System integration GW-electrolyser

The road to a 1-GW electrolyser – Challenges and opportunities

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Management summary (1/5)

Project context and scope

This report documents a study to the system integration of a 1 GW-electrolyser in the Schelde-Deltaregion executed by DNV and Witteveen+Bos in collaboration with Smart Delta Resources for the province of Zeeland.

The industrial Flemish-Dutch Schelde-Deltaregion is very suitable for large-scale production and use of green hydrogen. The region already represents the largest hydrogen consumption cluster in the Benelux and various suitable locations are suitable for large scale green hydrogen production.

The goal of this study is to identify opportunities and risks associated to the development of large-scale green hydrogen production in terms of technology, safety and permits and financing in the Schelde-Deltaregion. The scope of the project with respect to technology is limited to a hypothetical 1 GW electrolyser in Vlissingen Oost. Contrary to the technology part, safety and permits and financing are considered for the region as a whole.

Management summary (2/5)

Key findings

This study focusses on the system integration of a 1 GW electrolyser in Vlissingen Oost. Based on the existing, planned infrastructure in Vlissingen Oost, we recommend to split the development of this location in to at least 2 phases.

Phase 1: 400 MW electrolyser

The existing and planned infrastructure around Vlissingen Oost is sufficient to support a 400 MW electrolyser plant by 2025. The infrastructure for power and water supply is already in place and a regional hydrogen backbone is planned to be operational by 2025. In order for the electrolyser to be operational by 2025, development must start this year (2022). Critical to this timeline is the permitting process with potential court appeals lasting up to 2 years. Therefore it is important to start with the permitting process as soon as possible.

Management summary (3/5)

Since green hydrogen production fluctuates with renewable energy production, balancing supply and demand of hydrogen is essential. The existing hydrogen production capacity using steam methane reformers (SMR) in the Schelde-Deltaregion has sufficient flexibility to balance 650 MW equivalent of hydrogen production. Active coordination with the SMR operators is required to integrate renewable electrolysis in the SDR region before the hydrogen backbone is connected to national storage facilities (salt caverns).

However, there is a market risk to be covered. Green hydrogen projects are extremely challenging to finance due to the market risk under normal economic conditions. It is essential that these risk is covered as soon as possible to kick-start the green hydrogen economy with subsidies and/or involvement of parties such as InvestNL.

Current market conditions (Q1 - Q2 2022) with high natural gas prices are an opportunity for green hydrogen to be economically competitive.

Management summary (4/5)

Phase 2: 1 GW electrolyser

For extension to a 1 GW electrolyser plant in Vlissingen Oost additional infrastructure is required. Firstly, a new 380 kV substation from TenneT, planned to be ready between 2028 and 2032 is required. Secondly, connection to the national hydrogen infrastructure, planned to be ready by 2028, is required to balance supply and demand of green hydrogen. Finally, additional infrastructure for water supply must be developed to support a 1 GW electrolyser.

Management summary (5/5)

Other findings

Other findings with respect to the system integration of a 1 GW-electrolyser are the following:

- Oxygen utilization is considered. The only feasible option at this moment is a connection to the oxygen network of Air Liquide. It is recommended to evaluate the cost and benefits of this option.
- Two options for cooling of excess heat are considered: cooling with fans in a closed loop system and sea water cooling. The CAPEX of a sea water cooling system is comparable to a closed loop cooling system with fans. Furthermore, sea water cooling does not seem to be an issue in the Westerschelde. Sea water cooling seems preferable because it consumes less power. It is recommended to evaluate the OPEX of sea water cooling compared to a closed loop cooling system with fans and confirm it is possible from an environmental/permitting perspective.
- A 1 GW plant produces sufficient heat to cover the majority (fully in terms of energy, the majority in terms of time) of local heat demand in Vlissingen Oost.
- No major risks with respect to safety and environmental impact have been identified.

