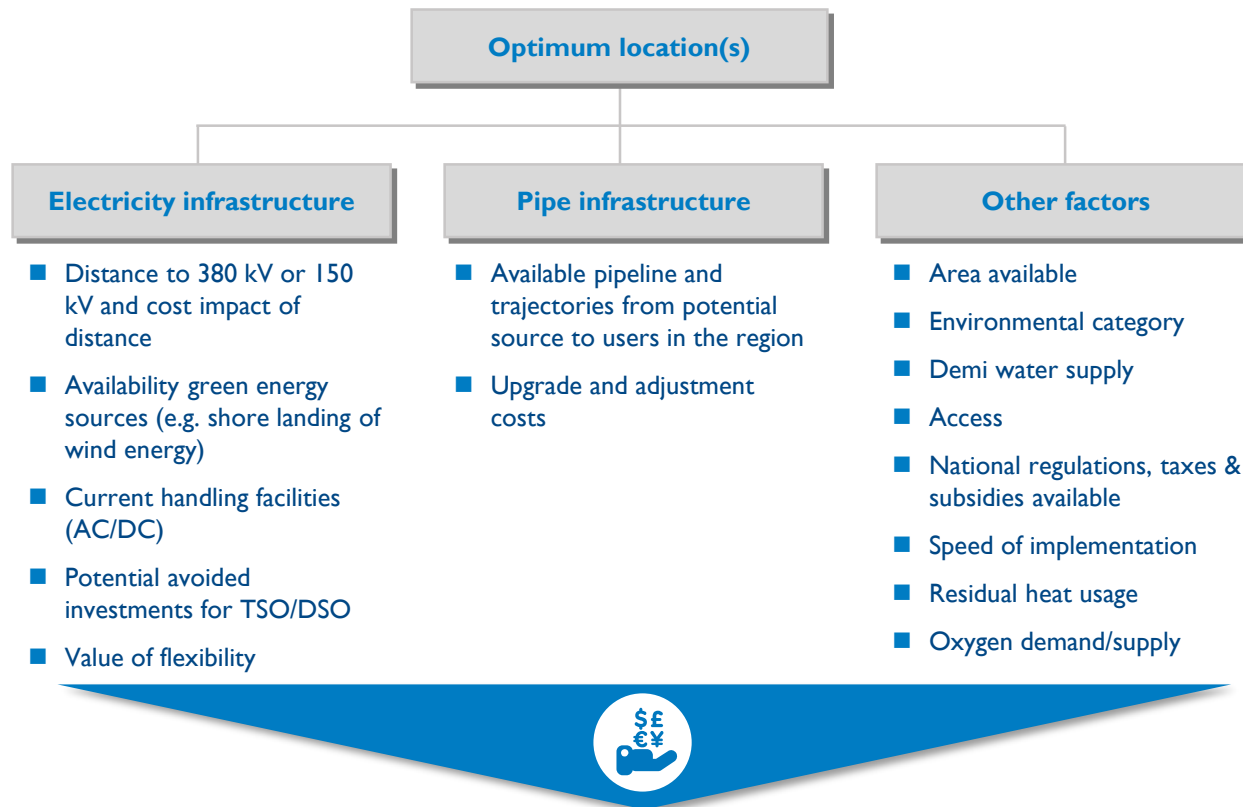
Chapter summary

Existing infrastructure

- Potential electrolyzer **locations** have been **evaluated** using **criteria** on existing **electricity** and **gas infrastructure**, as well as using additional inputs on e.g. available area, permitting, O₂ demand
- Two **decentral** locations, **Yara** and **Zeeland Refinery**, are identified as good **kick-start** locations
- Two most suitable **central** locations identified are **Vlissingen-Oost (NL)** and **Rodenhuize (BE)**
 - **Vlissingen-Oost** is ideally situated near the shore landing of **Borssele** wind parks and offers enough space for a GW scale electrolyzer
 - Engie's site in **Rodenhuize** is connected to the 380 kV grid and is located near future CCU projects at ArcelorMittal's and in the Flemish part of North Sea Port area. The Rodenhuize site is also directly connected with a 380 kV line to the **Zeebrugge** offshore wind landing station
 - Existing **380 kV** grid infrastructure can transmit **sufficient** amounts of renewable energy to **large scale** electrolyzers in Vlissingen-Oost and Rodenhuize
 - An extensive **network** of existing **gas infrastructure** can transport large amount of hydrogen throughout the SDR region

Electrolyzer locations have been evaluated using criteria on existing electricity and gas infrastructure as well as using additional inputs

Location evaluation criteria



Assessed in terms of costs/benefits and timing

- A number of **criteria** have been defined for the location choice of the electrolyzer(s)
- Grouped into three elements, electricity, gas and others
 - For **electricity**, the main criteria are distance to 380 kV and availability of 150 kV; CUST trajectories will be taken into account and once (a) location(s) has been decided on, system integration issues will also be addressed (e.g. does the 380 kV net needs to be beefed up anywhere ?)
 - For **gas**, currently available connections from source to users will be the main criterium
 - In the category **other**, various factors have been taken into account such as availability of land, environmental categories (permits required), O₂ demand/supply

Six possible electrolyzer locations were filtered down to two decentral and two central locations based on existing infrastructure criteria

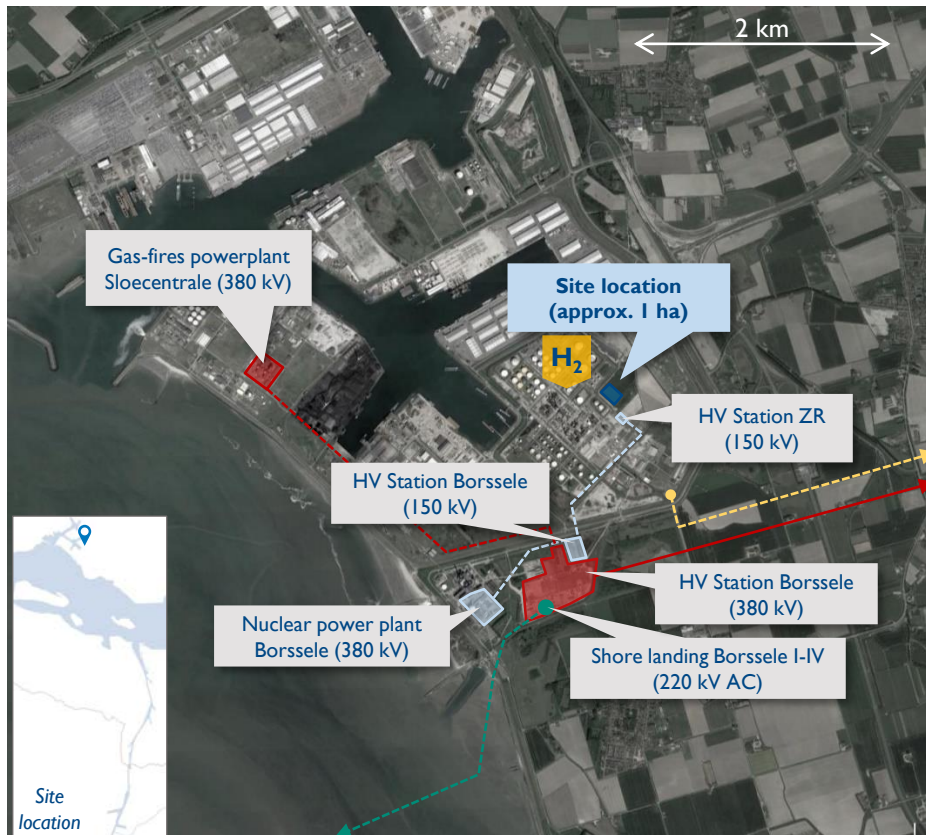
Potential site		(former) Thermphos or Zanddepot ¹	Zeeland Refinery	PZEM/EPZ	Valuepark Terneuzen ^{2,3}	Yara	Engie
Location (Harbor number)		Vlissingen-Oost (9890)	Vlissingen-Oost (6501)	Borssele (8099)	Terneuzen (85)	Sluiskil (2111)	Rodenhuize (4040A)
Central/Decentral		Central	Decentral	Central	Central	Decentral	Central
Electricity infra	Distance 380 kV	<ul style="list-style-type: none"> ~2 km from Borssele nuclear power plant ~2km (max) from Sloecentrale 	<ul style="list-style-type: none"> ~2 km from Borssele nuclear power plant 	<ul style="list-style-type: none"> 0 km 	<ul style="list-style-type: none"> ~10 km from Borssele nuclear power plant (through Westerschelde) 	<ul style="list-style-type: none"> ~15 km from Rodenhuize (through Ghent–Terneuzen Canal) ~20 km from Borssele nuclear power plant (through Westerschelde & Ghent–Terneuzen Canal) 	<ul style="list-style-type: none"> 0 km (recently reinforced to enable connection of wind farms to national 380 kV grid)
	Available capacity 150 kV	<ul style="list-style-type: none"> Former 150 kV HV Station Thermphos on site/close 	<ul style="list-style-type: none"> 142 MW (if redundant transformer is repurposed, otherwise 50 MW) 	<ul style="list-style-type: none"> Yes, HV station Borssele 150kV at <800m 	<ul style="list-style-type: none"> Underdeveloped electricity grid (not quantified) 	<ul style="list-style-type: none"> 140 MW 	<ul style="list-style-type: none"> HV Station Rodenhuize 150kV <100m 600 MW available
Pipe infra	Pipeline connections	<ul style="list-style-type: none"> ZR-DOW naphtha pipe <5km 	<ul style="list-style-type: none"> Naphtha (to Dow, willingness to repurpose) 	<ul style="list-style-type: none"> ZR-DOW naphtha pipe <1km 	<ul style="list-style-type: none"> Naphtha (from ZR, willingness to repurpose) Hydrogen (from DOW, capacity 18 kton: TBD mentioned as ambition) Hydrogen (from Air Liquide, capacity unknown) 	<ul style="list-style-type: none"> Hydrogen (from DOW, capacity 18 kt; stated as ambition) 	<ul style="list-style-type: none"> No large scale H2 usage close by (yet)
Other	Area available	~ 40 ha	~ 1 ha (4-9 in future)	8-12 ha	70-75 ha	20-25 ha	70-75 ha
	Environmental category	5.3 / 6	6	6	5.3	6	6
	Demi water supply	Supply seems guaranteed through Evides	Supply seems guaranteed through Evides	Supply seems guaranteed through Evides	Supply seems guaranteed through Evides	Supply seems guaranteed through Evides	Local water supplier Ghent (FARYS)
	Access	Road, rail & waterway	Road, rail & waterway	Road & waterway	Road & waterway	Road & waterway	Road, rail & waterway
	Other advantages ⁴	Independent from specific consortium partners; waste water synergies with Evides	150-200MW transformer capacity available; connected to the GTS network	DC current available	N/A	Largest H ₂ user in the region	Close to large O ₂ demand
Other disadvantages	N/A	N/A	Potential danger (and additional safety zones) of proximity nuclear plant	N/A	N/A	N/A	

