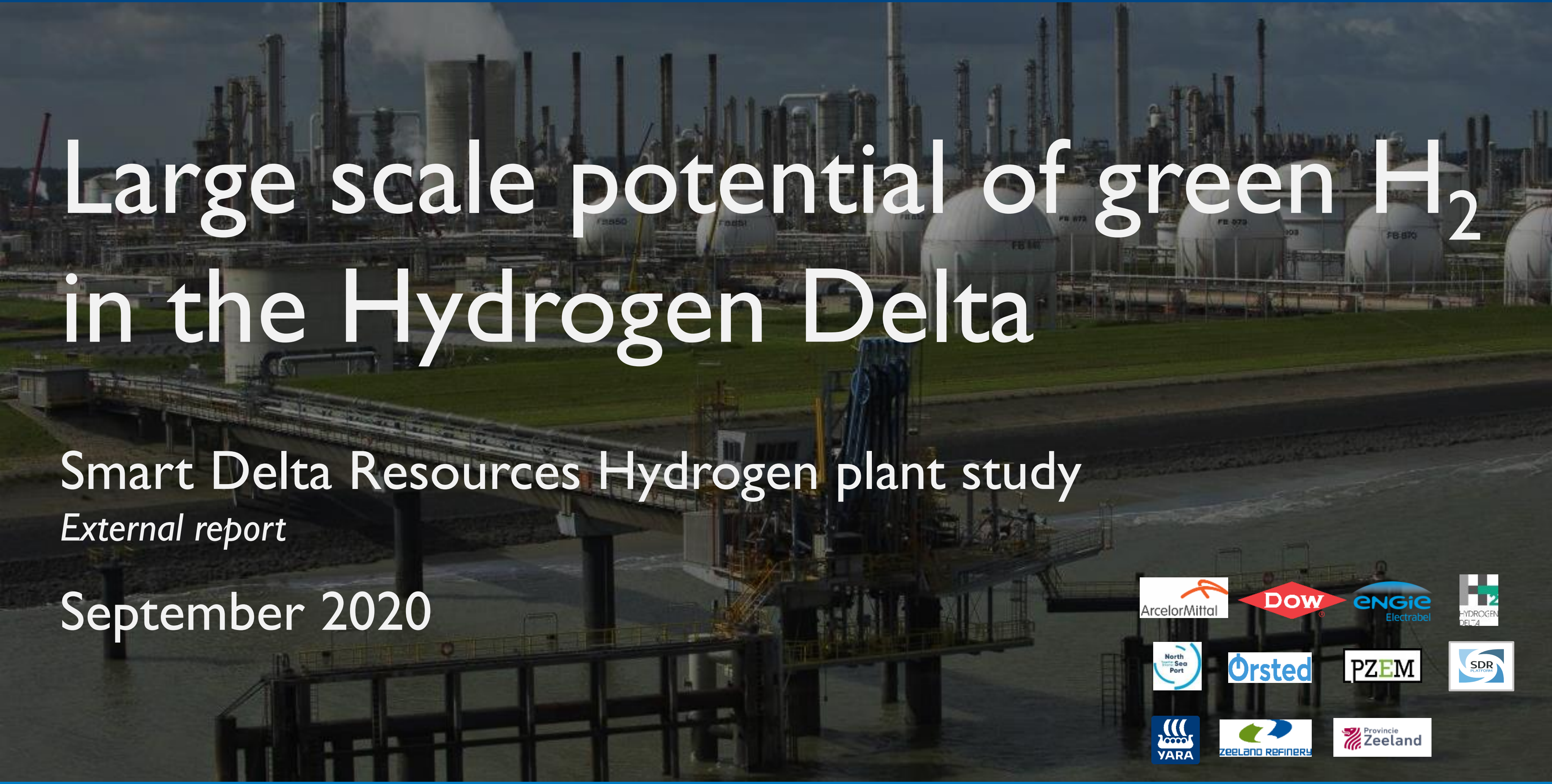
Arthur D Little



Large scale potential of green H_2 in the Hydrogen Delta

Smart Delta Resources Hydrogen plant study

External report

September 2020

ArcelorMittal
Dow
ENGIE Electrabel
Hydrogen Delta
North Sea Port
Ørsted
PZEM
SDR Platform
YARA
Zeeland Refinery
Provincie Zeeland

External report for SDR Consortium

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.

Arthur D. Little has not audited, nor should it be construed to have audited, any of the information provided to it by the SDR consortium or any other party. Arthur D. Little takes no responsibility for inaccurate information which has been supplied to it and any conclusions or opinions drawn from or relating to such information.

Arthur D Little specifically and expressly disclaims to the maximum extent permitted by law all liability to any third party, other than the SDR consortium, for any loss, damage, cost or expense of any kind whatsoever as a result of any inaccuracy, misinterpretation or omission in this report

Source: Arthur D. Little

This document contains the results of the study into a 1GW electrolyzer in the SDR region in the period Sept 2019 to May 2020

Project timing & available data

Project timing	Start of project	September 23rd, 2019
	End of project and report delivery	End of project May, 2020 Final report delivery July 3rd, 2020
Project duration	Seven months	
Interaction with SDR consortium	■ 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	■ Arthur D. Little has collected a high quantity of data for this study, which have not been independently assessed for robustness	

Source: Arthur D. Little

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

Source: Arthur D. Little

Table of contents

Page

1 Summary 6

2 Hydrogen demand in SDR region 10

3 SDR ambition 18

4 Existing infrastructure 30

5 Electrolyzer roadmap 40

6 Business case 2020-2030 46

7 Recommendations & action plan 51

A Appendix 54

Executive summary (1/3)

H_2

- **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 **CO_2-neutral** industry in their region by 2050. Key to this is the production of **green H_2** (electrolysis powered by CO_2-neutral electricity)[1]
- The SDR region is **well positioned** for large scale and fast implementation of electrolyzer-based green H_2 production:
  - Large current **H_2 demand** (~ 400 kt/a) that is forecasted to **double** by **2050** through significant planned green H_2/CCU projects; large scale **O_2 outlet**
  - Proximity to ample **renewable energy** supply (and possibly nuclear energy)
  - Existing gas / 380kV electricity **infrastructure**
  - Excellent opportunities for (connection to) a **H_2 backbone**
  - **Electricity balancing** options in BE/NL
  - Specific **SMR H_2 production** setups allow rapid deployment of electrolyzers

  For many of the Consortium members, **lowering CO_2** emissions is **mission critical** for long term survival in the region

---

[1] SDR foresees this to be supported by **blue** H_2 (CCS), **yellow** H_2 (import) and possible **orange** H_2 (nuclear)

Executive summary (2/3)

H_2

- 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 H_2 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 **CO_2 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 H_2)
  - **2028 – 2030**: After connection to the NL H_2 backbone, electrolyzer capacity can be expanded to **1 GW**, resulting in **CO_2 reduction** of **~ 740 kt/a** (4000 load hours/yr; producing 80 kt/a H_2)

    In Rodenhuize, requirements of 190 kt/a electrolytic H_2 at ArcelorMittal and CCU Hub Ghent necessitate additional 2.4 GW capacity. Connections to the NL H_2 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) H_2). The SDR region is **CO_2 neutral**

Executive summary (3/3)

H_2

- Lowest unsubsidized green **H_2** 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 H_2 in 2030, which is expected to increase to **€ 2.71/kg** by then (impact of ETS/CO_2 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 **H_2 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 if multi-GW scale electrolyzers will be located in Zeeuws-Vlaanderen in the long run (> 2030)

Table of contents

Page

1 Summary 6

2 Hydrogen demand in SDR region 10

3 SDR ambition 18

4 Existing infrastructure 30

5 Electrolyzer roadmap 40

6 Business case 2020-2030 46

7 Recommendations & action plan 51

A Appendix 54

Chapter summary

Hydrogen demand in SDR region

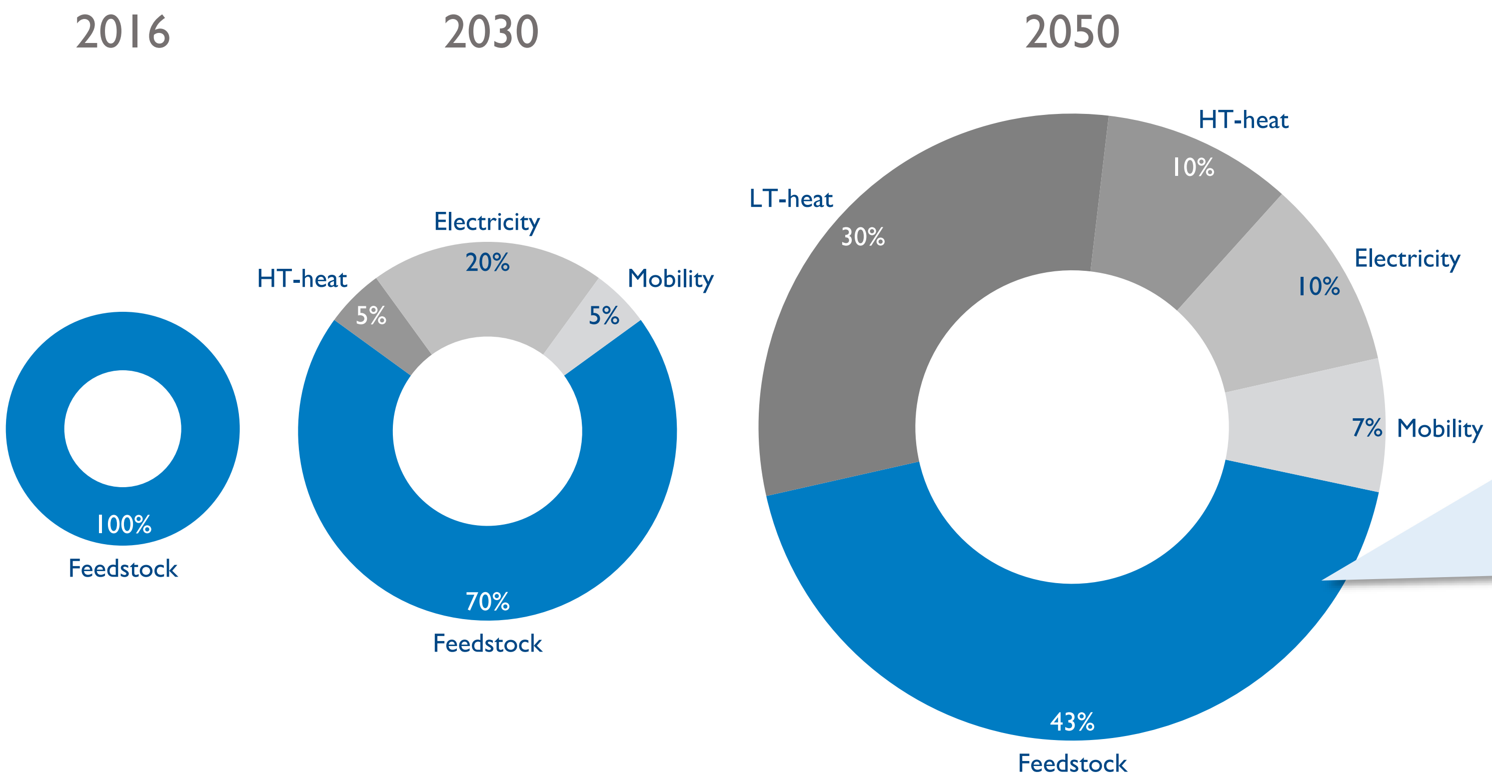
- **Hydrogen** is currently used predominantly as industrial **feedstock**, with other uses by 2030 still no more than 30%. **Mobility** applications are expected to be **5%** in **2030** and **7%** by **2050**
- **Steam Methane Reforming** (SMR) is the dominant technology to produce hydrogen (73% of total volume). This uses a **fossil** source and generates $CO_{2.}$ **Electrolysis** currently accounts for **~1%** of **H_2 production**
- In the SDR region, current H_2 **demand** is **~ 400 kt/a**, exclusively located in NL. Developments in BE make it a significant H_2 usage area in the long run, if all current green H_2 projects implemented[1]
  - 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 H_2 **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 CO_2** 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 H_2 demand is assumed to be static

In NL, 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[1]

In NL



Insight

Using hydrogen directly as feedstock has advantages over using hydrogen in other applications[2]

- No additional investment in conversion equipment (e.g. fuel cells)
- No losses incurred in the conversion of hydrogen to electricity or heat (~55%)