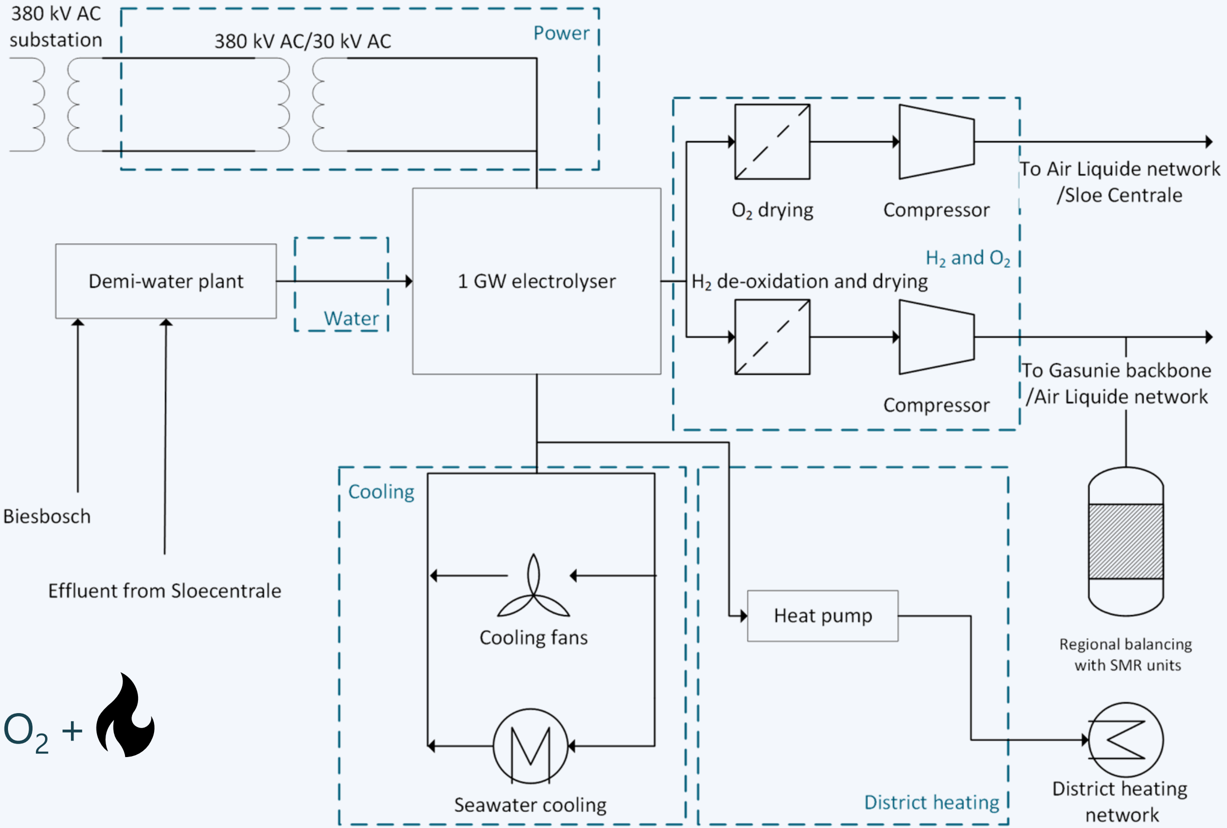
Witteveen+Bos DNV smart delta resources

The road to a 1-GW electrolyser in the SDR region

- Project context
- Key challenges and path forward
  - Supporting infrastructure routes
  - Water supply
  - Critical timeline
  - H_2 balancing
  - Financing
- Key takeaways

Project context

- 1 GW plant in Vlissingen Oost
  - Technology scope →
- Safety and permitting
- Financing