1) Two separate locations in Vlissingen-Oost; 2) JV between DOW and North Sea Port; 3) Limited suitability, to 100 MW. Above that, not suitable; 4) Relation with CUST trajectories will also be taken into account, as well as e.g. subsidies

Zeeland Refinery's site is surrounded by the required infrastructure for a kick-start project



Zeeland Refinery – Decentral option



Description	
Zeeland Refinery is one of the SDR stakeholders and a large scale consumer of H ₂ . Currently ~ 1 ha of land is designated for a 100 MW electrolyzer (another 4-9 ha of land might be available for expansion up to 1-2 GW, but this is currently earmarked for internal ZR requirements). Due to the proximity to the Borssele high voltage station, the electrolyzer can be connected to the 380 kV grid. Last of all, the ZR-DOW naphtha pipeline is close by and could provide cheap infrastructure for hydrogen transportation	

Onsite specifications			
Location (harbor #)	Vlissingen-Oost (6501)	Access	Accessible by road, rail & waterway
Size	± 1 ha (4-9 in future)	Environmental Category	6

Infrastructure specifications			
Electrolyzer input		Electrolyzer output	
✓	380 kV grid	✓	Hydrogen pipeline(s)
	HV Station Borssele 380kV at <2km		ZR-DOW naphtha pipe <1km
✓	150 kV grid	■	Oxygen pipeline(s)
	HV Station ZR 150kV on site		But potential small scale offtake ZR on site
✓	Demi water supply	✓	Waste water facilities
	Evides ¹ does not expect problems in water supply		ZR has contacts with technology providers
✓	Nearby (green) energy sources	?	District heating opportunities
	Shore landing of 1.4 GW Borssele I-IV on <3km		Under investigation
	Other		Other
	150-200MW transformer capacity available		Connected to the GTS network

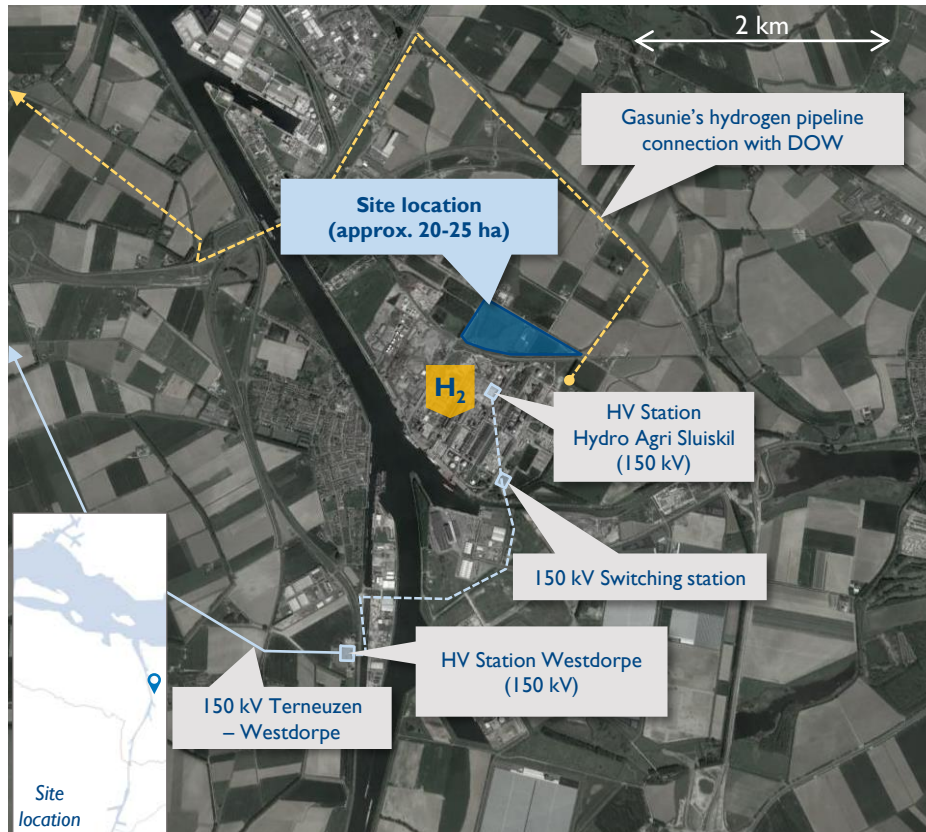
1) Evides is already industrial water supplier to i.a. Zeeland Refinery, Yara Sluiskil & Dow Terneuzen

Source: CUST Rapportage, Gasunie, Google Earth Pro, Hoogspanningsnet.com, North Sea Port, TenneT, Interview Zeeland Refinery, Arthur D. Little

Placement of an electrolyzer on the Yara site ensures production in the vicinity of large H₂ use, suitable for a kick-start project



Yara – Decentral option



Description																																			
Yara is the largest consumer of hydrogen in the region with 300 kt/yr. There may be enough land available to house an electrolyzer with a capacity of ~ 4 GW. However, the current environmental category of this land does not allow a hydrogen electrolyzer. This site is also limited to a 150kV connection. On the other hand, this site does offer access to a hydrogen pipeline from Yara to DOW. There is no nearby large demand for O ₂																																			
Onsite specifications																																			
Location (harbor #)	Sluiskil (2111)																																		
Access	Accessible by road & waterway																																		
Size	20-25 ha																																		
Environmental Category	4.2																																		
Infrastructure specifications																																			
	<table border="0"> <thead> <tr> <th colspan="2">Electrolyzer input</th> <th colspan="2">Electrolyzer output</th> </tr> </thead> <tbody> <tr> <td>✗</td> <td>380 kV grid</td> <td>No 380kV connection in Dutch Flanders</td> <td>✓</td> <td>Hydrogen pipeline(s)</td> <td>YARA-DOW H2 pipe <200m</td> </tr> <tr> <td>✓</td> <td>150 kV grid</td> <td>HV Station Hydro Agri Sluiskil 150kV <500m</td> <td>-</td> <td>Oxygen pipeline(s)</td> <td>Limited O₂ consumption to boost Nitric Acid</td> </tr> <tr> <td>✓</td> <td>Demi water supply</td> <td>Evides¹ does not expect problems in water supply</td> <td>?</td> <td>Waste water facilities</td> <td>To be determined (if necessary)</td> </tr> <tr> <td>✗</td> <td>Nearby (green) energy sources</td> <td>No large-scale electricity production nearby</td> <td>-</td> <td>District heating opportunities</td> <td>Potential expansion of WarmCo to provide district heating in Axel</td> </tr> <tr> <td></td> <td>Other</td> <td>-</td> <td></td> <td>Other</td> <td>Connected to the GTS network</td> </tr> </tbody> </table>	Electrolyzer input		Electrolyzer output		✗	380 kV grid	No 380kV connection in Dutch Flanders	✓	Hydrogen pipeline(s)	YARA-DOW H2 pipe <200m	✓	150 kV grid	HV Station Hydro Agri Sluiskil 150kV <500m	-	Oxygen pipeline(s)	Limited O ₂ consumption to boost Nitric Acid	✓	Demi water supply	Evides ¹ does not expect problems in water supply	?	Waste water facilities	To be determined (if necessary)	✗	Nearby (green) energy sources	No large-scale electricity production nearby	-	District heating opportunities	Potential expansion of WarmCo to provide district heating in Axel		Other	-		Other	Connected to the GTS network
Electrolyzer input		Electrolyzer output																																	
✗	380 kV grid	No 380kV connection in Dutch Flanders	✓	Hydrogen pipeline(s)	YARA-DOW H2 pipe <200m																														
✓	150 kV grid	HV Station Hydro Agri Sluiskil 150kV <500m	-	Oxygen pipeline(s)	Limited O ₂ consumption to boost Nitric Acid																														
✓	Demi water supply	Evides ¹ does not expect problems in water supply	?	Waste water facilities	To be determined (if necessary)																														
✗	Nearby (green) energy sources	No large-scale electricity production nearby	-	District heating opportunities	Potential expansion of WarmCo to provide district heating in Axel																														
	Other	-		Other	Connected to the GTS network																														