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 CO_2

Hydrogen production processes

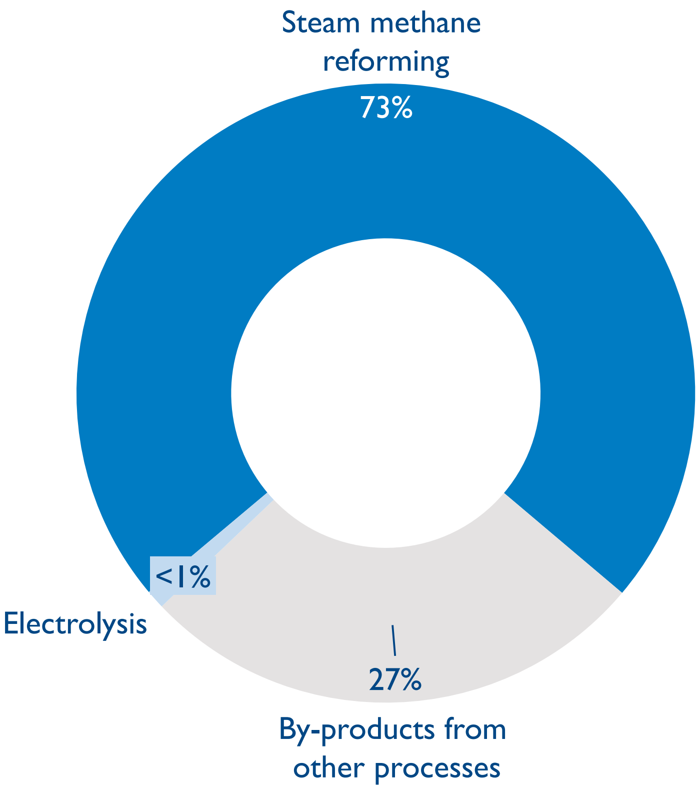
Process	Description
Steam methane reforming H_2 H_2 H_2	Steam-methane reforming, a mature process in which steam and methane are reacted at high temperature (700 – 1000°C) to produce hydrogen, resulting in either 'Grey H_2', 'Blue H_2' or 'Green H_2' (using biogas)
Electrolysis H_2 H_2	Electrolysis is 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)

Direct H_2 production process

In-direct H_2 production process

Hydrogen production volume by source

(Volume%, 2017)



---

1) When using imported green energy 'yellow' H_2 results, nuclear energy will provide 'orange' H_2

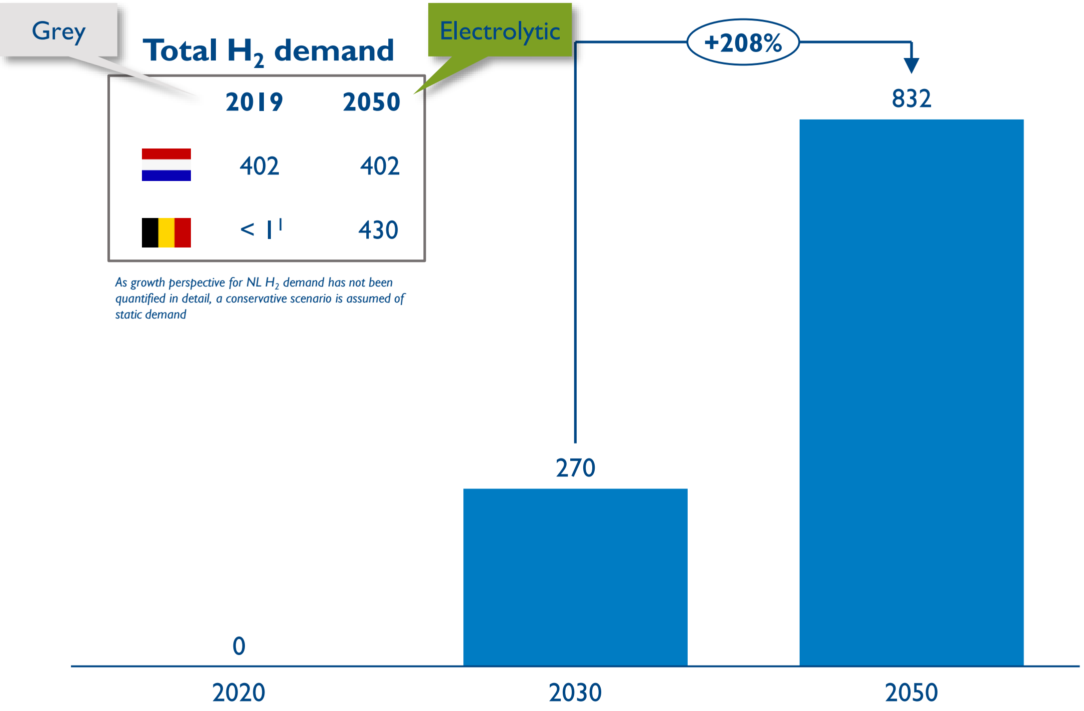
Source: Shell Hydrogen study (2017), Arthur D. Little

Legend H_2 H_2 H_2 Ability to produce Green, Blue and Grey H_2

Electrolytic H_2 demand in SDR region is expected to grow significantly, if all current electrolytic H_2 projects are implemented according to plan

Electrolytic H_2 demand outlook

SDR, 2020,2030,2050, H_2 kt/a



Total H_2 demand

	2019	2050
🇳🇱	402	402
🇧🇪	< 1[1]	430

As growth perspective for NL H_2 demand has not been quantified in detail, a conservative scenario is assumed of static demand

- Various projects in Ghent will create **H_2 demand** of **~190 kt/a** in the BE SDR region by 2030[2]
- **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 capacity[3]
  - 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 H_2 demand to **~430 kton/year** in the BE SDR region by 2050
- By **2050**, the industrial **H_2 demand** from existing industrial processes is assumed to be 100% electrolytic, primarily driven by regulatory demands. Coupled with new demand, the total **H_2 demand** in the SDR region is **832 kt/a**

---

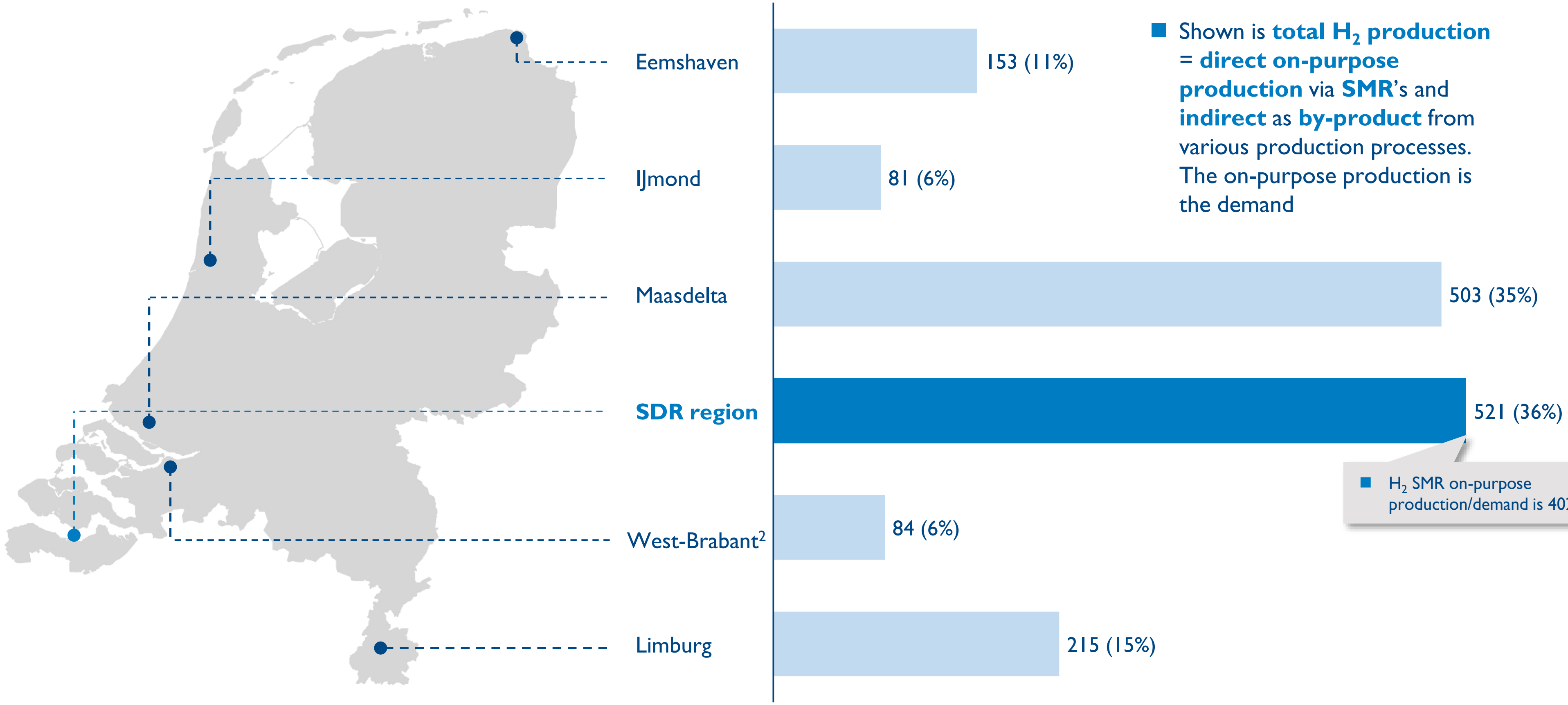
1) Only ArcelorMittal uses < 1 kt/a in current processes; 2) Total demand based on interviews with SDR partners and not visualizing individual demand for relatively small quantities of <5kt/year (e.g. for processes at DOW, ICL-IP, Eastman); 3) Depending on SMR unit and operator

2) Source: Stakeholder interviews, Arthur D. Little

Total current production of H_2 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/a[1]



- Shown is **total H_2 production = direct on-purpose production** via **SMR**'s and **indirect** as **by-product** from various production processes. The on-purpose production is the demand

- H_2 SMR on-purpose production/demand is 402 kt

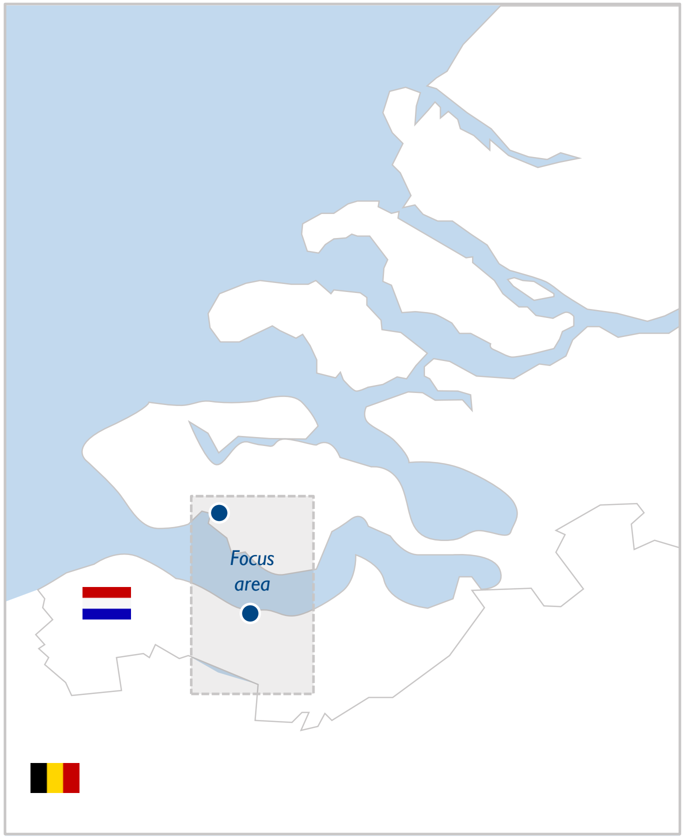
1) Source: DNV-GL; 2) Includes Moerdijk, value is estimated

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

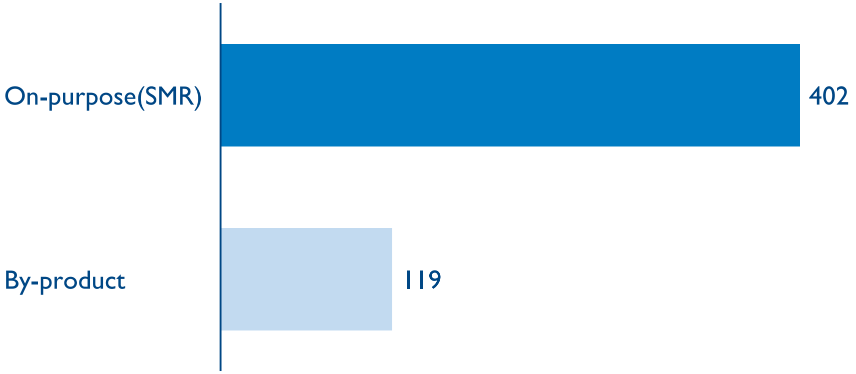
In the NL SDR region all on-purpose hydrogen is currently produced using Steam Methane Reformers, emitting ~4 Mton CO_2 per year

Hydrogen production in NL SDR

2019, kt/a[1]