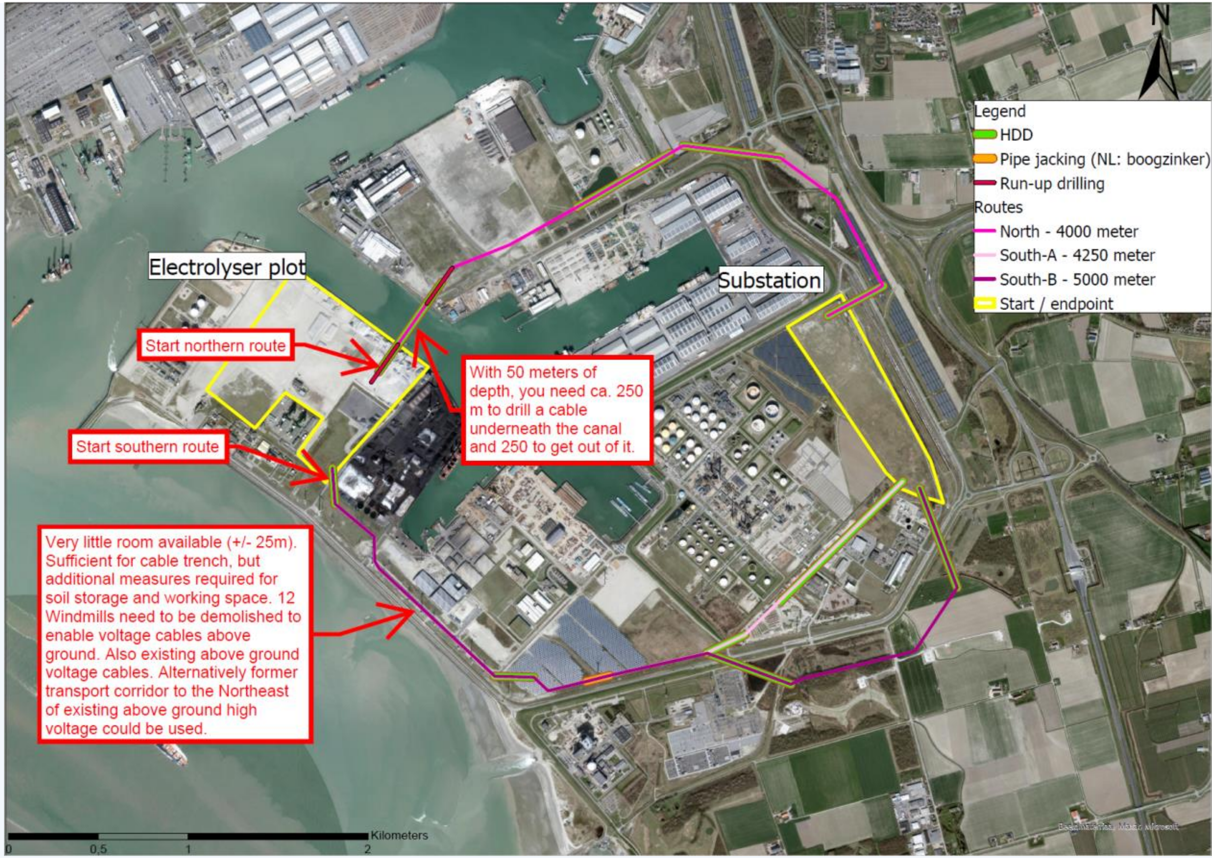
- Electrolysis: H_2O + ⚡ → H_2 + ½ O_2 + 🔥

Witteveen + Bos

Supporting infrastructure (pipes and cables) has significant spatial impact on large areas of land (and sea), from Bergen op Zoom to Vlissingen.

For example: The route of the high voltage line as seen on the right must cross a narrow corridor or water way.

Determine routes for supporting infrastructure early and integrally. Active and early collaboration between **TenneT, Gasunie, Evides** (and **Air Liquide**) is required.