1) Evides is already industrial water supplier to i.a. Zeeland Refinery, Yara Sluiskil & Dow Terneuzen

Source: CUST Rapportage, Gasunie, Google Earth Pro, Hoogspanningsnet.com, North Sea Port, TenneT, Interview Yara Sluiskil, Arthur D. Little



Hydrogen demand



Available electrolyzer site



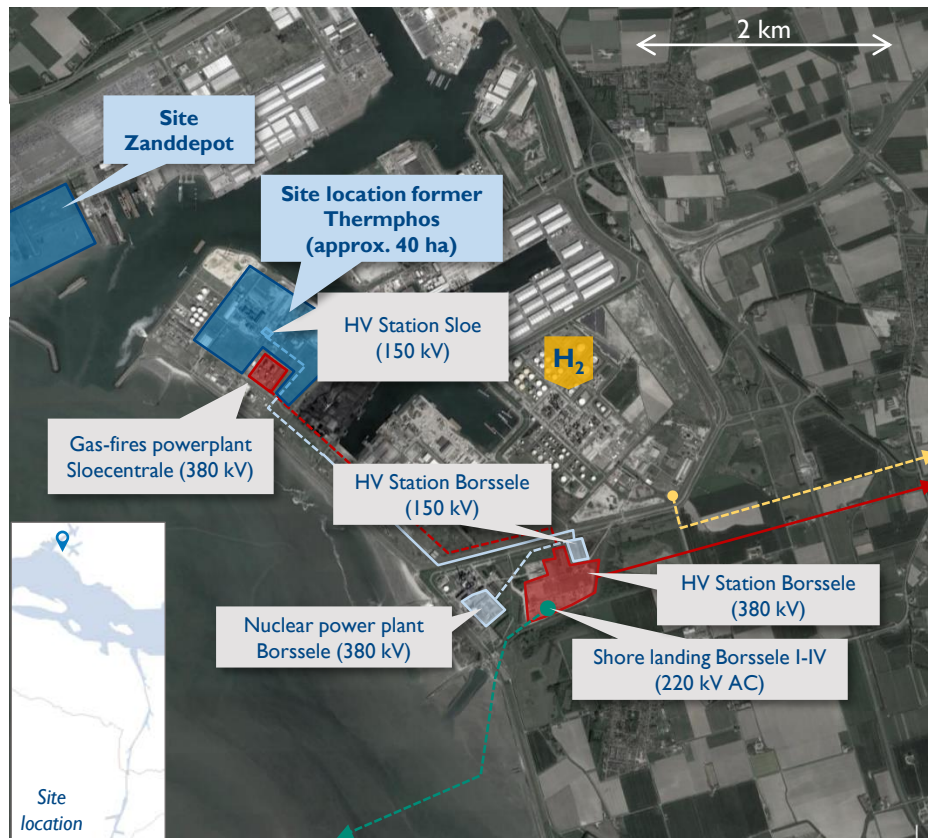
150 kV facility/cable



Relevant pipeline

Vlissingen-Oost (former Thermphos) is ideally situated near Borssele wind parks shore landing and offers space for GW scale electrolyzer

Vlissingen-Oost¹ – Central option



Description			
Former Thermphos site is located in the Port of Vlissingen. Site sufficiently large for an electrolyzer with a capacity > 10 GW and some H ₂ storage. Close to the Sloe power station and connected to the 380 kV grid. The ZR-DOW naphtha pipeline is close by and could provide cheap infrastructure for H ₂ transport. There is no O ₂ demand nearby. Discussions still to be held with North Sea Port concerning detailed site availability; alternative in the area could be the Zanddepot site on the other side of the harbor			
Onsite specifications			
Location (harbor #)	Vlissingen-Oost (9890)	Access	Accessible by road, rail & waterway
Size	~ 40 ha	Environmental Category	5.3 / 6
Infrastructure specifications			
Electrolyzer input		Electrolyzer output	
✓ 380 kV grid	Sloecentrale-Borssele cable on < 2000m ²	✓ Hydrogen pipeline(s)	ZR-DOW naphtha pipe <5km
✓ 150 kV grid	Former 150 kV HV Station Thermphos on site/close	■ Oxygen pipeline(s)	Potential small scale demand ZR <5km
✓ Demi water supply	Evides ³ does not expect problems in water supply	■ Waste water facilities	Potential synergies with Evides
✓ Nearby renew. energy sources	Shore landing of 1.4 GW Borssele I-IV on <4km	✓ District heating opportunities	Potential synergy with Sloe heat. Further exploration ongoing
Other	-	Other	-

1) In addition to the former Thermphos site, another option could be the Zanddepot in the same area across the harbor; 2) Cable owned by Sloe, not Tennet; 3) Evides already supplies i.a. Zeeland Refinery, Yara Sluiskil & Dow Terneuzen; Source: CUST Rapportage, Evides, Gasunie, Google Earth Pro, Hoogspanningsnet.com, North Sea Port, TenneT, Arthur D. Little

Engie's site in Rodenhuiize is connected to 380 kV grid and is located near future CCU projects at ArcelorMittal/Port of Ghent and Zeebrugge



ENGIE Rodenhuiize – Central option



Description

The site of ENGIE Rodenhuiize is located <4km south of ArcelorMittal. The site is large enough for an electrolyzer with more than 10 GW of capacity. This site also offers direct access to the 380 kV grid due to its proximity to the Rodenhuiize high voltage station. However, there is currently no infrastructure for hydrogen transportation, initiatives ongoing with future hydrogen consumers. Due to its proximity to ArcelorMittal, there is ample demand for the produced oxygen

Onsite specifications

Location (harbor #)	Rodenhuiize, BE (4040A)	Access	Accessible by road, rail & waterway
Size	70-75 hectares	Environmental Category	6

Infrastructure specifications

Electrolyzer input		Electrolyzer output	
✓ 380 kV grid	HV Station Rodenhuiize 380kV <100m	✗ Hydrogen pipeline(s)	Also, no large scale H ₂ demand close by yet ¹
✓ 150 kV grid	HV Station Rodenhuiize 150kV <100m	✓ Oxygen pipeline(s)	But potential large scale O ₂ demand at AM
✓ Demi water supply	Local water supplier Ghent	✓ Waste water facilities	Synergies with existing industrial cluster Rodenhuiize
✓ Nearby renew. energy sources	380kV connection BE off-shore wind Zeebrugge	✓ District heating opportunities	Studied in the Restwarmte Kanaalzone project
Other	-	Other	-

1) Initiatives ongoing with future H₂ consumers, e.g. planned H₂ demand ArcelorMittal by 2030 is 121 kt/a

Source: CUST Rapportage, Gasunie, Google Earth Pro, Hoogspanningsnet.com, North Sea Port, TenneT, Interview Engie, Website ENGIE Electrabel, Arthur D. Little



Hydrogen demand



Available electrolyzer site



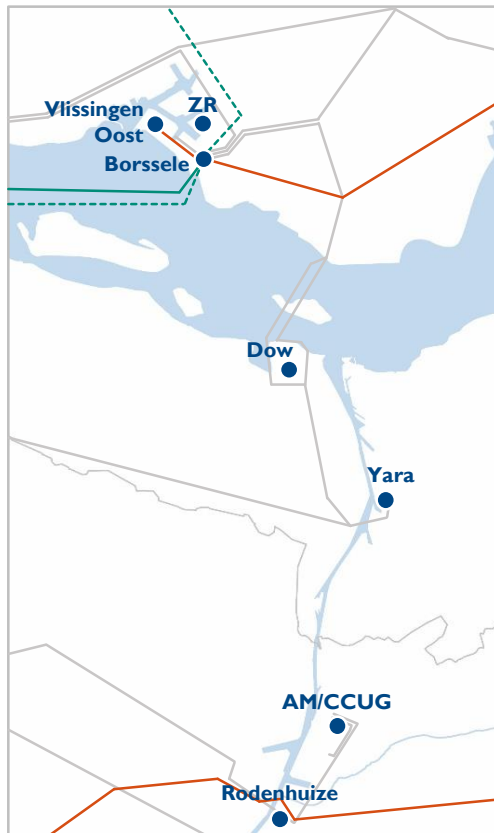
380 kV facility/cable



150 kV facility/cable

Existing 380 KV grid infrastructure can transmit sufficient renewable energy to large scale central electrolyzers in Vlissingen-Oost/Rodenhuize