- 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 CO_2
- SMRs emit ~9 ton CO_2 per ton hydrogen produced
  - For NL SDR, this amounts to ~4 Mton CO_2 per year
  - Part of the CO_2 is used for e.g. indoor horticulture, feed grade CO2 and urea

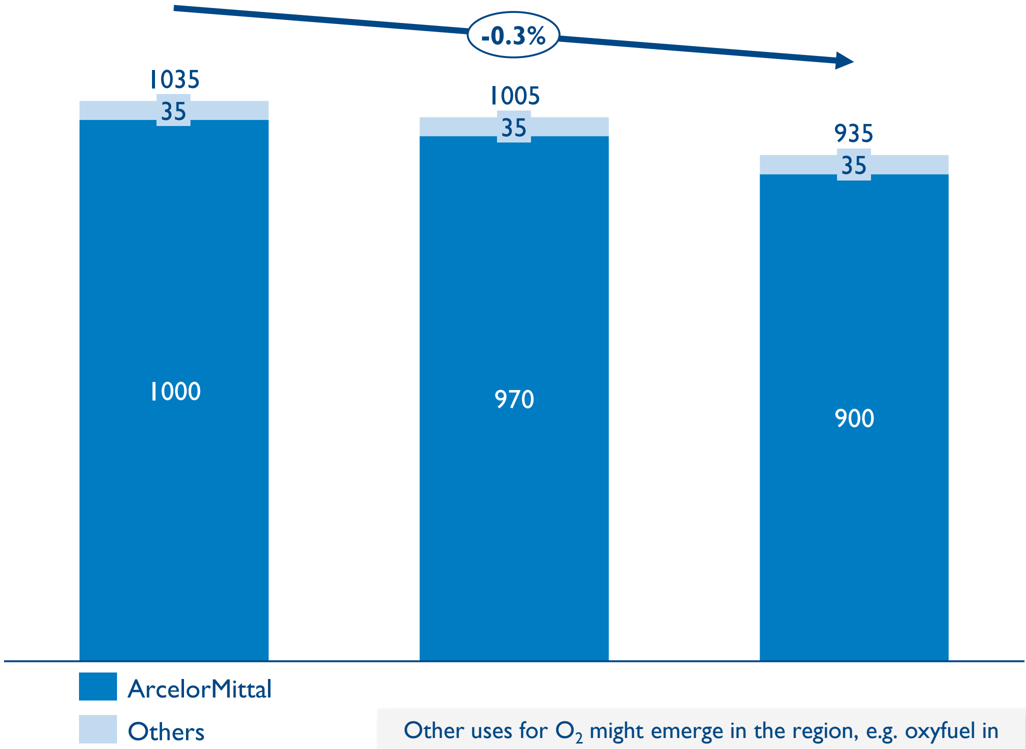


1) Based on interviews with SDR partners. Any CO_2 possibly produced through H_2 production as by-product is not taken into account, CO_2 production mentioned concerns CO_2 generated from SMRs only

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



Other uses for O_2 might emerge in the region, e.g. oxyfuel in the Sloecentrale and at ZR. Potential future use in SDR region >> 1000 kt/a

- Current demand for O_2 by SDR partners is **~1035 kt/a** and originates almost entirely from ArcelorMittal (97%)
  - Current on-site production of O_2 (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 O_2 consumption to decrease with ~10% by 2050, driven by the need to lower CO_2 emissions

Industrial Oxygen

- Air Liquide & Air Products are the main suppliers of industrial O_2 in the SDR region
- Oxygen is currently mostly produced via air separation. Selling prices are ~€ 20-30/t O_2
- Price is largely driven by electricity, transport and depreciation costs
- O_2 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

Table of contents

		Page
1	Summary	6
2	Hydrogen demand in SDR region	10
3	SDR ambition	18
4	Existing infrastructure	30
5	Electrolyzer roadmap	40
6	Business case 2020-2030	46
7	Recommendations & action plan	51
A	Appendix	54

Chapter summary

SDR ambition

- The **NL climate agreement** sets out ambitious goals for GHG emission reductions and foresees an important role for **green H_2**, just as the **Flanders**[1] governmental **policy** does
  - **Electrolysis**, splitting water into H_2 and O_2, allows production of **green H_2** 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 H_2 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 **Rodenhuize (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, H_2 demand in the SDR region is constant; to supply all **SMR H_2** 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 **H_2 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 agreement[1] sets out ambitious goals for fossil GHG emission reductions and foresees an important role for green hydrogen

Climate agreement[1]

- 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 CO_2 reduction target
- The agreement contains an ambitious H_2 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 H_2 and the availability subsidies for the H_2 economy
- The Flanders climate policy is less ambitious than the NL agreement, targeting CO_2 reduction in 2030 by 35%. Also here, H_2 will play a key role

Hydrogen targets per sector[2]

Sector	Role of hydrogen	Objective	Approach
Industry	For the process industry, hydrogen will act as a CO2-free feedstock and energy carrier for high temperature heat	**Installation of 3-4GW electrolysis capacity in 2030 (500MW in 2025)** Reduction of 65% of investment cost for electrolyzers between today and 2030	€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 National vision and adjustment of legislation Development of (EU) H2 certificates
Electricity generation	Use hydrogen as a carbon-neutral dispatchable source of energy	Up to 17 TWh hydrogen-based electricity production in 2030 Development of North sea green powerhouse, 60 GW in 2050	
Mobility and transport	Hydrogen vehicles are especially suitable for long distance passenger and heavy road transport	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	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	Use of hydrogen to decarbonize heating of buildings	Determine by 2030 how hydrogen can contribute to the reduction goal of 2050	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 CO_2-neutral industry by 2050
- Power2Hydrogen (P2H2) has been identified as one of eight pillars to significantly reduce CO_2 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 H_2**, SDR also views **blue H_2** (grey + CCU/CCS), **yellow H_2** (using imported green energy) and **orange H_2** (using nuclear energy) possible routes in their vision for H_2 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 Ørsted[1]

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

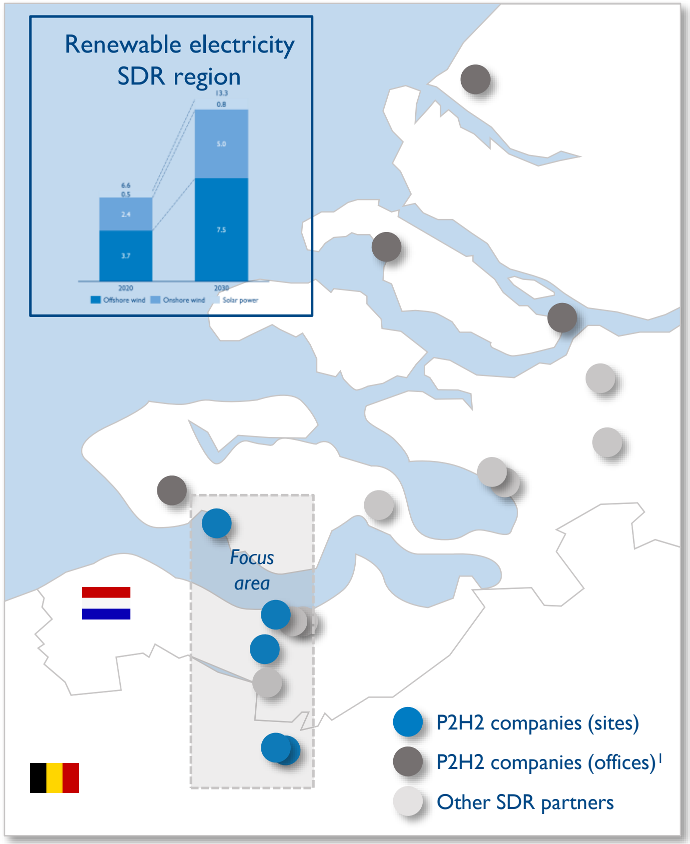
1) The port of Ghent plans to realize a Carbon Capture and Use (CCUG) hub. While not a Consortium member, their interests are also represented in this report

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

Source: SDR roadmap - Towards a climate neutral industry in the Delta Region (2018)

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



1) Including ArcelorMittal Staalhaven Rotterdam

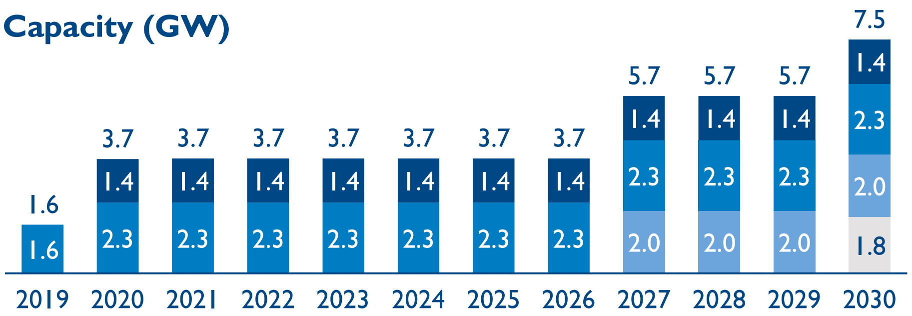
Focus area

- Production sites of the SDR consortium companies, that are or will be using green H_2, 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)

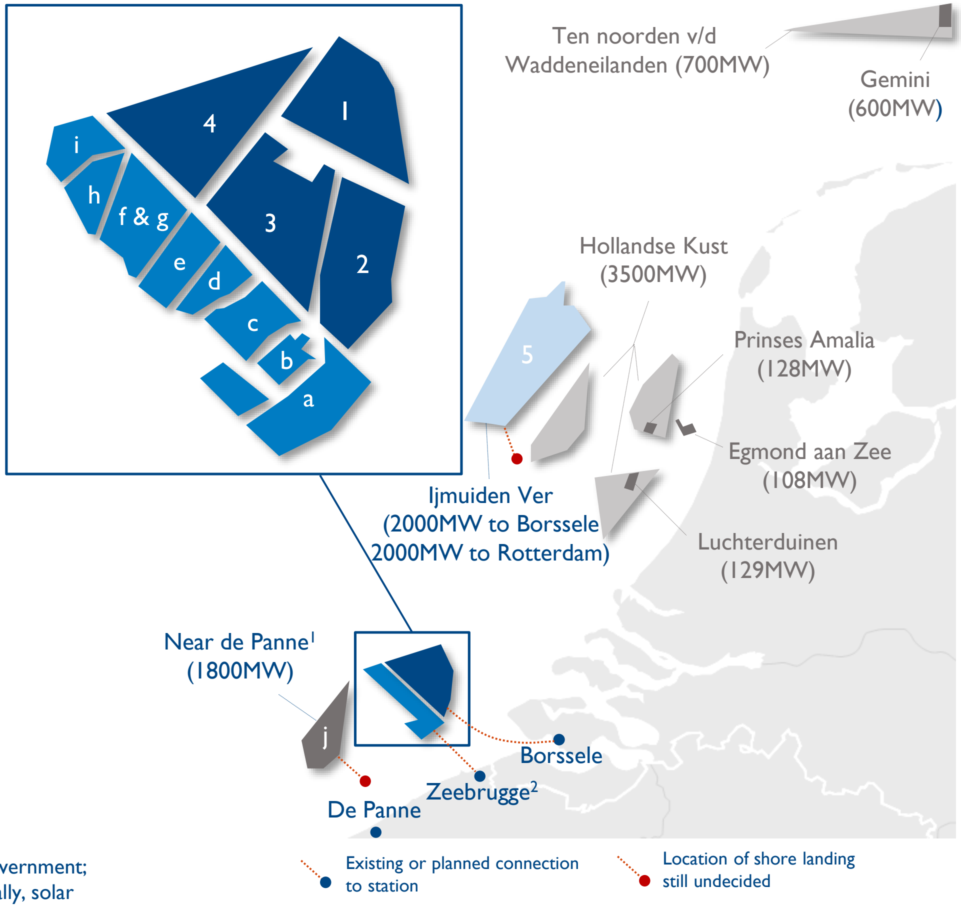
Offshore wind projects near SDR until 2030