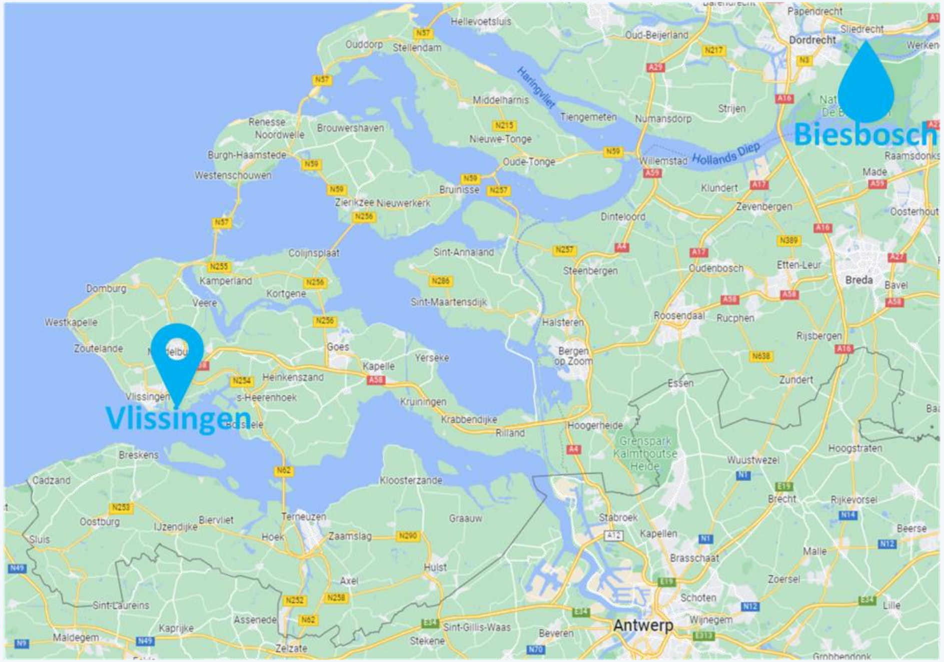
Challenges and path forward – Water supply

With the existing infrastructure Evides can supply sufficient demi water for 400 MW electrolysis capacity. An additional pipeline from the Biesbosch to Vlissingen is required to supply sufficient demi water for 1 GW electrolysis capacity. The Biesbosch is also a source for drinking water.

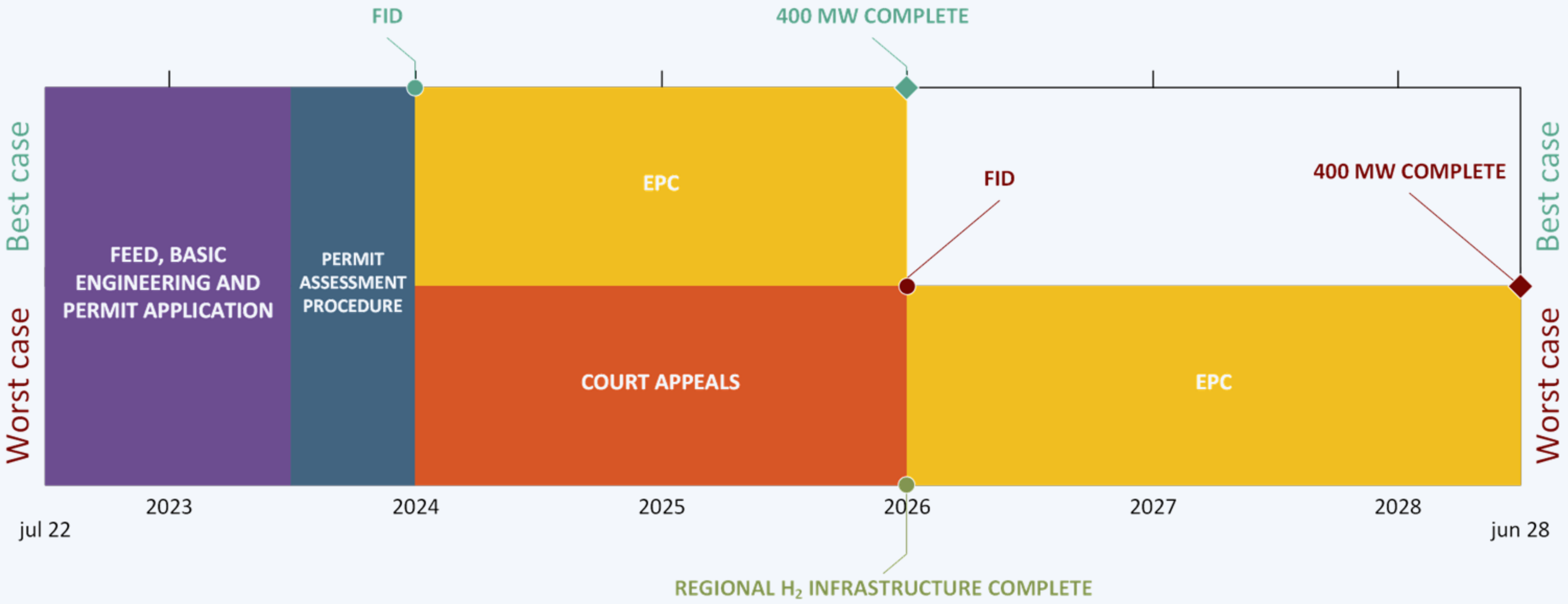
Evides requires ~3 years to develop and construct an additional pipeline. Ensure **Evides** can start on time.