Grid infrastructure¹



Grid infrastructure specifications²

Grid type	Location	Total capacity
150 kV grid	All relevant locations	250 MW ²
380 kV grid	Borssele Rodenhuize	2500 MW ²
Borselle I-IV landing	Borssele	1400 MW
IJmuiden Ver landing	Borssele / Geertruidenberg	2000 MW (another 2000 MW to land in Rotterdam)

Observations

- A large scale electrolyzer (>250 MW) should be placed in **Vlissingen-Oost** or **Rodenhuize**
 - Vlissingen-Oost/Rodenhuize are SDR only locations with existing 380kV connection
 - New high voltage grid segments take over 10 years to realize²
 - New connections to existing high voltage grid take < 2 years²
- At **Dow**, **Yara** and **AM/CCUG** the maximum on-site **electrolyzer** capacity is **limited to < 250 MW** (e.g. ~100 MW)²
 - 150 kV grid has a capacity of ~250 MW, a significant share of which is already used for existing power consumption²
- An electrolyzer in **Vlissingen-Oost** could absorb peaks of the wind farms, preventing need for grid reinforcement
 - Borselle I-IV is landed in Vlissingen-Oost
 - IJmuiden Ver's landing point still tbd; possibilities Vlissingen-Oost & Geertruidenberg³





Sources: 1) Hoogspanningsnet.com; 2)TenneT call (2019); TenneT website. Zeeuws-Vlaanderen desires to be connected to the 380kV grid; while this may take 10-15 years, this will make Yara/Dow viable central locations as well; 3) High desirability for landing in Vlissingen-Oost (costs)

An extensive network of existing gas infrastructure can transport large volume of hydrogen throughout the SDR region

Grid infrastructure



Grid infrastructure specifications

Pipeline	Availability
 Dow-Yara Hydrogen	Current operation for H ₂ in a divergent quality; able to facilitate regional demand to 2030 ⁶
 ZR-Dow Naphtha	Possibilities for converting, but competing interest for CO ₂ transport ⁶
 Zebra network Hydrogen Backbone	Option to convert for H ₂ transport & backbone connect, facilitate regional demand to 2030. Compete with CO ₂ ⁶
 Midden Zeeland pipeline	Possibilities to convert from gas to H ₂ . A possible new route can be developed if market commitment exists

Observations

- The SDR region boasts an **operational H₂ pipeline** between **Dow and Yara**
- The **H₂ backbone** connecting the SDR region to salt cavern H₂ storage is planned to be **operational from 2028⁶**
 - Initially, a connection will only be realized south of the Westerschelde³
- The **naphtha pipeline** between ZR and Dow can be **converted to H₂**, serving as potential crossing of the Westerschelde until the H₂ backbone is operational. With the Dow-Yara pipeline, the ZR-Dow pipeline could form a **regional hydrogen network**
- There are **competing interests** to convert existing pipelines for **CO₂** rather than **H₂** transport; choices have to be made based on market demand
- Realizing a **regional harbor H₂ backbone** requires existing infrastructure to be converted (or new to be created) to connect **AM / Rodenhuize**, for which **no current plans exist**

Notes: 1) Under 'capacity' are listed: outer diameter (inch), maximum operating pressure (bar) and hydrogen transport capacity (MW equivalent); 4) Estimation, to be verified; 5) Calculation, assuming 120 MJ/kgH₂

Sources: 2) Risicokaart.nl (2020; no in depth-assessment done); 3) Stroomstudie energie-infrastructuur Zeeland (CE Delft, 2020); 6) Input Gasunie by email (June 2020)

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Chapter summary

Electrolyzer roadmap

- An electrolyzer **roadmap** has been defined for the SDR region by Arthur D. Little
 - In **2022-2023**, Yara and ZR can **kick-start** electrolytic hydrogen production in the region with **100 MW** on-site projects
 - These 100 MW projects would immediately **reduce CO₂** emission by **~70 kt/a each**
 - In **2024-2027**, **690 MW** total electrolyzer capacity is planned, of which **490 MW** is **centrally** located in **Vlissingen-Oost**, from which existing gas infra will be able to transport hydrogen. This total electrolyzer capacity can help **reduce CO₂** emissions by **~ 500 kt/a**
 - Around **2028-2030**, the hydrogen **backbone** enables **1 GW** capacity in **Vlissingen-Oost** and **new processes** will demand **2.4 GW** electrolyzer in **Rodenhuize**
 - The capacity in Vlissingen-Oost will allow for SMRs in the region to be temporarily switched off or even phased out. **CO₂** emission **avoidance** of **~740 kt/a** can be achieved with **1 GW** electrolyzer capacity
 - In **Rodenhuize**, the nearest location to the 380kV grid, the requirement of **190 kt/a** electrolytic **H₂** at **ArcelorMittal** and the **CCU hub Ghent** requires a **2.4 GW** electrolyzer. Both ArcelorMittal/CCU hub and the Rodenhuize electrolyzer would have to be connected to the hydrogen **backbone** with **cross-border pipelines**
 - Around **2050**, up to **~ 10 GW** electrolyzer capacity could be located in **Vlissingen-Oost** and **Rodenhuize**, achieving **CO₂ neutrality** for the SDR region¹

1) Achieved fully by green H₂, but possibly also by combining with blue and maybe orange H₂

In **2022-2023**, Yara/ZR can kick-start electrolytic hydrogen production in the region with 100 MW on-site projects, reducing CO₂ by ~ 70 kt/a

Electrolyzers & gas infra



Observations

- A **GW scale electrolyzer** (in Vlissingen- Oost or Rodenhuize) requires supportive **infrastructure**, which takes several years to realize:
 - **690 MW** electrolyzer commissioning
 - **380 kV grid** construction (e.g. from landing point to electrolyzer site)
 - **H₂ pipeline** construction (e.g. between Vlissingen-Oost and ZR) and conversion (e.g. naphtha pipeline between ZR and Dow)
- **On-site projects** allow **ZR / Yara** to **kick-start** electrolytic H₂ production, without need for supportive infrastructure
- The scale of the on-site **electrolyzers** will be **limited** to the **~100 MW** capacity of the 150 kV grid and the available area²
- These **on-site** projects are intended to **kick-start** the region's **H₂ project**, on a way to realize the **ambitions** set out by **SDR** – they already **reduce CO₂ emissions** by **~70 kt/a** for each 100 MW electrolyzer

1) Assuming 4000 load hours; 2) Zeeland Refinery has designated ~ 1 ha for a 100 MW electrolyzer; a large scale electrolyzer requires at least 3-4.5 ha / GW. While ZR might have another 4-9 ha of land available, this is currently earmarked for internal ZR requirements

In **2024-2027**, Vlissingen-Oost is well-suited for 490 MW central electrolyzer capacity, enabling total SDR NL to reduce CO₂ by ~ 500 kt/a

Electrolyzers & gas infra



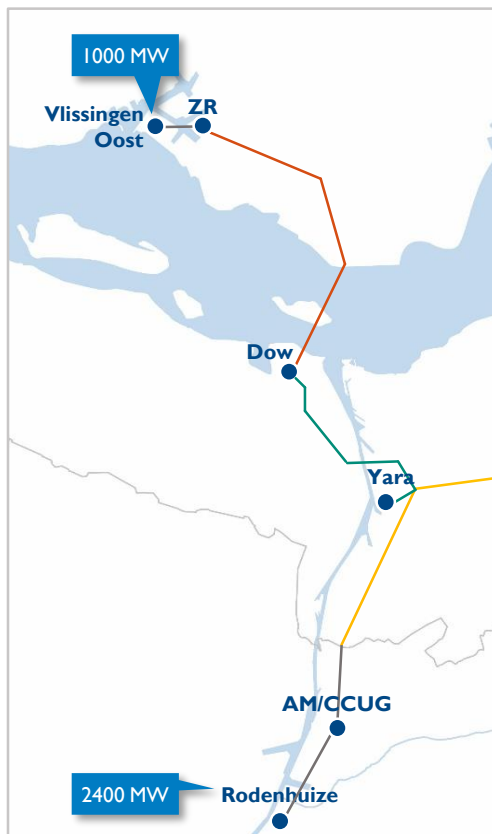
Observations

- Before salt caverns can be accessed via the **H₂ backbone** in **2028**, NL SDR's total electrolyzer capacity can reach up to **690 MW¹**,
 - Producing **55 kt/a H₂** at 4000 load hours
 - CO₂ emissions reduced by **~500 kt/a**
- The ambition to add **490 MW** capacity requires a large scale electrolyzer in **Vlissingen-Oost**
 - A 380 kV connection is required for a large scale electrolysis (>250 MW); the 380 kV grid passes Vlissingen-Oost
- **Existing gas infrastructure** is almost entirely sufficient for **peak production** capacity
 - Naphtha pipeline between ZR and Dow has sufficient capacity
 - Pipeline construction (~ 5km) between Vlissingen-Oost and Zeeland Refinery is required
- **Dow-Yara pipeline** transports H₂ as by-product of cracking (impurities); decision needed regarding pipeline usage and purification² location