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



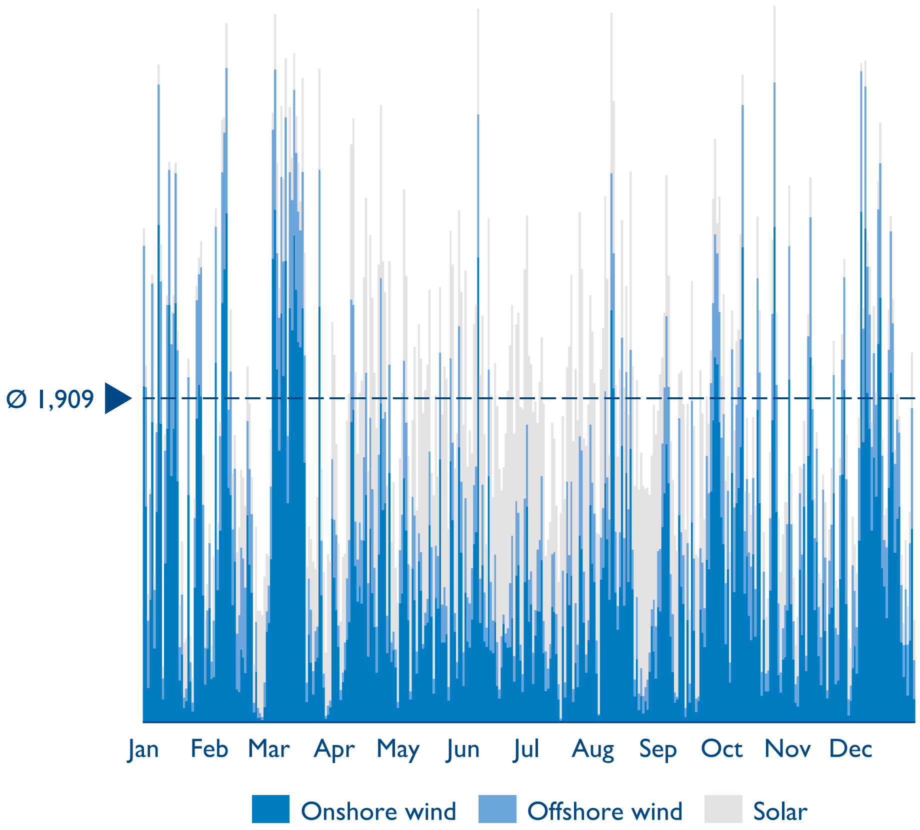
---

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 cold 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

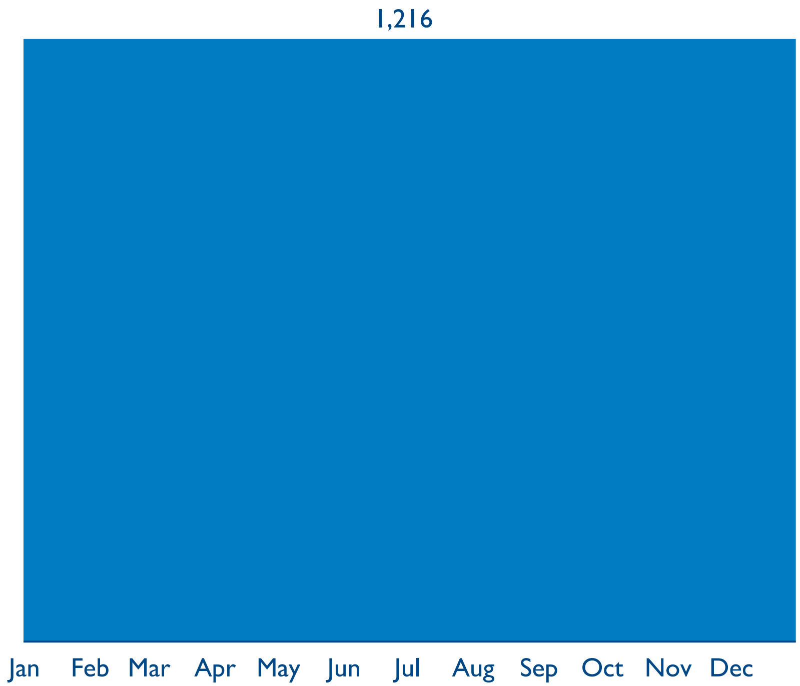
Variable renewable energy supply

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 H_2 made via electrolysis using renewable energy requires a ~5 GW electrolyzer & 50 kt H_2 storage

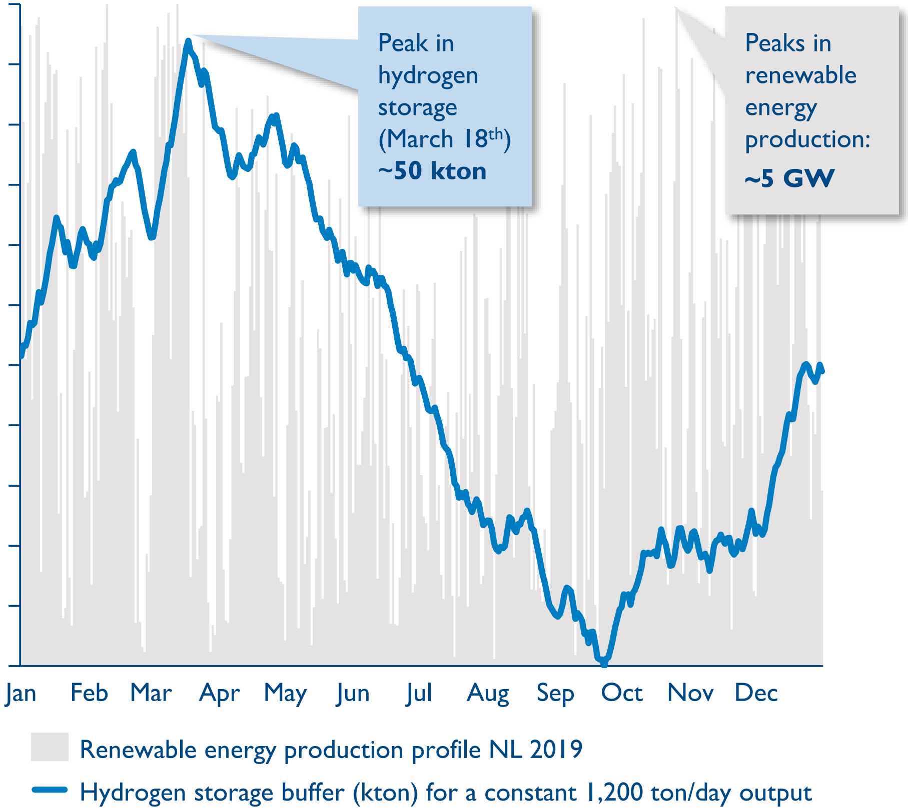
Required hydrogen storage buffer (kt)

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 H_2 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


Peak in hydrogen storage (March 18th) **~50 kton**

Peaks in renewable energy production: **~5 GW**

Note: For CCU hub Ghent, no H_2 storage has been included. A PPA for renewable energy for the necessary operating hours will be negotiated; Source: Energieopwek.nl; Arthur D. Little analysis

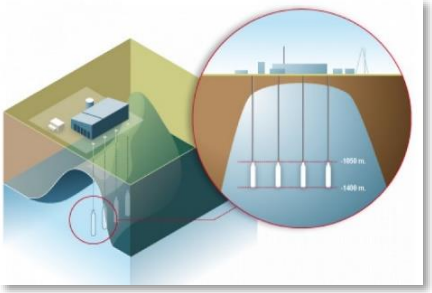
Underground salt caverns are the only feasible option to store 50 kt of H_2, which will be accessible via the NL hydrogen backbone from 2028

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 liquefication 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 hydrogen[5]
- 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 H_2 storage
- Caverns are planned to be accessible from Zeeland via the ‘H_2 back bone’ from 2028[5]

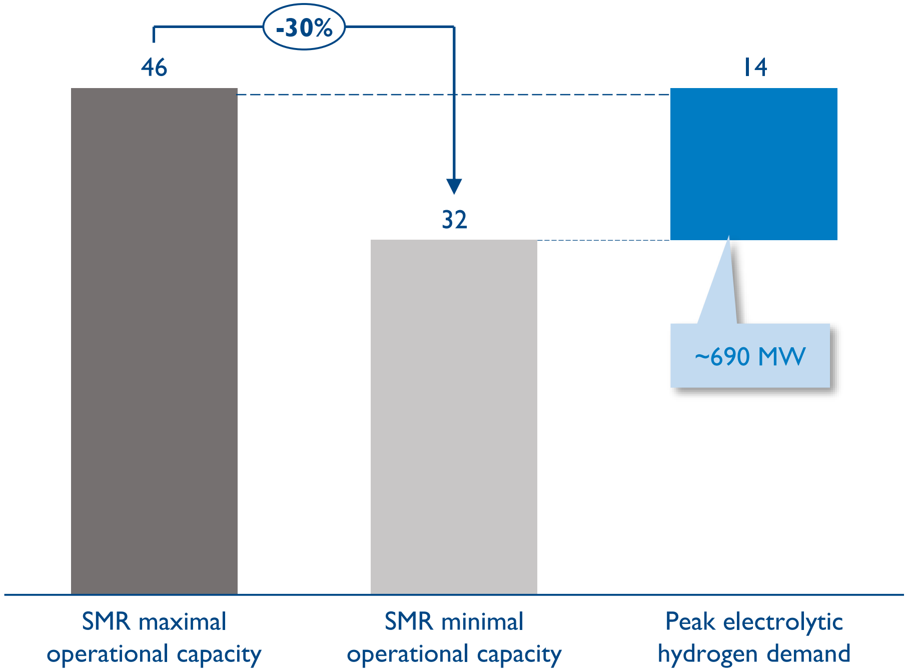


Sources: 1) Large scale storage of hydrogen (International journal of hydrogen energy, 2019); 2) National Hydrogen Roadmap Australia (2018); 3) Smart Port position paper Rotterdam hydrogen hub (2019); 4)Energy stock presentation (2017); 5) Gasunie reports, meeting, call (2019), email (June 2020); 6) 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 supply[1], until the H_2 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 H_2 demand was 402 kt/a
- The demand was met by SMRs producing a constant supply of ~46 ton/hour
  - The processes using H_2 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 2028[2], the existing SMRs can serve as a back-up source of H_2 to ensure constant supply
- While SMRs serve as back-up, peak electrolytic hydrogen demand is 30%[3] of the SMRs' production capacity (or ~14 ton/hr)[4]
  - SMRs can operate flexibly between 70% and 100% of capacity, 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; 2) Gasunie reports, meeting and call; 3) 30% may be the upper limit, Yara might be restricted to 20-25%, 4) Arthur D. Little analysis

Source: Company interviews

As existing SMR's at Yara/Zeeland Refinery will gradually scale down, their electrolytic H_2 demand is 55 kt/a in 2027[2] and 402 kt/a in 2050

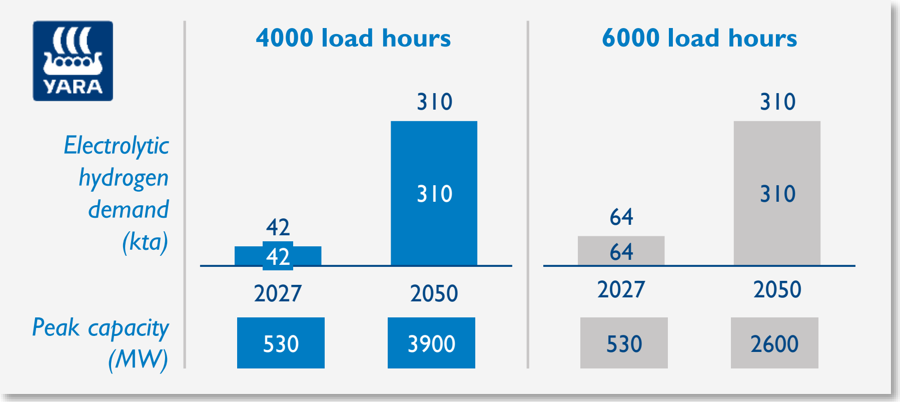
Yara and Zeeland Refinery electrolytic hydrogen demand

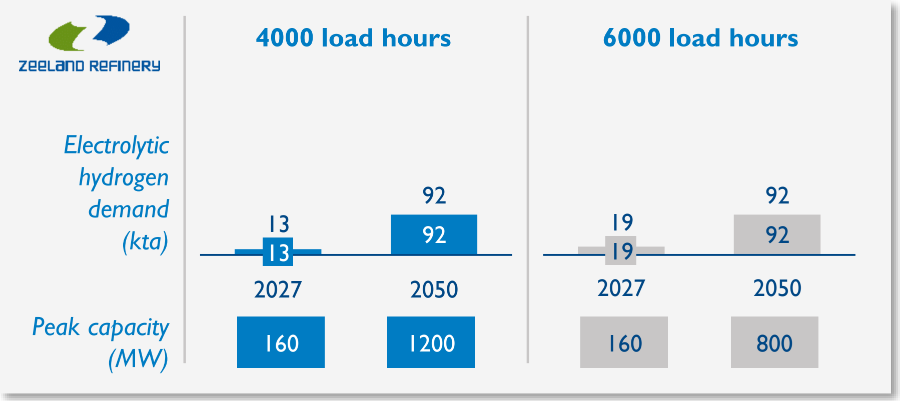
(2027 & 2050)

- Yara and Zeeland Refinery will use electrolytic hydrogen to increasingly replace SMR hydrogen in existing processes[1]
  - 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)