Residual heat from the electrolysis process can be used to produce demi water on-site from the Schelde at competitive prices.

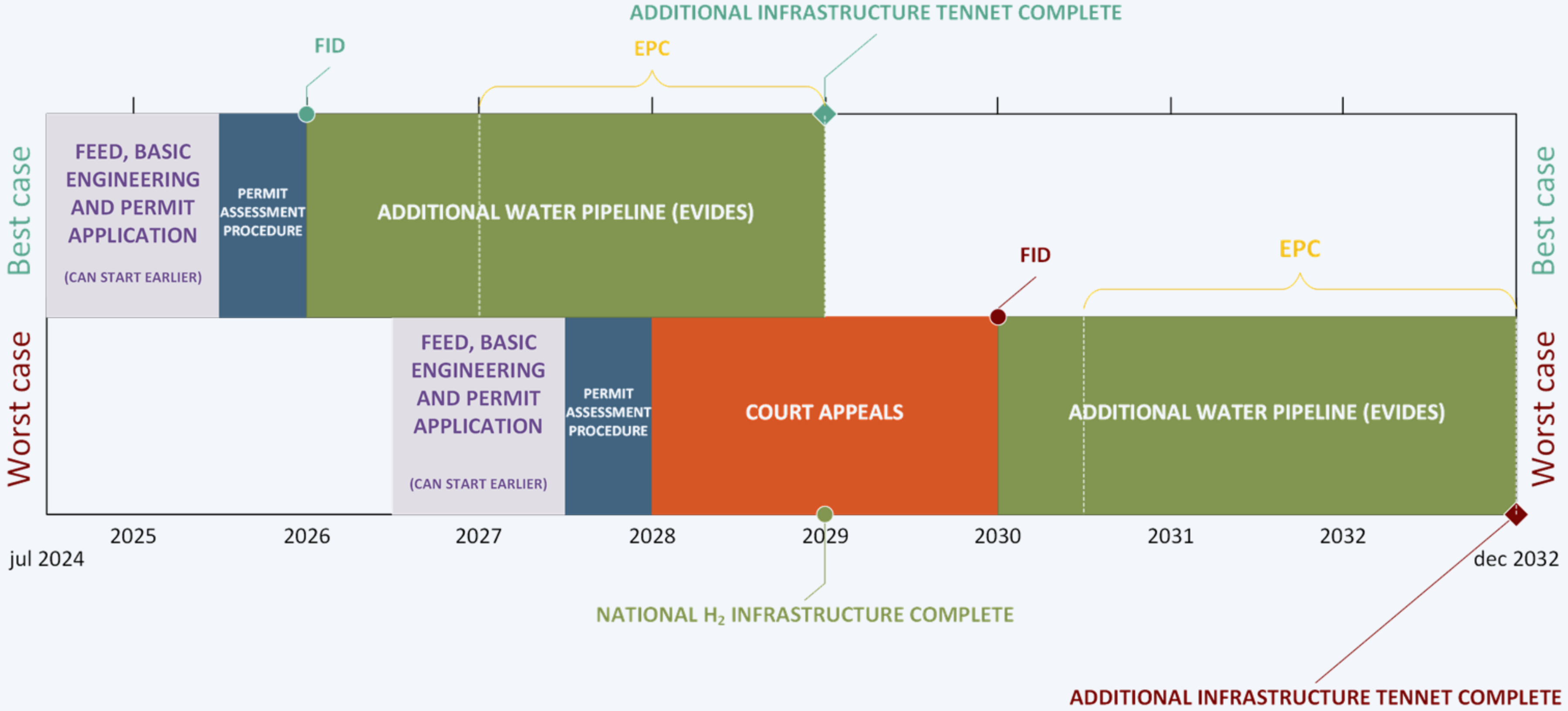
Explore with **Evides** if effluent water in the Bergen op Zoom area can be used as a source.