1) Assuming 4000 load hours; 2) Options include: i) Yara will receive a mix of pure electrolytic hydrogen and impure cracker hydrogen through a single pipeline, purification is done at Yara; ii) Yara will receive a mix of pure electrolytic hydrogen and purified cracker hydrogen through a single pipeline, purification is done at Dow; iii) Yara will receive hydrogen through two pipelines: one for pure electrolytic hydrogen and for impure cracker hydrogen, purification is done at Yara

Around 2028-2030, H₂ backbone enables 1 GW capacity in Vlissingen-Oost and new processes will demand 2.4 GW electrolyzer in Rodenhuize

Electrolyzers & gas infra



Observations

- From **2028**, the ambition for the **H₂ backbone** is to connect **Yara** (and Zeeuws-Vlaanderen) to **salt cavern storage**
 - in 2030 the backbone will not yet connect north of the Westerschelde (Gasunie plans²)
- **Connection between Vlissingen-Oost, ZR and Yara** needs to be realized by a **regional pipeline** across Westerschelde
 - Until 2030, existing pipeline between ZR/ Dow is sufficient for electrolytic H₂
 - If needed, additional H₂ pipeline trans-Westerschelde pipeline can be constructed²
- Around **2030**, electrolyzer **capacity** for ZR / Yara will be expanded to **1000 MW**. SMRs no longer operate at >70% capacity to function as back-up; ZR/Yara can switch off (temporarily) or even phase out SMRs³
 - **CO₂ emission avoidance** of ~740 kt/a is achieved with 1 GW electrolyzer
- **AM/CCUG's 190 kt/a electrolytic H₂ demand** requires **2.4 GW electrolyzer** in Rodenhuize (nearest location to 380kV grid)
- **AM/CCUG and Rodenhuize electrolyzer** have to be **connected** to the **Gasunie backbone** with **cross-border pipelines**⁴

1) Assuming 4000 load hours; 2) Source: CUST rapportage; 3) SMRs can be kept open, to keep flexibility, but coupled with CCU/S, i.e blue hydrogen: 4) AM/CCUG will have to be connected to the hydrogen backbone because AM/CCUG's hydrogen demand is constant over time, AM/CCUG don't have local SMRs that can serve as back-up, and Belgium does not have salt caverns

Around **2050**, up to ~10 GW capacity could be located in Vlissingen-Oost and in Rodenhuize, achieving CO₂ neutrality for the region

Electrolyzers & gas infra



Observations

- ~ **2050**, the **SDR** region's complete **H₂ demand** can be met with **electrolytic H₂** from renewable energy
 - ~830 kt/a electrolytic H₂
 - Requiring ~10 GW capacity¹
 - Potential H₂ demand of AM/CCUG exceeds that of ZR/ Yara
- **H₂ backbone** will run along the **north** and **south** of the **Westerschelde** and interconnect **Vlissingen-Oost** and **Yara** (Gasunie plans for 2050²)
 - Role of regional trans-Westerschelde H₂ pipeline is to be determined
- As **all H₂ users** are **interconnected**, electrolyzer **locations** depend on the **landing point of renewable electricity** in Vlissingen-Oost and transport of renewable electricity to Rodenhuize³
- **2050 SDR vision** assumes region **H₂ demand** is fully met by **green H₂** in combination with **blue, yellow** and (if feasible) **orange H₂**. Gas infra and 380kV grid will have to be strengthened / expanded
 - Region is **CO₂ neutral**

1) Assuming 4000 load hours; Sources: 2) Stroomstudie energie-infrastructuur Zeeland (CE Delft, 2020); 3) Availability of renewable energy will determine electrolyzer size limit

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Chapter summary

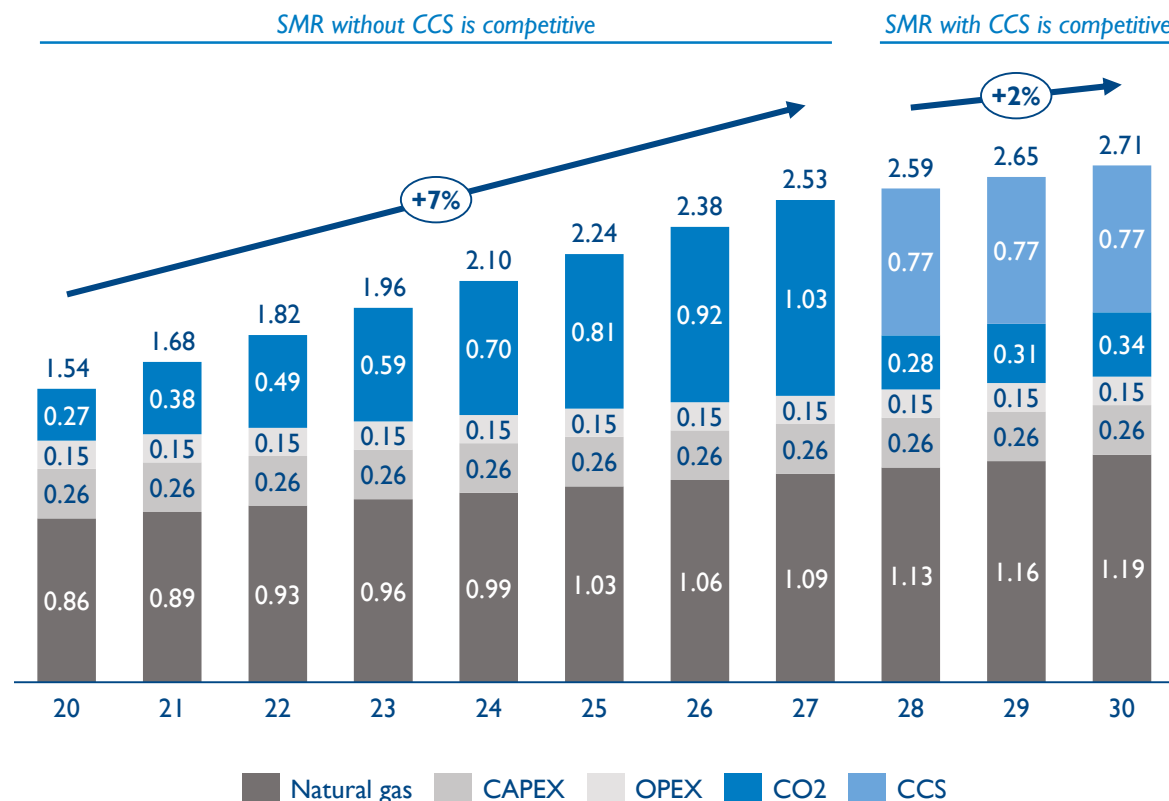
Business case

- The cost of **SMR hydrogen** is forecasted to increase to **€ 2.71/kg** by **2030** from **€ 1.54/kg** today, following **ETS/CO₂ tax** increases
 - Electrolytic **H₂** produced at **8000 load hours** is forecasted to cost **€ 3.33/kg** in **2030**
 - By **optimizing** the number of load **hours** to **6000**, the electrolytic hydrogen **cost** can be reduced to **€ 3.20/kg**
- The lowest possible price for electrolytic hydrogen is **€ 2.90/kg** (at **4000 load hours**) if existing transmission **tariff discounts** would be applicable
- The **unsubsidized** production of hydrogen based on a **1 GW electrolyzer** leads to significant **annual losses** regardless of the number of load hours
- Various **EU** and **national subsidies** could **enhance** the **business case** for electrolytic hydrogen production
 - If awarded, the Dutch **SDE++** subsidy seems to be the most impactful, fully covering the unprofitable top margin of electrolytic hydrogen production. However, it only subsidizes **2000 load hours**
 - Extending this to **4000 load hours**, the **SDE++** subsidy would enable a **1 GW electrolyzer** to make a **profit** of **€ 5 mln/a** in **2030** (no tariff/taxes discounts for green H₂)
 - Operating at **4000 load hours** **avoids** total **CO₂ emissions** of **740 kt/a**