---

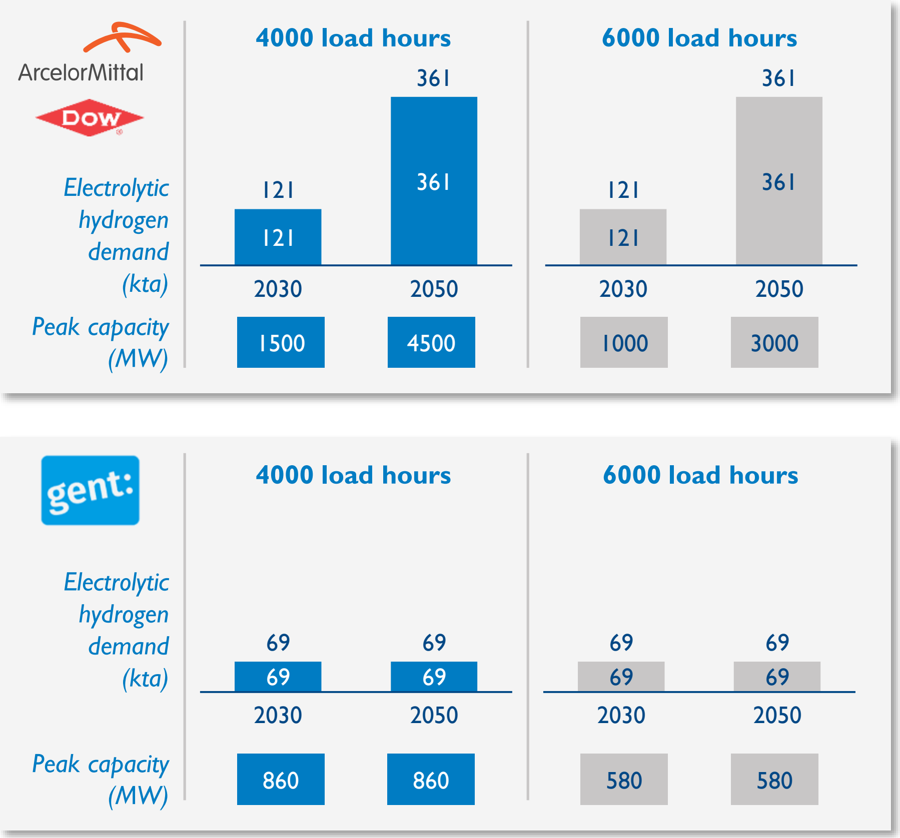
1) Total H_2 demand of Yara and Zeeland Refinery (regardless of production method) assumed to be roughly stable until 2050; 2) Assuming that the electrolyzer is operational for 4000 load hours (due to the fluctuating nature of renewable energy) at an efficiency of 50 kWh/kgH_2, yielding 80 kton/GW

Sources: Company interviews; Arthur D. Little analysis. Figures are indicative

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 CO$_2$ 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 H$_2$ demand of 10 kt/a in 2030 and 250 kt/a in 2050[1]
  - **Direct injection** (of H$_2$ in blast furnace to reduce CO$_2$ 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 H$_2$ for **annealing** (heat treatment of steel)
- Within the BE part of North Sea Port at Rodenhuize a consortium plans to realize a CCU hub by 2030, for synthesis of chemicals with CO$_2$ and H$_2$[3]:
  - **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)
- **H$_2$ demand** depends on successful implementation of **new processes**
- AM/CCUG do not have access to SMRs that can serve back-up, so the H$_2$ demand must be met by electrolytic H$_2$
  - Furthermore, the H$_2$ demand is constant and AM/CCUG should therefore be connected to H$_2$ storage buffers via the hydrogen backbone[4]



---

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/kgH$_2$, 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

Table of contents

		Page
1	Summary	6
2	Hydrogen demand in SDR region	10
3	SDR ambition	18
4	Existing infrastructure	30
5	Electrolyzer roadmap	40
6	Business case 2020-2030	46
7	Recommendations & action plan	51
A	Appendix	54

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, O_2 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

Optimum location(s)

Electricity infrastructure

- Distance to 380 kV or 150 kV and cost impact of distance
- Availability green energy sources (e.g. shore landing of wind energy)
- Current handling facilities (AC/DC)
- Potential avoided investments for TSO/DSO
- Value of flexibility

Pipe infrastructure

- Available pipeline and trajectories from potential source to users in the region
- Upgrade and adjustment costs

Other factors

- Area available
- Environmental category
- Demi water supply
- Access
- National regulations, taxes & subsidies available
- Speed of implementation
- Residual heat usage
- Oxygen demand/supply

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), O_2 demand/supply

1) Relation with CUST trajectories will also be taken into account

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

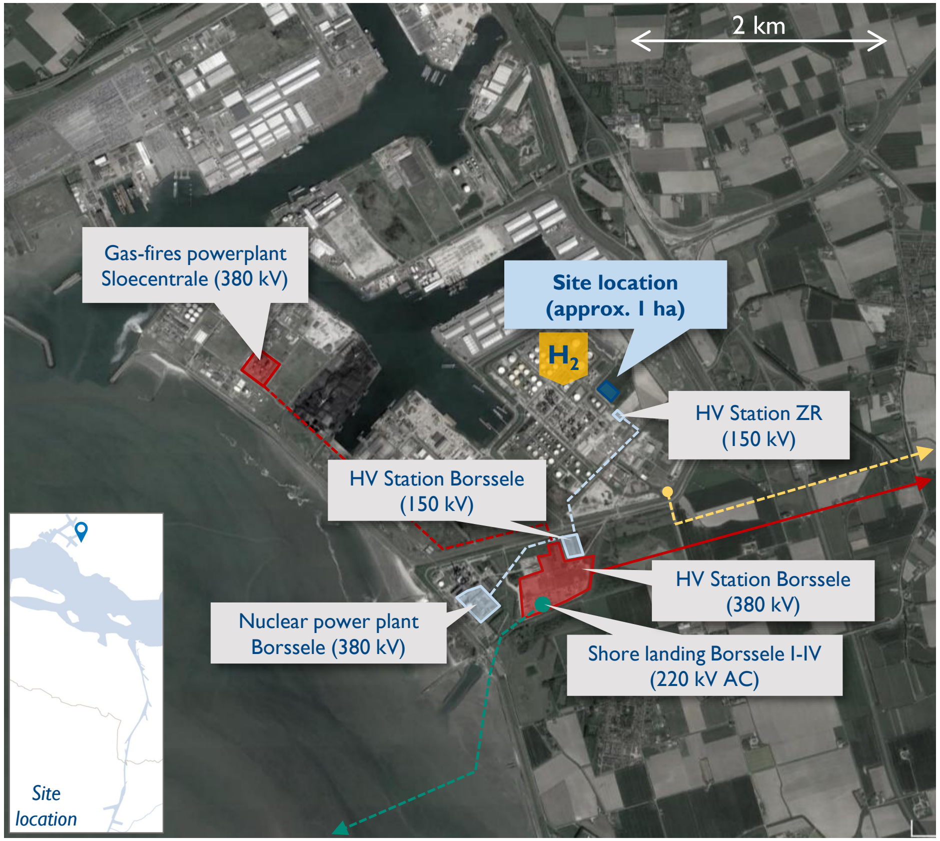
Potential site		**(former) Thermphos or Zanddepot**[1]	**Zeeland Refinery**	**PZEM/EPZ**	**Valuepark Terneuzen**[2,3]	**Yara**	**Engie**
Location *(Harbor number)*		Vlissingen-Oost (9890)	Vlissingen-Oost (6501)	Borssele (8099)	Terneuzen (85)	Sluiskil (2111)	Rodenhuize (4040A)
Central/Decentral		Central	Decentral	Central	Central	Decentral	Central
Electricity infra	Distance 380 kV	■ ~2 km from Borssele nuclear power plant ■ ~ 2km (max) from Sloecentrale	■ ~2 km from Borssele nuclear power plant	■ 0 km	■ ~10 km from Borssele nuclear power plant (through Westerschelde)	■ ~15 km from Rodenhuize (through Ghent–Terneuzen Canal) ■ ~20 km from Borssele nuclear power plant (through Westerschelde & Ghent-Terneuzen Canal)	■ 0 km (recently reinforced to enable connection of wind farms to national 380 kV grid)
	Available capacity 150 kV	■ Former 150 kV HV Station Thermphos on site/close	■ 142 MW (if redundant transformer is repurposed, otherwise 50 MW)	■ Yes, HV station Borssele 150kV at <800m	■ Underdeveloped electricity grid (not quantified)	■ 140 MW	■ HV Station Rodenhuize 150kV <100m ■ 600 MW available
Pipe infra	Pipeline connections	■ ZR-DOW naphtha pipe <5km	■ Naphtha (to Dow, willingness to repurpose)	■ ZR-DOW naphtha pipe <1km	■ Naphtha (from ZR, willingness to repurpose) ■ Hydrogen (from DOW, capacity 18 kton: TBD mentioned as ambition) ■ Hydrogen (from Air Liquide, capacity unknown)	■ Hydrogen (from DOW, capacity 18 kt; stated as ambition)	■ 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

🟩 Central option 🟩 Decentral option 🟧 Limited suitability 🟥 Not suitable

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

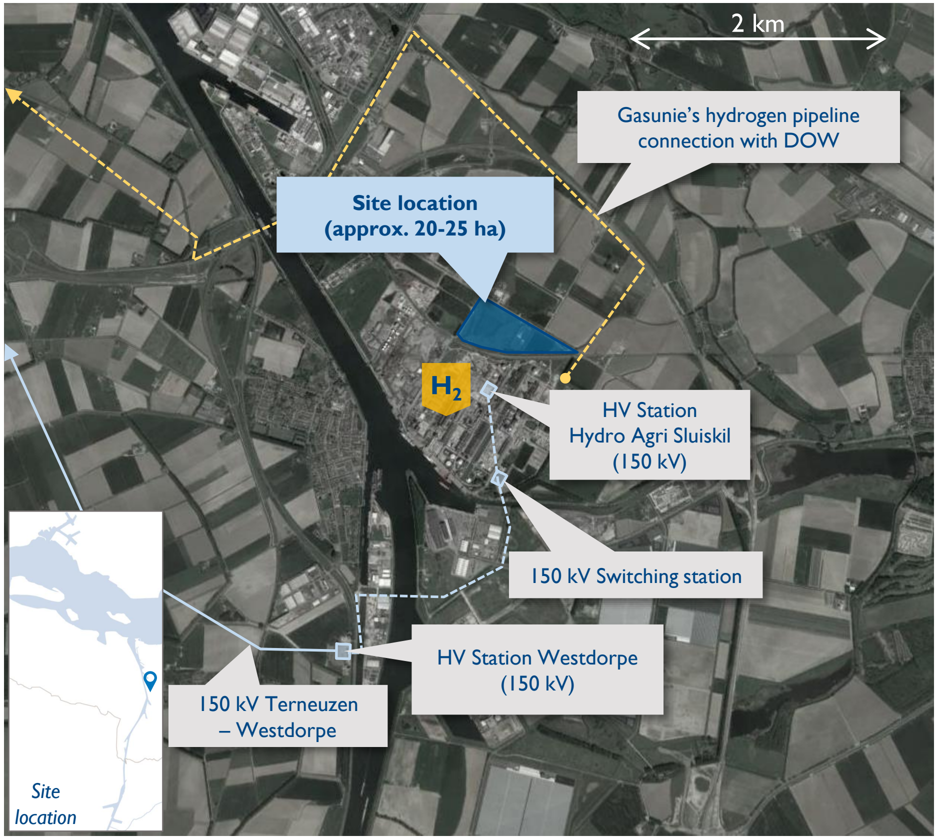
1) Evides is already industrial water supplier to i.a. Zeeland Refinery, Yara Sluiskil & Dow Terneuzen; 2) Limited relevance for kickstart phase

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

H_2 Hydrogen demand · Available electrolyzer site · 380 kV facility/cable · 150 kV facility/cable · 220 kV facility/cable · Relevant pipeline

Placement of an electrolyzer on the Yara site ensures production in the vicinity of large H_2 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 site is 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

	Electrolyzer input			**Electrolyzer output**	
✗	**380 kV grid**	No 380kV connection in Dutch Flanders	✓	**Hydrogen pipeline(s)**	YARA-DOW H2 pipe <200m[2]
✓	**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