Critical timeline to 400 MW



Critical timeline to 1 GW



Challenges and path forward

An additional 380 kV from **TenneT** is required to extend from 400 to 1 000 MW. Estimated completion: 2028 – 2032.

Active collaboration with **TenneT** to ensure timely completion of substation.

Explore possibilities to develop a 380 kV substation as **electrolyser project developer** with **TenneT.**

Project development must start **this year** in order to complete 400 MW by the end of 2025.

Start now and cover financial risks.

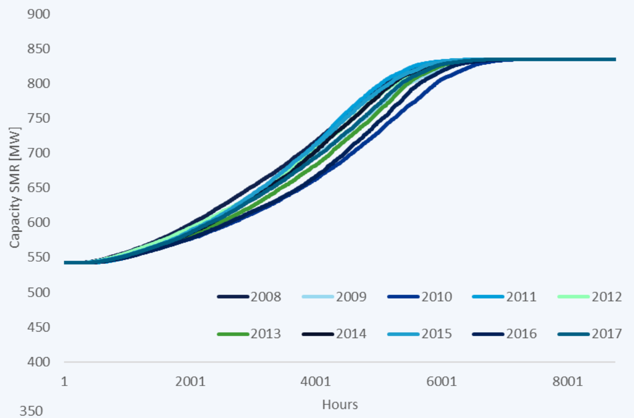
Court appeals with respect to the permit can slow development down up to 2 years.

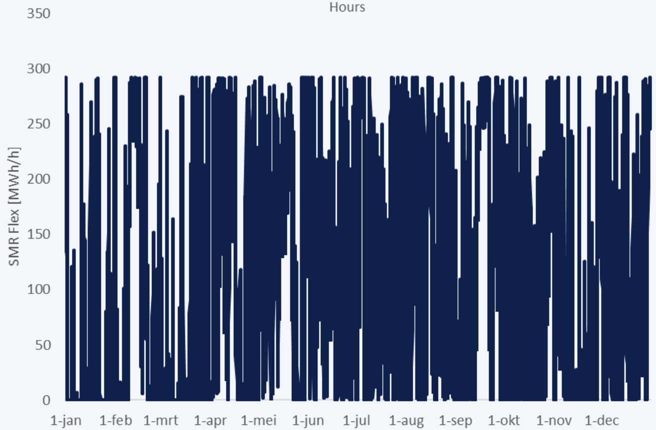
Engage with stakeholders early in the process to increase support and select a strategic location like Vlissingen Oost.

Challenges and path forward – H_2 balancing

Around 650MW of renewable electrolyzer capacity can be balanced with the existing SMR capacity in the SDR region. Another option to use end-user flexibility for dual fuel burning is limited.

Active coordination with the SMR operators is required to integrate renewable electrolysis in the SDR region before the backbone connection including storages is established.



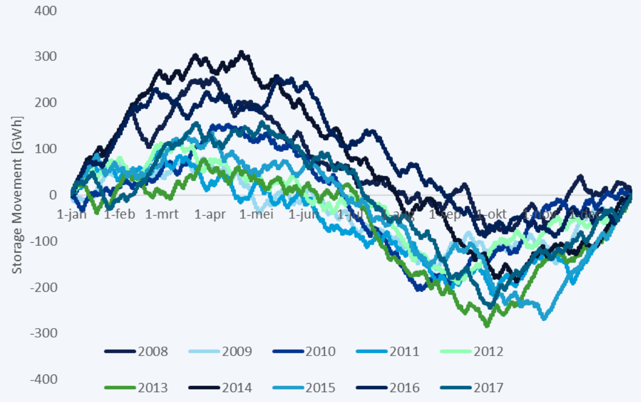


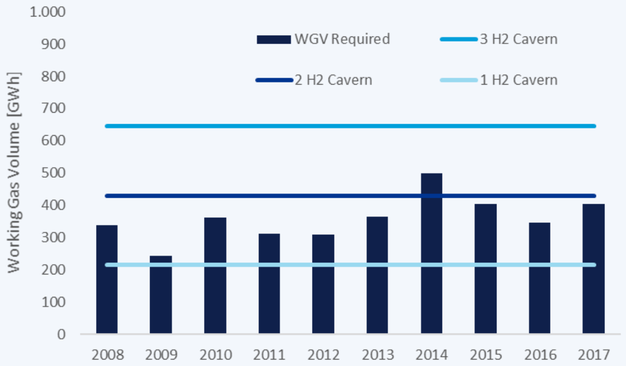
Challenges and path forward – H_2 balancing