The cost of SMR hydrogen is forecasted to increase to € 2.71/kg in 2030

SMR-based hydrogen cost prices

Forecast: 2020-2027 without CCS, 2028-2030 with CCS, €/kg



Observations

- The most economical method of processing CO₂ determines the competitive SMR hydrogen price
 - In SMR H₂ production without CCS, 9 tCO₂/tH₂¹ is emitted, increasingly taxed
 - In SMR H₂ production with CCS, 75% of CO₂ is captured and stored, the rest emitted / taxed
- SMR without CCS is forecasted to be the most economical method to produce SMR H₂ until 2027
 - CO₂ tax forecasted to increase by ~17% CAGR (€ 0.27 to € 1.35/kgH₂) between 2020 / 2030³
 - SMR hydrogen cost price will increase by ~7% CAGR (from € 1.54 to € 2.53/kgH₂) between 2020 and 2027
- SMR with CCS is forecasted to be most economical method to produce SMR-based hydrogen from 2028¹
 - CCS costs are approximated to remain stable at 0.77 €/kgH₂ (114 €/tCO₂)
 - Costs for SMR H₂ with CCS will continue to increase due to rising gas prices (3% CAGR) and rising CO₂ taxes (for non-captured CO₂)

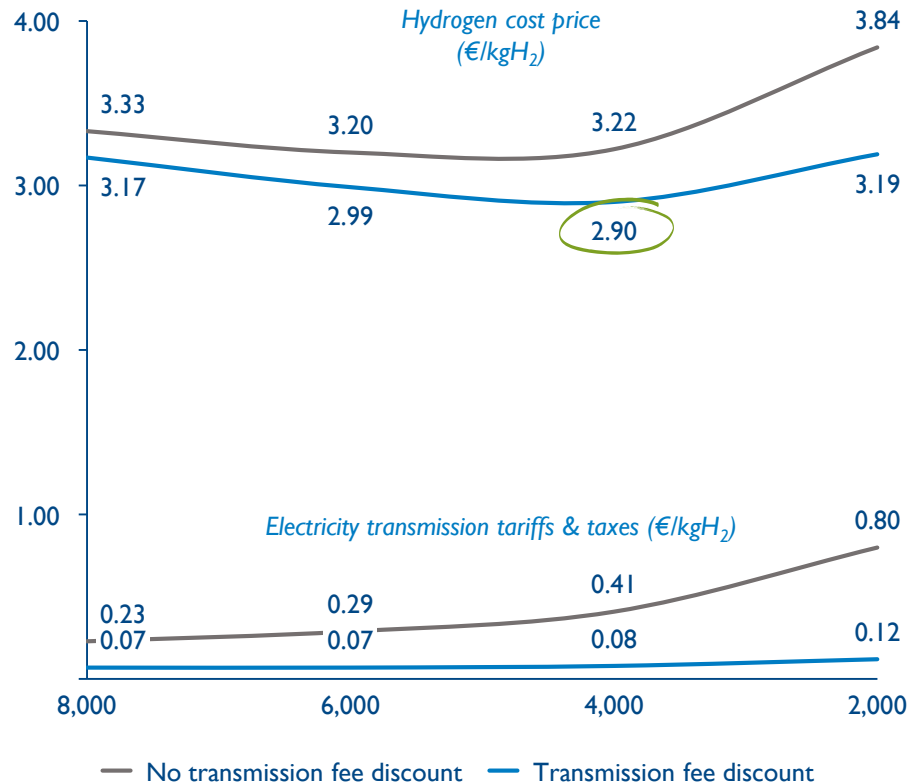
Sources: Please refer to assumption overview in the appendix of this document

Note: 1) CCS is dependent on the infrastructure to capture, transport and store CO₂, which is currently lacking in the SDR region; 2) Natural gas price is traded price

The lowest possible price for electrolytic hydrogen is € 2.90/kg (4000 load hours) if existing transmission tariff discounts would be applicable

Impact transmission fee discount

Various load hours, 1 GW, 2030, NL tariffs/taxes¹



Key assumptions & observations

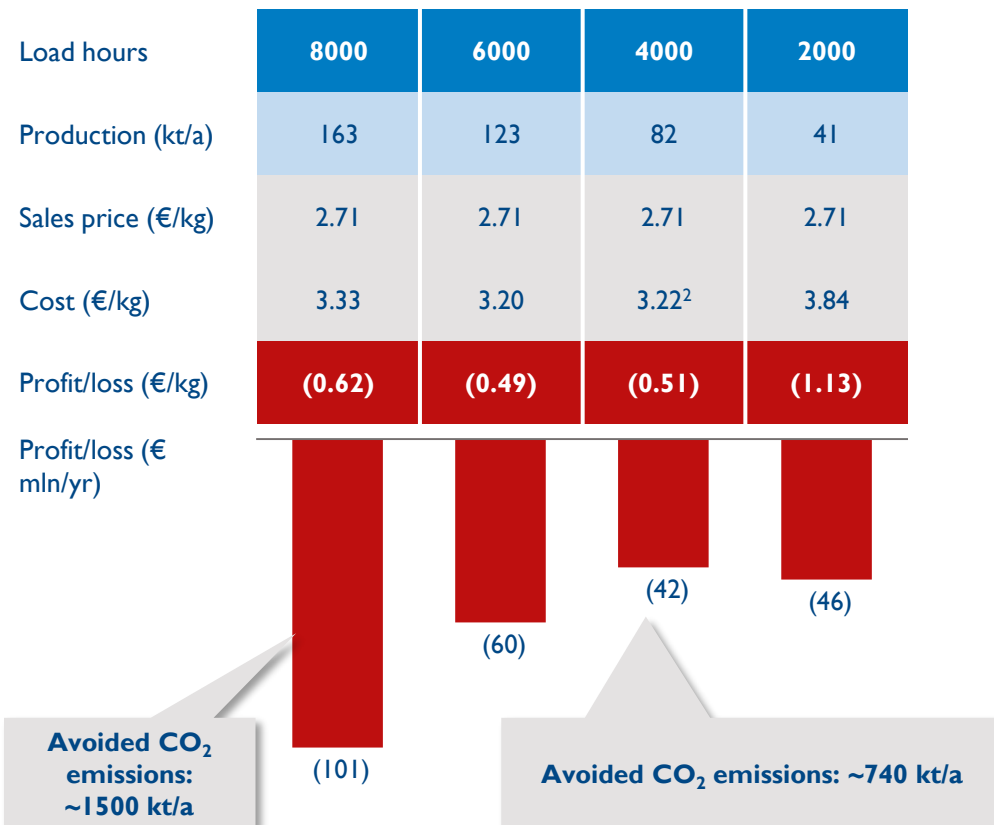
- The Dutch 380 kV² electricity transmission tariffs (TT) are assumed, as set out by the Dutch energy regulator ACM
 - Majority of TT are calculated on capacity basis (per kW), rather than consumption basis (per MWh)
 - So these (fixed) TT costs increase on a per kg H₂ basis as the number of load factor decreases, as distributed over fewer kgs; TT costs increase by over 200% per kg hydrogen, when decreasing the load hours from 8000 hours to 2000 hours
- Consequently, the TT costs are a significant share of the hydrogen cost price per kg at fewer load hours. TT costs represent 8% of cost per kg at 8000 load hours, which increases to 21% at 2000 load hours
- The ‘Energiewet 1998’ stipulates a discount on TT of up to 90% for users of > 50 GWh with uptime of at least 65% in off peak hours (23:00-7:00), to stimulate electricity use during off-peak hours³
- A TT discount of 90% when using renewable electricity to produce H₂ significantly improves unit economics. By 2030 electrolytic H₂ cost could come down to € 2.90/kg at 4000 load hours, € 0.19 more than SMR H₂
- A discount would be in the interest of grid operator and in line with government policy; it drives electricity consumption at times of renewable electricity over-supply and prevents grid congestion while stimulating the energy transition
 - Load shedding in case of grid congestion can also lead to TT discounts, feasible if operated in combination with H₂ storage

1) Key assumptions: AEL electrolyzer, no hydrogen storage (the other base-case assumption on which these cost price forecasts are based can be found at the end of this document); 2) The T&T costs are even higher for 150 kV grid; 3) Offtakers receive between 0 and 90% with a load factor between 65 and 85% (linear increase, load factor above 85% results in 90% discount); Source: Arthur D. Little analysis

Unsubsidized H₂ production by a 1 GW electrolyzer is loss-making, load hours independent; at 4000 hrs minimum loss, avoids ~740 kt/a CO₂

Profitability at various load hours

1 GW, 2030, incl. NL tariffs and taxes (no discount)¹



Observations

- The production of **electrolytic hydrogen** based on a **1 GW electrolyzer** built in **2030** is forecasted to be **unprofitable, regardless** of the number of **load hours**
 - The cost disparity between electrolyzer-based hydrogen and SMR-based hydrogen is forecasted to vary between € 0.62 and € 1.13 per kg for 8000 to 2000 load hours
 - The minimum cost disparity per kg is forecasted at 6000 load hours (€ 0.49/kg H₂), but 4000 load hours leads to a very similar cost price that is only € 0.02/kg higher
- Operating a **1 GW electrolyzer** in **2030** is forecasted to lead to a minimal **total loss** of **€ 42 mln/yr**, when operated at **4000 load hours**
 - At 6000 load hours the loss per kg hydrogen is slightly lower, but the amount of hydrogen produced is 50% higher, resulting in a higher overall loss
 - At 2000 load hours the amount of hydrogen produced is 50% lower, but the loss per kg H₂ is € 0.62 per kg higher, resulting in a higher overall loss