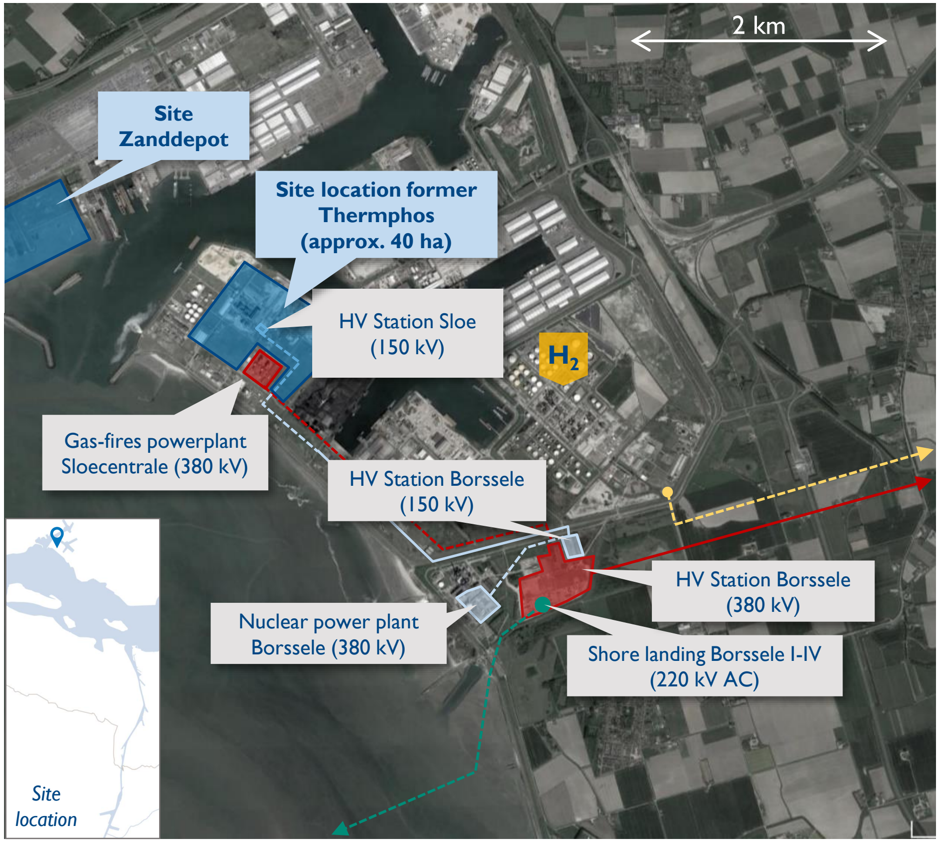
1) Evides is already industrial water supplier to i.a. Zeeland Refinery, Yara Sluiskil & Dow Terneuzen; 2) Limited relevance for kickstart phase

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

H_2 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-Oost[1] – 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

H_2 Hydrogen demand | Available electrolyzer site | 🟥 380 kV facility/cable | 150 kV facility/cable | 220 kV facility/cable | Relevant pipeline

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

ENGIE Rodenhuize – Central option

Description

The site of ENGIE Rodenhuize 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 Rodenhuize 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 #)	Rodenhuize, 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 Rodenhuize 380kV <100m	-	**Hydrogen pipeline(s)**	Also, no large scale H_2 demand close by yet[1]
✓	**150 kV grid**	HV Station Rodenhuize 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 Rodenhuize
✓	**Nearby renew. energy sources**	380kV connection BE off-shore wind Zeebrugge	✓	**District heating opportunities**	Studied in the Restwarmte Kanaalzone project
	Other	-		**Other**	-

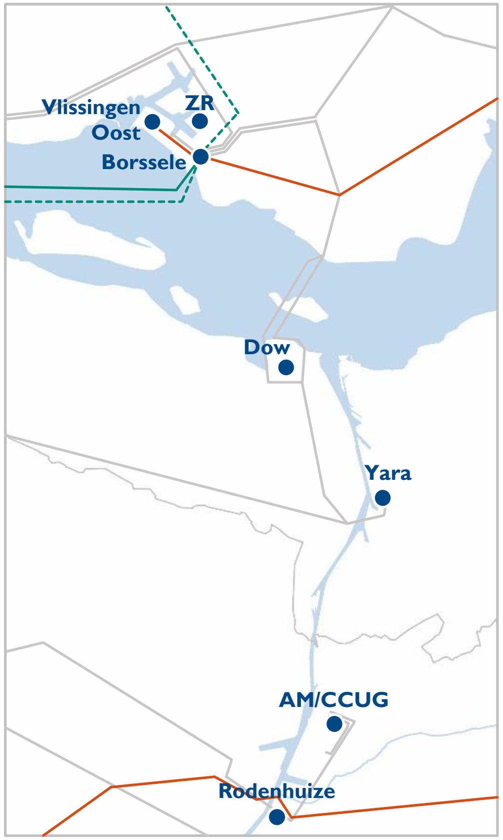
[1] Initiatives ongoing with future H_2 consumers, e.g. planned H_2 demand ArcelorMittal by 2030 is 121 kt/a

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

H_2 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 infrastructure[1]



Grid infrastructure specifications[2]

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)**

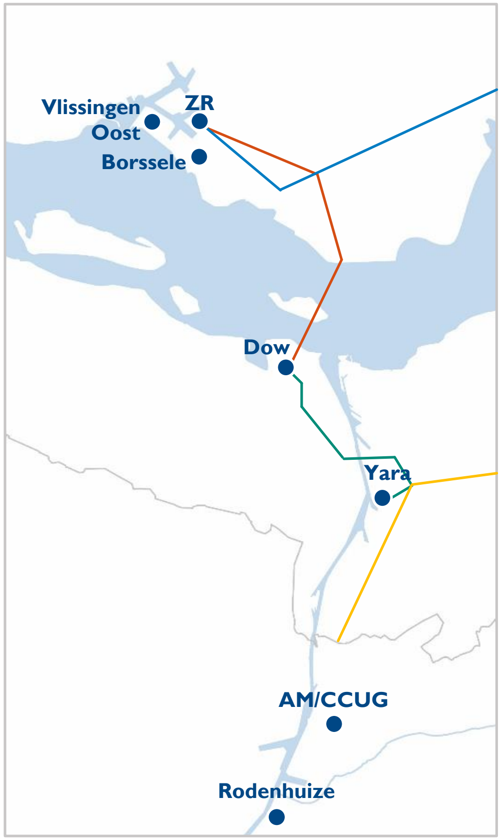
Observations

- 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 realize[2]
  - New connections to existing high voltage grid take < 2 years[2]
- 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 consumption[2]
- 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 & Geertruidenberg[3]

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 H_2 pipeline** between **Dow** and **Yara**
- The **H_2 backbone** connecting the SDR region to salt cavern H_2 storage is planned to be **operational** from **2028**[6]
  - Initially, a connection will only be realized south of the Westerschelde[3]
- The **naphtha pipeline** between ZR and Dow can be **converted** to **H_2**, serving as potential crossing of the Westerschelde until the H_2 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 **CO_2** rather than **H_2** transport; choices have to be made based on market demand
- Realizing a **regional harbor H_2 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/kgH_2

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

Table of contents

		Page
1	Summary	6
2	Hydrogen demand in SDR region	10
3	SDR ambition	18
4	Existing infrastructure	30
5	Electrolyzer roadmap	40
6	Business case 2020-2030	46
7	Recommendations & action plan	51
A	Appendix	54

Chapter summary

Electrolyzer roadmap

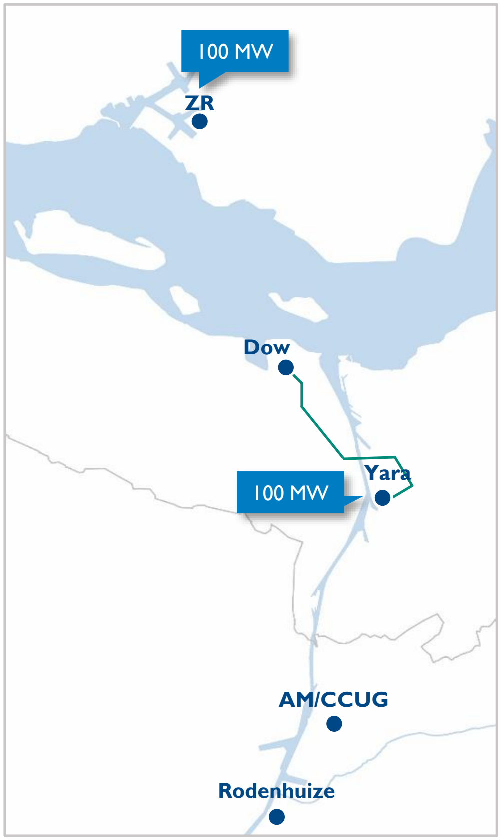
- An electrolyzer **roadmap** has been defined for the SDR region by Arthur D. Little
  - In **2022-2023**, Yara and ZR can **kick-start** electrolytic hydrogen production in the region with **100 MW** on-site projects
    - These 100 MW projects would immediately **reduce CO_2** emission by **~70 kt/a 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 CO_2** 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. **CO_2** 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 **H_2** 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 **CO_2 neutrality** for the SDR region[1]

---

1) Achieved fully by green H_2, but possibly also by combining with blue and maybe orange H_2

In **2022-2023**, Yara/ZR can kick-start electrolytic hydrogen production in the region with 100 MW on-site projects, reducing CO_2 by ~ 70 kt/a

Electrolyzers & gas infra



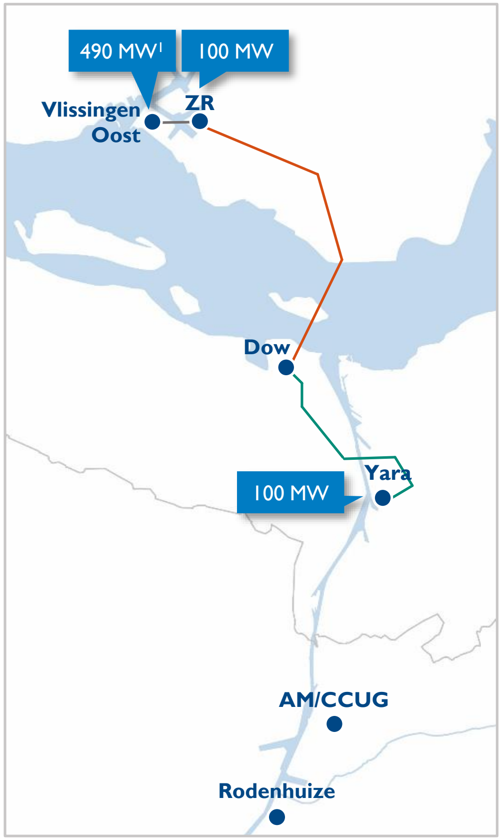
Observations

- 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)
  - **H_2 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 H_2 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 area[2]
- These **on-site** projects are intended to **kick-start** the region's **H_2 project**, on a way to realize the **ambitions** set out by **SDR** – they already **reduce CO_2 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 CO_2 by ~ 500 kt/a

Electrolyzers & gas infra



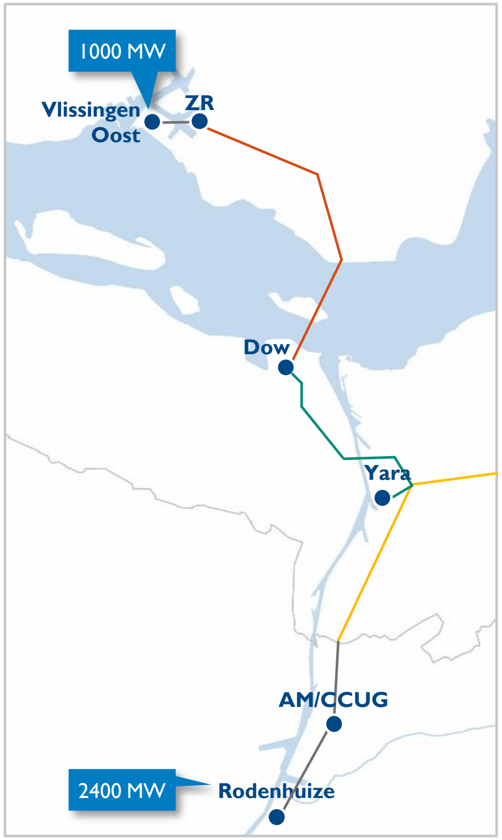
Observations

- Before salt caverns can be accessed via the **H_2 backbone** in **2028**, NL SDR's total electrolyzer capacity can reach up to **690 MW**[1],
  - Producing **55 kt/a H_2** at 4000 load hours
  - CO_2 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 H_2 as by-product of cracking (impurities); decision needed regarding pipeline usage and purification[2] 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**, H_2 backbone enables 1 GW capacity in Vlissingen-Oost and new processes will demand 2.4 GW electrolyzer in Rodenhuize