Two to three salt cavern storages are needed to balance 1 GW of renewable electrolyzer capacity. Large scale energy storage is required to align weather (wind and solar) driven hydrogen production and base load industrial demand.

Align with salt cavern storage developers to coordinate the time line of electrolyzer capacity and storage capacity.

Explore potential balancing services an import terminal for hydrogen can provide





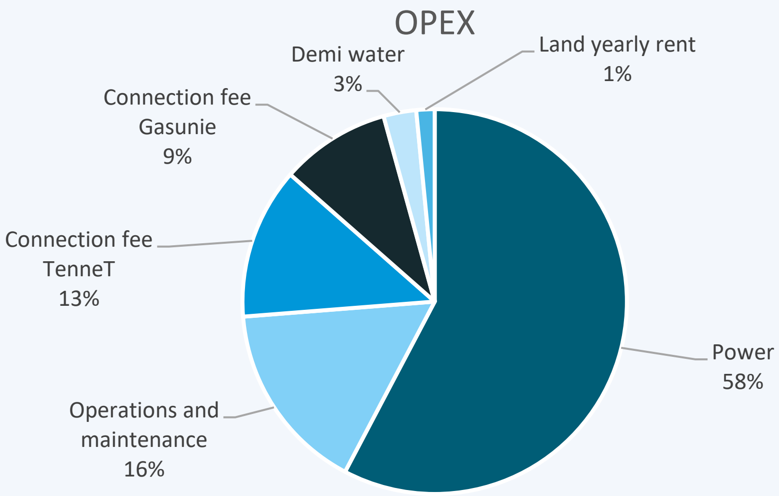
Challenges and path forward – Financing

Main cost is power (transport).

Reduction cost for electricity may lead to a positive business case.

Explore with **TenneT** possibilities for **free landing zone**.
Reduce cost by usage of smart systems to reduce high electricity prices.

~€ 260 million/yr @ 5000 full load hours/year; 30 EU/MWh



Challenges and path forward – Financing

No positive business case.

Subsidies are a necessity to make green hydrogen competitive.

Also, by-products (oxygen) contribute slightly to business case (>3% revenue).

(see slide 33 for more info on oxygen utilization)

Average power price (per MWh)	Required H_2 price for NPV = 0 after 25 years (per kg)
€ 15	€ 3.50-4.00
€ 30	€ 4.50-5.00
€ 45	€ 5.50-6.00

H_2 price in 2021: € 1 – € 2,50 /kg
Current H_2 price: € 5 – € 7 /kg

Key takeaways

- For the realisation of 400 MW electrolysis by the end of 2025:
  - Development must start this year (2022)
  - Supporting infrastructure is in place (electrical, water) or will be in place by the end 2025 (H_2 backbone)
  - The SDR region is able to balance supply and demand with existing SMR units
  - There is a financial gap to be covered - Projects are extremely challenging to finance due to H2 market risk

- For the extension to 1 GW electrolysis:
  - Additional electrical infrastructure is required
  - Connection to the national H_2 backbone including central storage capacity is required to balance supply and demand

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Additional slides

- Project information
- Hydrogen and oxygen compression
- Additional slides H2 balancing
- Oxygen utilization
- Cooling
- District heating
- HAZID/ENVID
- Permitting
- Additional slides financing

Project information

- **Contractors**: Witteveen+Bos and DNV GL
- **Client**: Province of Zeeland
- **Steering committee**: Smart Delta Resources, Air Liquide, Dow, Ørsted and Zeeland Refinery
- **Project duration**: September 2021 – April 2022