1) Key assumptions: AEL electrolyzer, no hydrogen storage (the other base-case assumption on which these cost price forecasts are based can be found at the end of this document); 2) If transmission tariffs are discounted, this cost reduces to € 2.90/kg

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A number of recommendations are made for enhancing the chances of a successful implementation of a GW electrolyzer in SDR region

Recommendations

#	Recommendations
1	Start decentralized projects at Yara / ZR to enable CO ₂ emission reductions asap and show how SDR region can lead the way with green H ₂ , and aid achievement of NL climate agreement. Ensure close coordination to enable economies of scale with respect to procurement, subsidies, publicity
2	Initiate creation of business case for regional H ₂ backbone with connection to countrywide H ₂ backbone
3	Prepare for planning central electrolyzer in Vlissingen-Oost and Rodenhuize
4	Market the SDR plan and region to allow for investment preferences for the SDR region
5	Immerse in SDE++ and prepare for submission. Build understanding of timing/other requirements to apply for other NL/BE/EU subsidies (e.g. IPCEI)
6	Expand offshore wind landing in SDR region to ensure sufficient green electricity availability in the longer term (> 2030)
7	Enhance the 380kV electricity grid in Zeeuws-Vlaanderen to enable multi-GW scale electrolyzers in NL SDR in the long run (> 2030)

#	Key conditions
1	Discount on electricity transport tariffs
2	Connection to H ₂ backbone
3	SDE++ subsidy increase to 4000 load hours ¹
4	Subsidies combination from various sources (e.g. SDE++ and DEI+)
5	Legal maximum hydrogen transport and storage fee (as Gasunie holds a monopoly; this is already in place for natural gas)
6	ETS certificates awarded even if electrolytic hydrogen is sourced off-site/internationally

1) Current logic states that only 2000 load hours are 100% renewable; 4000 load hours however will increase demand of electricity during all hours that renewables are produced

Immediate actions start with Consortium members defining interest and roles in the implementation of a GW electrolyzer in SDR region

Immediate action plan

TIMING TBD

Action	Comment
1 Role distribution of consortium members (and 3 rd parties) to be agreed for the implementation (develop, build, operate)	Earlier conversations around interest (WSIII) should be solidified. 3 rd parties can also be engaged, e.g. notably Air Products has expressed specific interest to be involved in building or operating an electrolyzer
2 Debate and decide on desired ownership and ownership structure (e.g. corporate, PPP, institutional investors)	Depending on outcome, an investor package for the project may need to be created
3 Create and staff a separate and independent Project Management Office (PMO) for the entire implementation phase	PMO charter needs to cover at least organization, remit, funding, timing, resource requirements and governance. It may be best served by setting up a separate legal entity
4 Prepare and execute lobby and marketing campaign	As the recommendations indicate, lobbying will be required to influence the business case (e.g. transport tariffs). A marketing campaign, once above issues, particularly around ownership, have been resolved, needs to be designed and executed to help boost the region's competitive position

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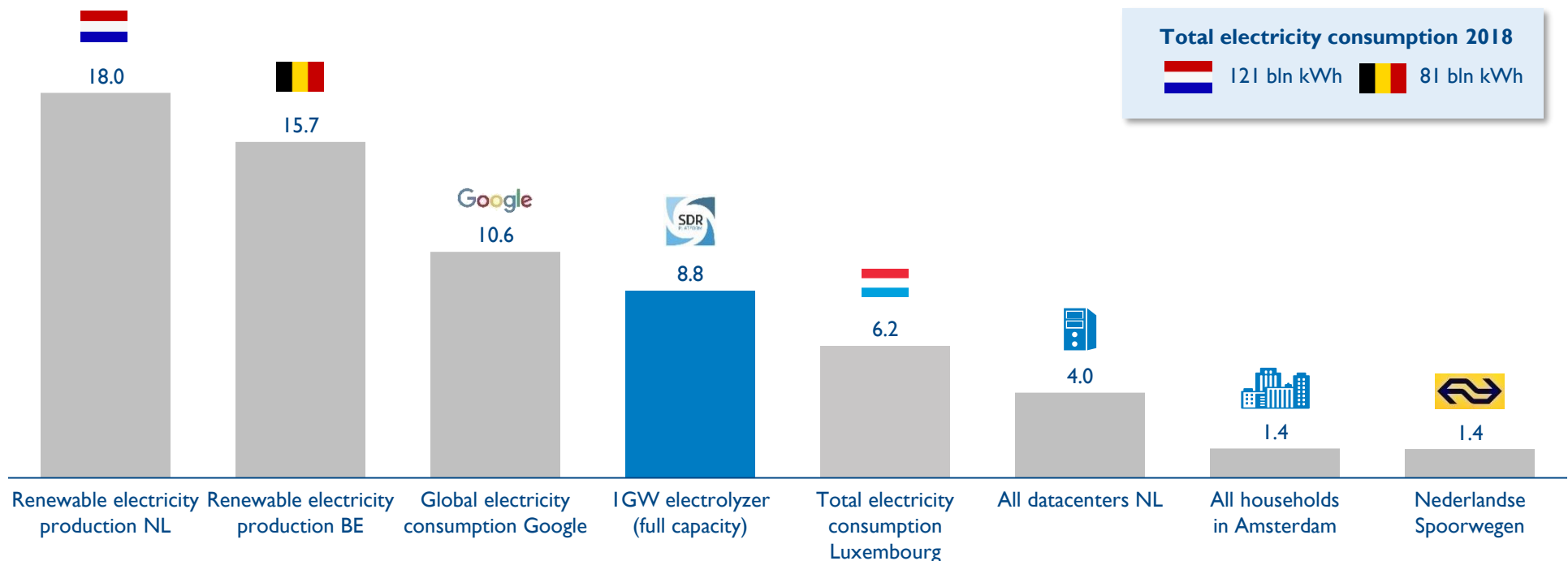
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A.1 Renewable electricity in SDR region

A.2 Boundary conditions

A IGW electrolyzer in the SDR region will be a very large electricity user compared to e.g. BE/NL renewable production as well as data centers use

Major electricity consumers & producers 2018, bln kWh

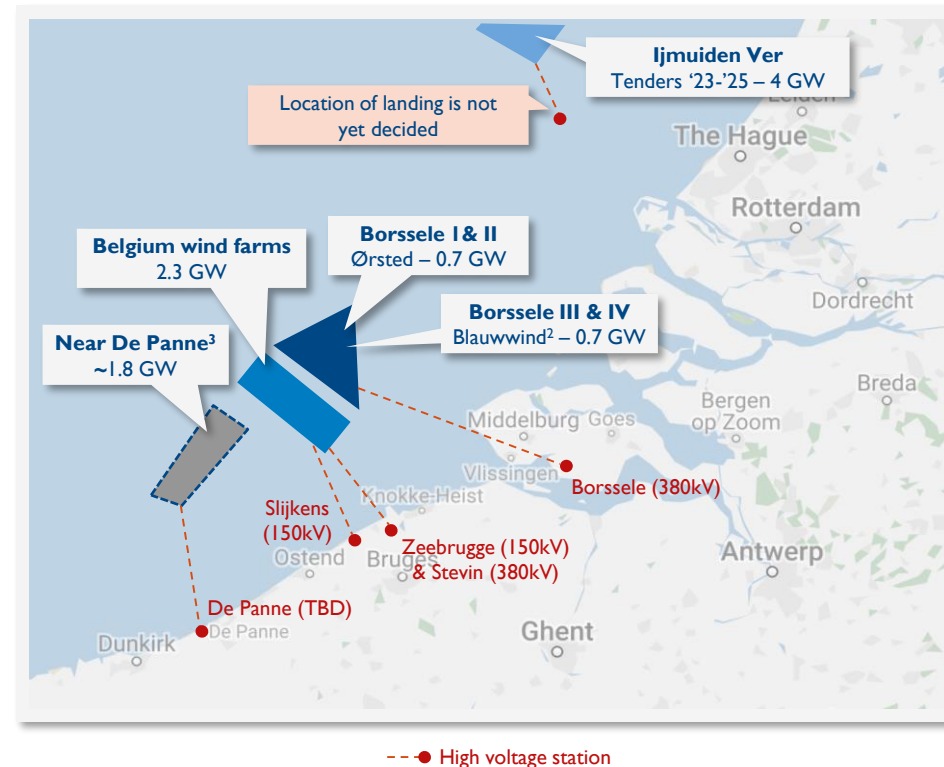
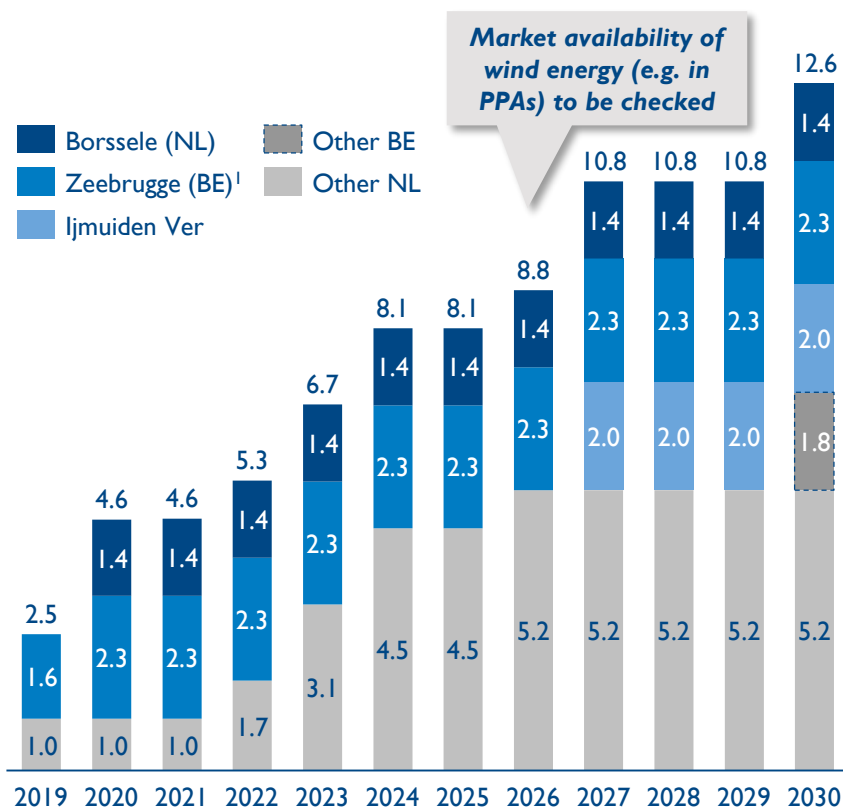