Electrolyzers & gas infra



Observations

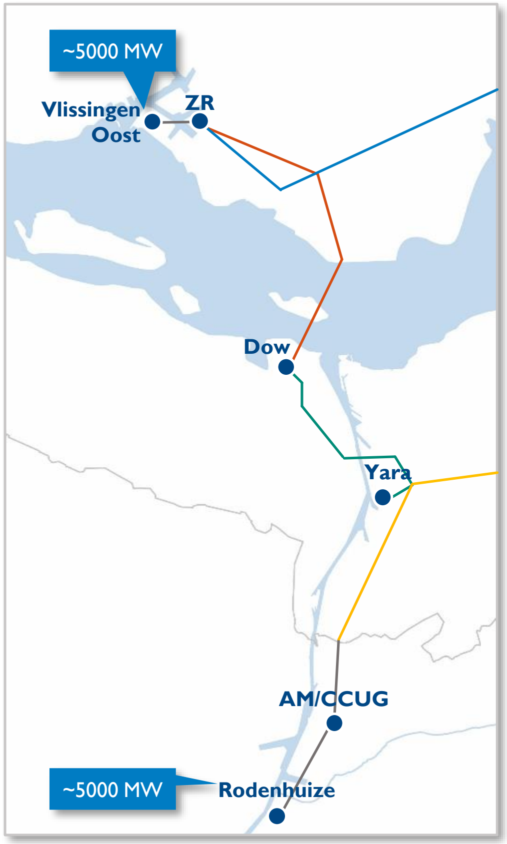
- From **2028**, the ambition for the **H_2 backbone** is to connect **Yara** (and Zeeuws-Vlaanderen) to **salt cavern** storage
  - in 2030 the backbone will not yet connect north of the Westerschelde (Gasunie plans[2])
- **Connection** between **Vlissingen-Oost, ZR and Yara** needs to be realized by a **regional pipeline** across Westerschelde
  - Until 2030, existing pipeline between ZR/ Dow is sufficient for electrolytic H_2
  - If needed, additional H_2 pipeline trans-Westerschelde pipeline can be constructed[2]
- 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 SMRs[3]
  - **CO_2 emission avoidance** of **~740 kt/a** is achieved with 1 GW electrolyzer
- **AM/CCUG's 190 kt/a electrolytic H_2** 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 CO_2 neutrality for the region

Electrolyzers & gas infra



Observations

- ~ **2050**, the **SDR** region's complete **H_2 demand** can be met with **electrolytic H_2** from renewable energy
  - ~830 kt/a electrolytic H_2
  - Requiring ~10 GW capacity[1]
  - Potential H_2 demand of AM/CCUG exceeds that of ZR/ Yara
- **H_2 backbone** will run along the **north** and **south** of the **Westerschelde** and interconnect **Vlissingen-Oost** and **Yara** (Gasunie plans for 2050[2])
  - Role of regional trans-Westerschelde H_2 pipeline is to be determined
- As **all** H_2 **users** are **interconnected,** electrolyzer **locations** depend on the **landing** point of **renewable electricity** in Vlissingen-Oost and transport of renewable electricity to Rodenhuize[3]
- **2050 SDR vision** assumes region **H_2 demand** is fully met by **green H_2** in combination with **blue**, **yellow** and (if feasible) **orange H_2**. Gas infra and 380kV grid will have to be strengthened / expanded
  - Region is **CO_2 neutral**

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

Table of contents

Page

1	Summary	6
2	Hydrogen demand in SDR region	10
3	SDR ambition	18
4	Existing infrastructure	30
5	Electrolyzer roadmap	40
6	Business case	46
7	Recommendations & action plan	51
A	Appendix	54

Chapter summary

Business case[1]

- Currently **grey hydrogen** cost is **€ 1.54/kg**, which is forecasted to increase to **€ 2.71/kg** by **2030**, following **ETS/CO_2 tax** increases
- In 2030 the **lowest possible** price for **electrolytic hydrogen** will be **€ 2.90/kg** (at 4000 load hours) if existing transmission **tariff discounts** would be applicable. This represents a 7% cost premium of green H_2 over grey H_2
  - The **electrolytic H_2** cost is a **function** of **load hours** of the electrolyzer and moves between **€ 3.19/kg** and **€ 2.90/kg** depending on load hours, if transmission tariff reductions are applied
- The **cost premium** of **electrolytic H_2** over grey H2 in 2030 means that the **unsubsidized** production of hydrogen based on a **1 GW electrolyzer** leads to significant **annual losses** regardless of the number of load hours
  - These losses are minimized at 4000 load hrs, at € 42 mln/a
- However, various **EU** and **national subsidies** could **enhance** the **business case** for electrolytic hydrogen production
  - The NL **SDE++** subsidy is potentially the most impactful, fully covering the unprofitable top margin of electrolytic H_2 production. It is limited to 2000 load hours however; extending this to 4000 load hours, it would enable a 1 GW electrolyzer to make a profit of ~€ 5 mln/a in 2030
- Operating the electrolyzer at **4000** load **hours avoids** total **CO_2 emissions** of **740 kt/a**

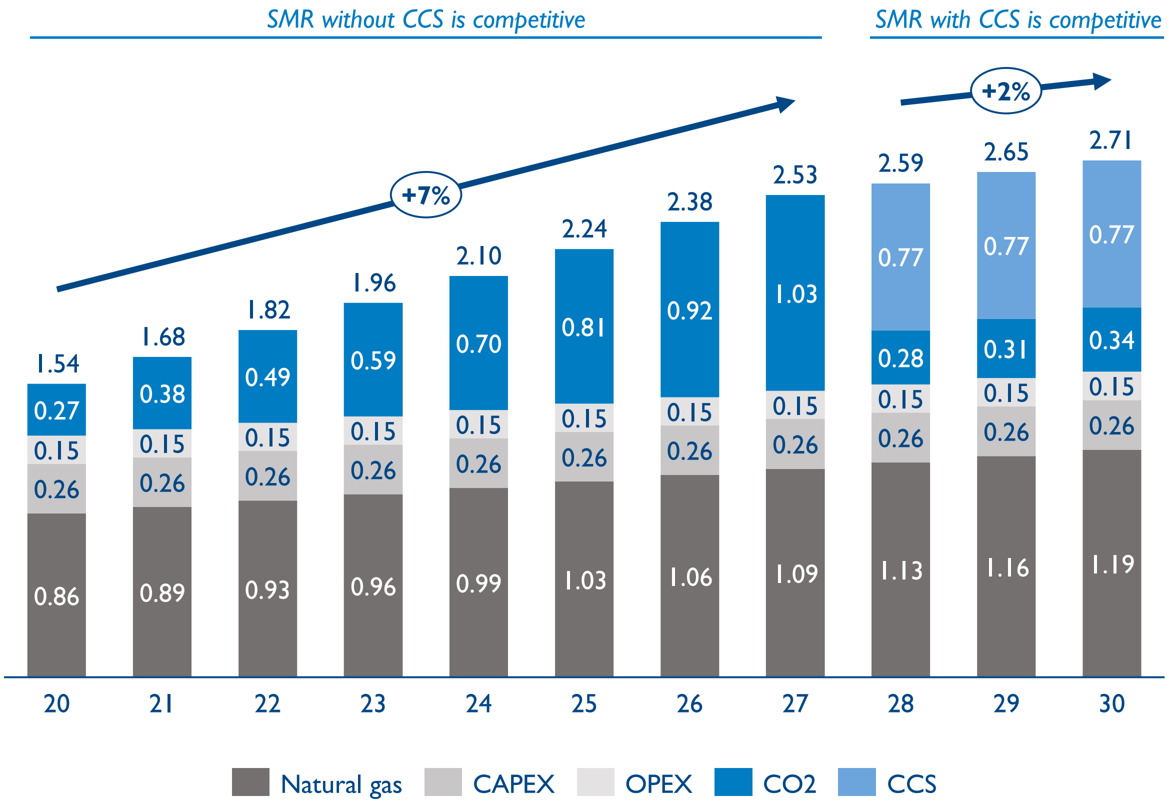
---

1) Business case is based on open source information

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 CO_2 determines the competitive SMR hydrogen price
  - In SMR H_2 production without CCS, 9 tCO_2/tH_2[1] is emitted, increasingly taxed
  - In SMR H_2 production with CCS, 75% of CO_2 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
  - CO_2 tax forecasted to increase by ~17% CAGR (€ 0.27 to € 1.35/kgH_2) between 2020 / 2030[3]
  - SMR hydrogen cost price will increase by ~7% CAGR (from € 1.54 to € 2.53/kgH_2) between 2020 and 2027
- SMR with CCS is forecasted to be most economical method to produce SMR-based hydrogen from 2028[1]
  - CCS costs are approximated to remain stable at 0.77 €/kgH_2 (114 €/tCO_2)
  - Costs for SMR H_2 with CCS will continue to increase due to rising gas prices (3% CAGR) and rising CO_2 taxes (for non-captured CO_2)

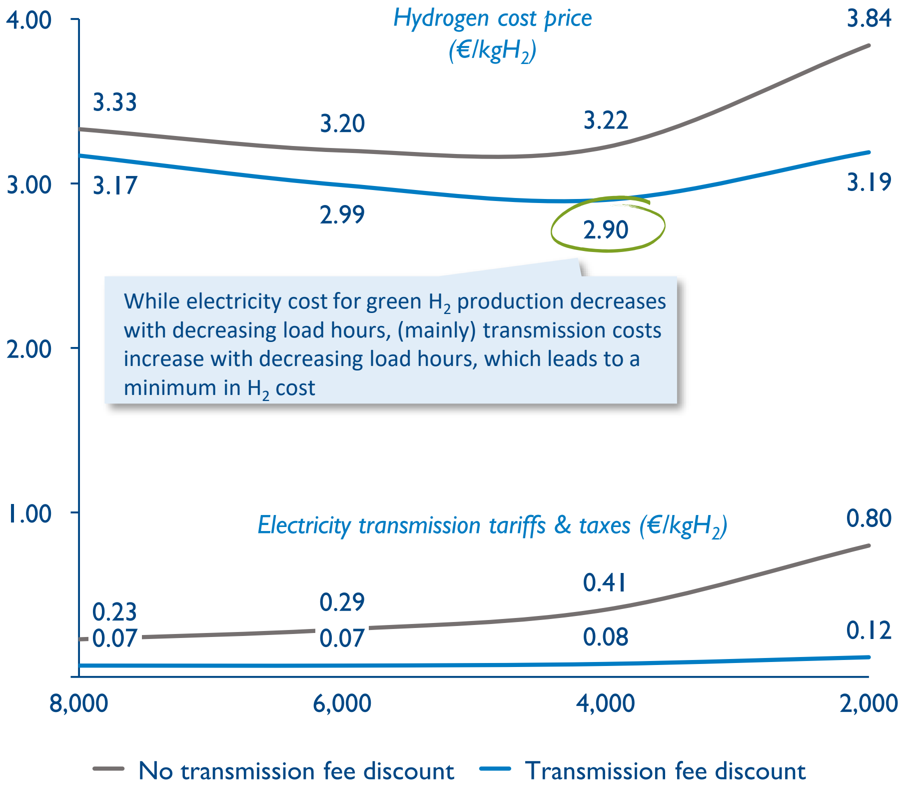
Sources: Please refer to assumption overview in the appendix of this document

Note: 1) CCS is dependent on the infrastructure to capture, transport and store CO_2, 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/taxes[1]



While electricity cost for green H_2 production decreases with decreasing load hours, (mainly) transmission costs increase with decreasing load hours, which leads to a minimum in H_2 cost

Key assumptions & observations

- The Dutch 380 kV[2] 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 H_2 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 hours[3]
- A TT discount of 90% when using renewable electricity to produce H_2 significantly improves unit economics. By 2030 electrolytic H_2 cost could come down to € 2.90/kg at 4000 load hours, € 0.19 more than SMR H_2
- 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 H_2 storage

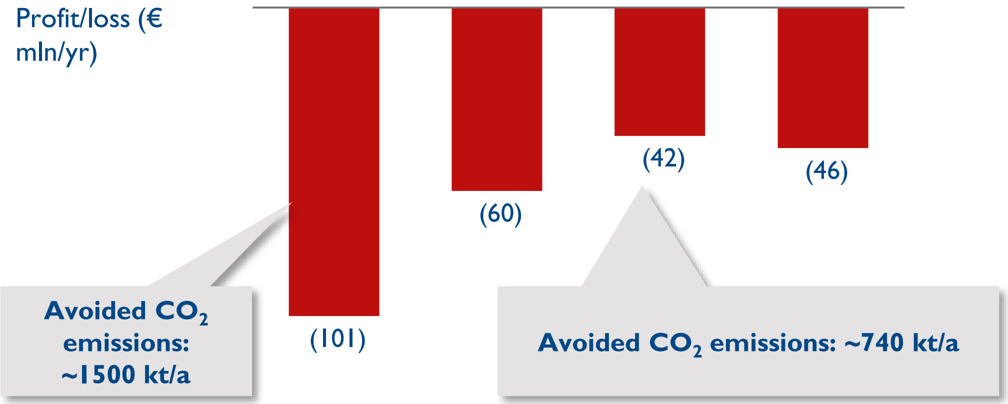
1) Key assumptions: AEL electrolyzer, no hydrogen storage (the other base-case assumption on which these cost price forecasts are based can be found at the end of this document); 2) The T&T costs are even higher for 150 kV grid; 3) Offtakers receive between 0 and 90% with a load factor between 65 and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