Given the scale of the project, close collaboration with the Dutch and Belgium TSO's, respectively TENNET and Elia, will be essential for success

By 2030, ~12.6 GW offshore wind capacity is installed along the Dutch and Belgium coastlines with 3.7 – 7.5 GW landing near the SDR region

Offshore wind outlook SDR region, 2019-2030, GW

PRELIMINARY



1) Includes wind parks landing at the Slijkens, Zeebrugge & Stevin stations; 2) Consortium of Partners Group (45%), Shell (20%), DGE (15%), Eneco Groep (10%) & Van Oord (10%); 3) Potential new location for Belgium offshore wind parks by 2030, based on early stage plans of the Belgium government
Source: 4C Offshore, Belgium Offshore Platform, Hoogspanningsnet.com, Net op Zee, Rijksoverheid, Van Oord company website, VRT, Arthur D. Little

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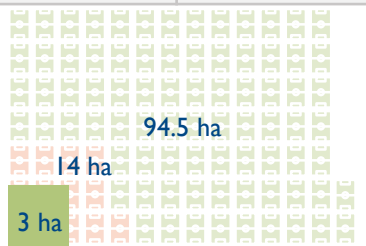
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A.1 Renewable electricity in SDR region

A.2 Boundary conditions

For a GW scale electrolyzer and associated equipment between 14 - 95 hectares is required, depending on i.a. chosen technology & storage

Breakdown of area requirements for a 1GW electrolyzer

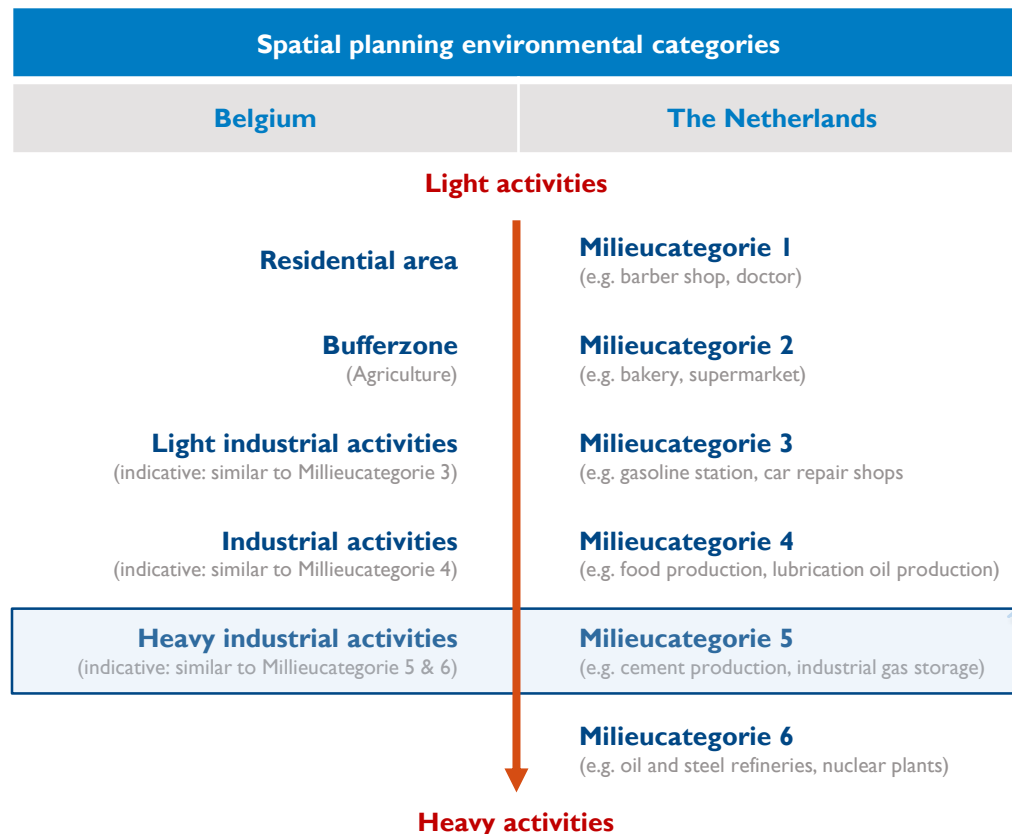
	Electrolyzer incl. BoP		Hydrogen storage (at 200 bar)		Safety Zone ¹		Total	
	AEL	PEM	0.5 kton	7 kton	No storage	Storage (7 kton)	Lower limit	Upper limit
Area (ha)	4.5	3	0.3	4	Min. 11	Min. 86	14	94.5
Specifics	Consists of: <ul style="list-style-type: none"> Stacks (~ 5-10%) Electricity supply (~ 15-20%) <ul style="list-style-type: none"> Transformers Rectifiers Pumps (~ 8-14%) Heat-exchangers (~ 5-10%) Separators (~ 8-14%) Compressors (~12-18%) Monitors (~ 1-4%) Void space (~ 25-40%) 		<ul style="list-style-type: none"> 0.5 kton hydrogen is roughly equivalent to daily production of a 1GW electrolyzer 7 kton hydrogen is roughly equivalent to the production of 2 weeks Size is highly dependent on the required storage capacity Inflow and outflow debit of hydrogen determines the amount of compressors that are needed and thus also influences the total required area 		<ul style="list-style-type: none"> 'Safety Zone' is the distance that an industrial facility needs to be from non-industrial area², but this does not need to be owned by the owner of the electrolyzer In NL this is determined by the 'milieucategorie' of the facility and for BE it is defined by the principle of 'inwards zoning' For a electrolyzer this distance is approx. 200m – 300m, and for hydrogen storage this distance is approx. 500m - 700m 		 <ul style="list-style-type: none"> Lower limit is based on PEM without hydrogen storage, safety zone outside the plant Upper limit is based on AEL with 7kton hydrogen storage, including safety zone 	

A minimum of 14 ha is required for a 1 GW electrolyzer including the safety zone in the absence of any storage facilities

1) Based on a square electrolyzer site of 3 ha; 2) The required distance to residential areas is larger, respectively 300 m and 1000 m for an electrolyzer without - and with hydrogen storage
Source: CE Delft; ontwikkelstrategie energietransitie NZKG, Website Nel hydrogen, Arthur D. Little analysis

Both in Belgium & The Netherlands an future electrolyzer site must be designated for heavy industrial activities according to land-use plans

Environmental categories in spatial planning BE vs. NL



- Both in BE and NL all municipal areas are designated for a certain type of activity ranging from housing to heavy industry
 -  In NL, each area is assigned an environmental category that defines the type of business that can settle there
 - Businesses are categorized into an environmental category (NL: 'Milieu categorie') ranging from 1 to 6 based on their activity profile
 - An electrolyzer will likely be classified as a **milieucategorie 5.3** industry activity¹
 -  In BE, municipalities also designate zones in different categories that determine which type of business can operate therein
 - In Flanders, the VLAREM law classifies business by activities in different environmental categories
 - There is no as comprehensive register of activities as in NL and no classification for an electrolyzer exists
 - An electrolyzer is assumed to be classified as **heavy industry activity**²

 Likely category of an electrolyzer with storage

1) Currently no categorization exists within legislation, an estimation is thus made based on CE Delft a study;

2) Belgian categorization of electrolyzer is assumed to be classified as similarly heavy industrial activity as it could be on the Dutch Milieucategorie scale

Source: CE Delft, Rijksoverheid, VLAREM, Arthur D. Little

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