Unsubsidized H_2 production by a 1 GW electrolyzer is loss-making, load hours independent; at 4000 hrs minimum loss, avoids ~740 kt/a CO_2

Profitability at various load hours

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

Load hours	8000	6000	4000	2000
Production (kt/a)	163	123	82	41
Sales price (€/kg)	2.71	2.71	2.71	2.71
Cost (€/kg)	3.33	3.20	3.22[2]	3.84
Profit/loss (€/kg)	(0.62)	(0.49)	(0.51)	(1.13)



Comments

- 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 hrs**
  - 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 hrs
  - The minimum cost disparity per kg is forecasted at 6000 load hours (€ 0.49/kg H_2), 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 **hrs**
  - At 6000 load hrs the loss per kg H_2 is slightly lower, but the amount of H_2 produced is 50% higher, resulting in a higher loss
  - At 2000 load hrs the amount of H_2 produced is 50% lower, but the loss per kg H_2 is € 0.62 per kg higher, resulting in a higher loss
- Various **subsidies** at EU and national level can improve the business case; the **NL SDE++** subsidy, if extended to cover **4000** electrolyzer load **hrs** (from 2000 today) and awarded, would make the business case **positive** to **~ € 5 mln/yr** by 2030

[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

Table of contents

Page

1 Summary 6

2 Hydrogen demand in SDR region 10

3 SDR ambition 18

4 Existing infrastructure 30

5 Electrolyzer roadmap 40

6 Business case 46

7 Recommendations & action plan 51

A Appendix 54

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 grid in Zeeuws-Vlaanderen if multi-GW scale electrolyzers will be located in Zeeuws-Vlaanderen 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 3rd parties) to be agreed for the implementation (develop, build, operate)	Conversations around interest should be solidified. 3rd parties can also be engaged, some of these have 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

Source: Arthur D. Little

Table of contents

		Page
1	Summary	6
2	Hydrogen demand in SDR region	10
3	SDR ambition	18
4	Existing infrastructure	30
5	Electrolyzer roadmap	40
6	Business case	46
7	Recommendations & action plan	51
A	Appendix	54

Table of contents

A Appendix

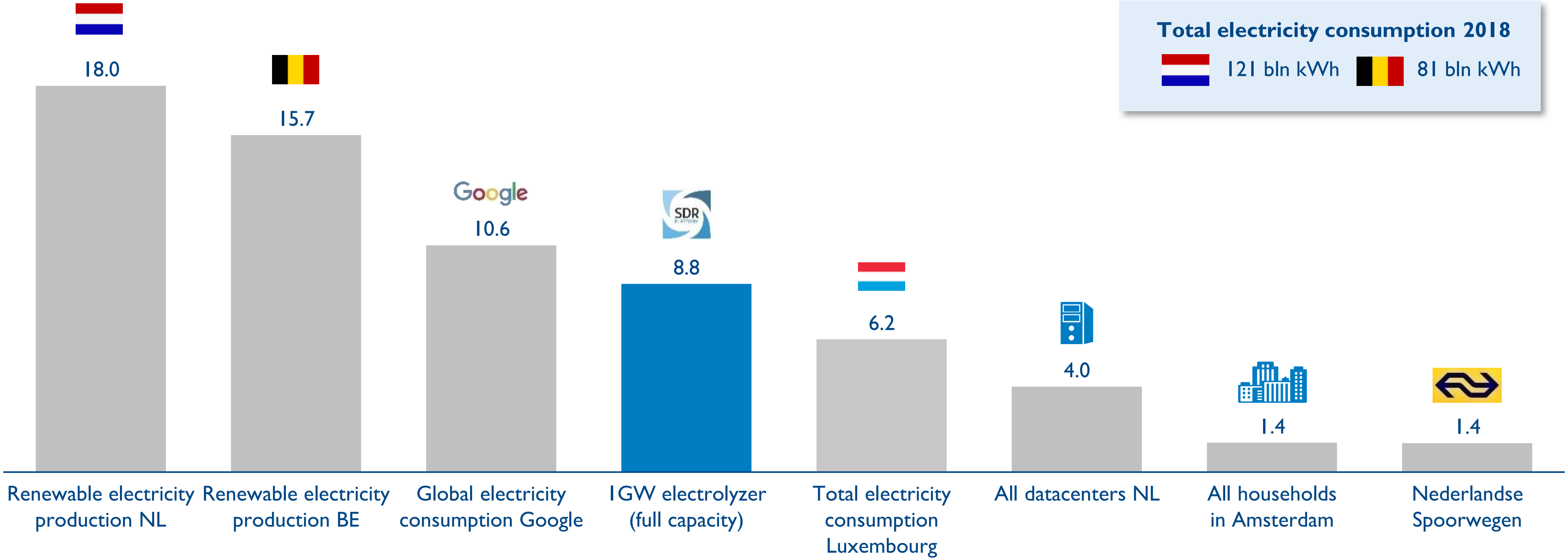
A.1 Renewable electricity in SDR region

A.2 Boundary conditions

A 1GW 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



Total electricity consumption 2018

🇳🇱 121 bln kWh 🇧🇪 81 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

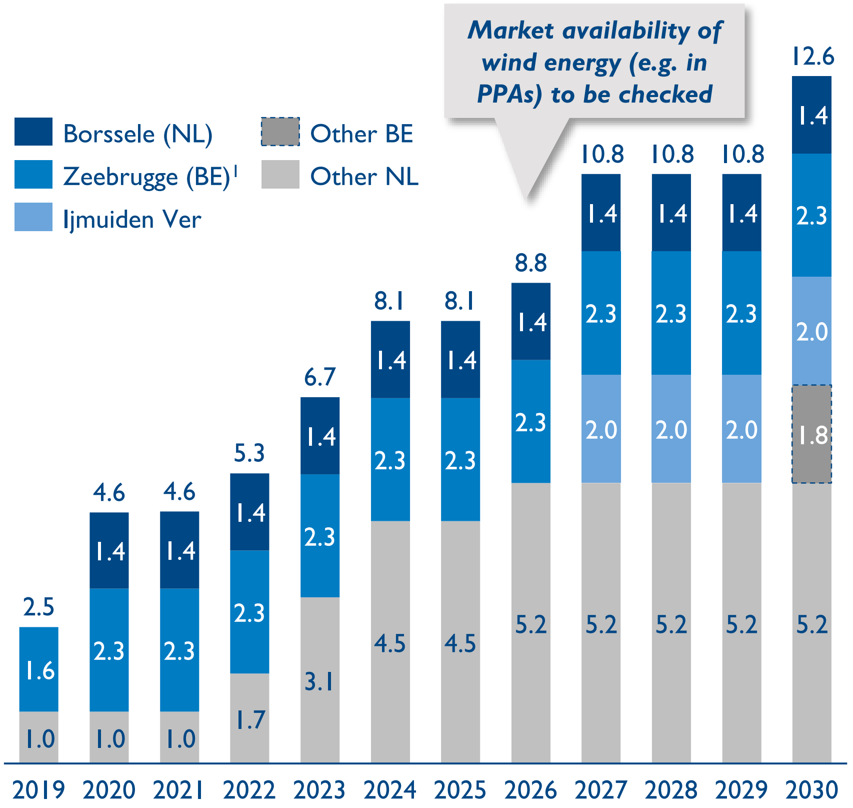
Source: CBS, Febeg, IndexMundi, NRC, Statista, Arthur D. Little

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

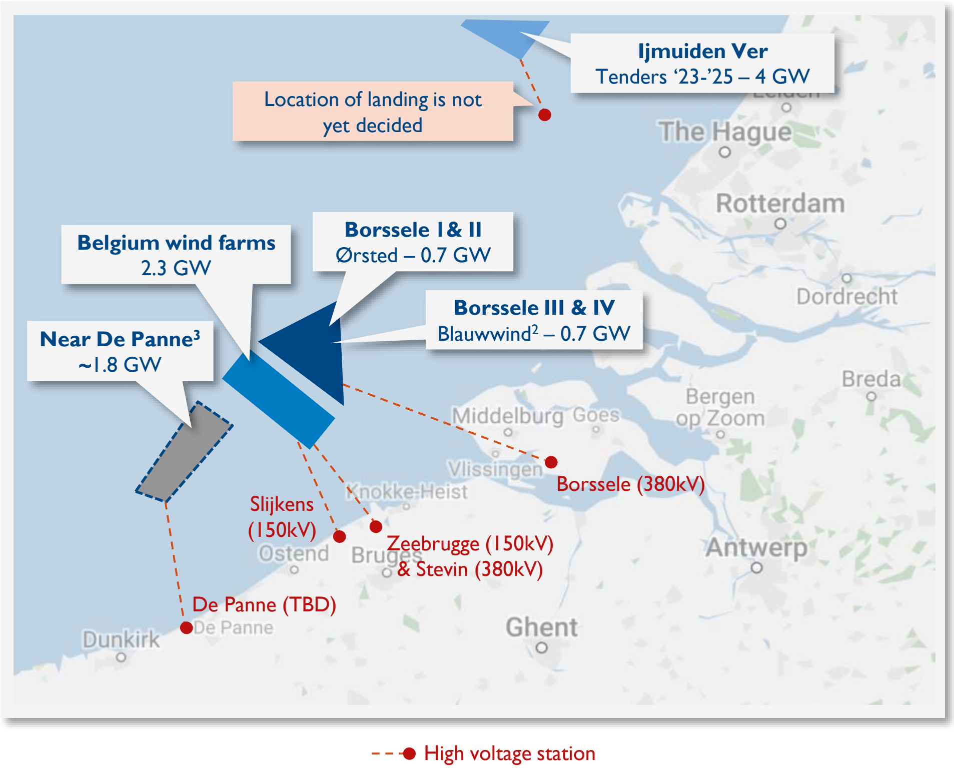
PRELIMINARY

Offshore wind outlook

SDR region, 2019-2030, GW



Market availability of wind energy (e.g. in PPAs) to be checked



Ijmuiden Ver
Tenders '23-'25 – 4 GW

Belgium wind farms
2.3 GW

Borssele I& II
Ørsted – 0.7 GW

Borssele III & IV
Blauwwind² – 0.7 GW

Near De Panne³
~1.8 GW

---

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

Table of contents

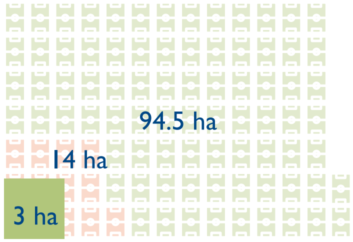
A Appendix

  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: ■ Stacks (~ 5-10%) ■ Electricity supply (~ 15-20%) – Transformers – Rectifiers ■ Pumps (~ 8-14%) ■ Heat-exchangers (~ 5-10%) ■ Separators (~ 8-14%) ■ Compressors (~12-18%) ■ Monitors (~ 1-4%) ■ Void space (~ 25-40%)		■ 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		■ 'Safety Zone' is the distance that an industrial facility needs to be from non-industrial area[2], 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		 ■ 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

Spatial planning environmental categories

Light activities

Belgium	**The Netherlands**
Residential area	**Milieucategorie 1** (e.g. barber shop, doctor)
Bufferzone (Agriculture)	**Milieucategorie 2** (e.g. bakery, supermarket)
Light industrial activities (indicative: similar to Millieucategorie 3)	**Milieucategorie 3** (e.g. gasoline station, car repair shops
Industrial activities (indicative: similar to Millieucategorie 4)	**Milieucategorie 4** (e.g. food production, lubrication oil production)
Heavy industrial activities (indicative: similar to Millieucategorie 5 & 6)	**Milieucategorie 5** (e.g. cement production, industrial gas storage)
	Milieucategorie 6 (e.g. oil and steel refineries, nuclear plants)

Heavy activities

INDICATIVE

- 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 activity[1]
  - 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

Arthur D Little

Arthur D. Little has been at the forefront of innovation since 1886. We are an acknowledged thought leader in linking strategy, innovation and transformation in technology-intensive and converging industries. We navigate our clients through changing business ecosystems to uncover new growth opportunities. We enable our clients to build innovation capabilities and transform their organizations.

Our consultants have strong practical industry experience combined with excellent knowledge of key trends and dynamics. ADL is present in the most important business centers around the world. We are proud to serve most of the Fortune 1000 companies, in addition to other leading firms and public sector organizations.

For further information please visit **www.adlittle.com** or **www.adl.com**.

Martijn Eikelenboom
Managing Partner

E: Eikelenboom.martijn@adlittle.com
M: +31 6 551 788 80

Marc de Pater
Principal

E: depater.marc@adlittle.com
M: +31 621 198 205