H_2 and O_2 compression and treatment

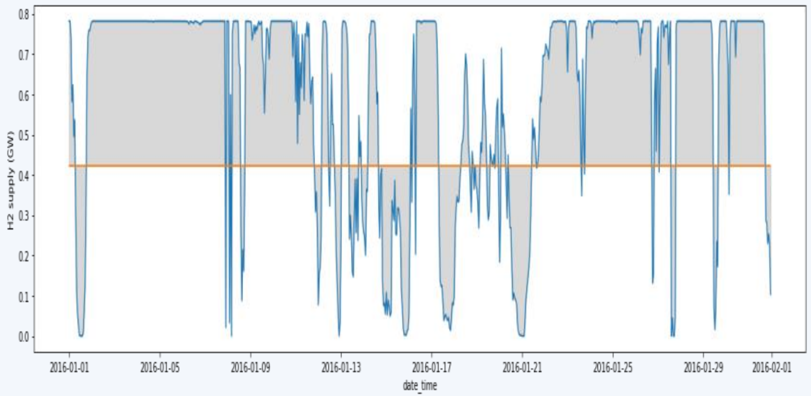
Case	Gas	Compression and treatment	CAPEX (x million)	Compression energy
1 Alkaline electrolyser (1 GW)	Hydrogen	From atmospheric pressure to Gasunie backbone (50 bar)	195 EUR (+/- 50%)	2,2 kWh/kg
	Oxygen	Vented to atmosphere	n.a.	n.a.
2 PEM* electrolyser (1 GW)	Hydrogen	From 30 bar to Gasunie backbone (50 bar)	82 EUR (+/- 50%)	0,3 kWh/kg
	Oxygen	n.a.	n.a.	n.a.
3 PEM* electrolyser (1 GW)	Hydrogen	From 30 bar to Air Liquide network (90 bar)	109 EUR (+/- 50%) (on-site) 50 EUR (+100%/-50%) (off-site piping)	0,6 kWh/kg
	Oxygen	From 10 bar to Air Liquide network (50 bar) 60 kNm^3/h	40 EUR (+/- 50%) (on-site) 50 EUR (+100%/-50%) (off-site piping)	0,06 kWh/kg

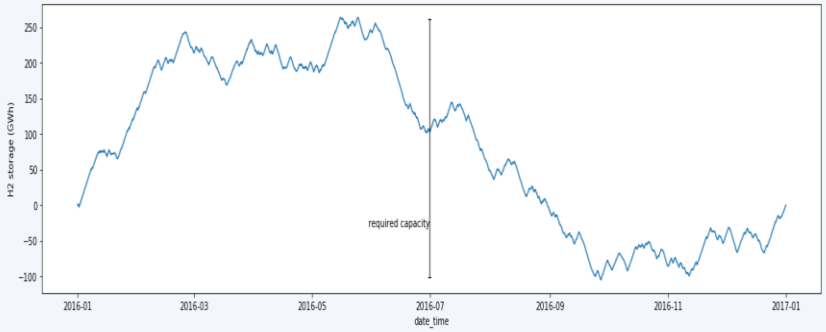
*Pressurized alkaline electrolyser is also possible

Hydrogen balancing

Method:

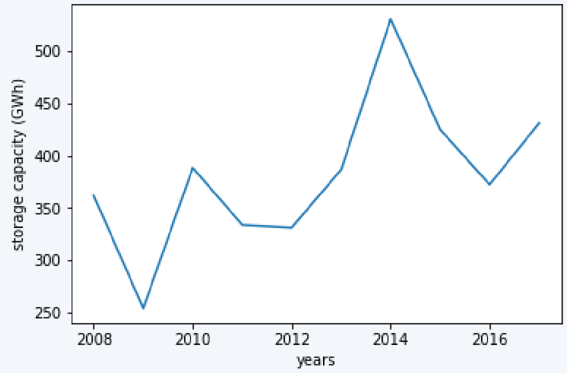
- Simulating hourly electricity production profiles from an offshore wind farm for 10 historical years (2008-2017)
- Assuming (industrial) baseload off-take
- Balancing requirement is the hourly difference between the demand and supply
- The working gas volume is determined by substracting the maximum and minimum storage level

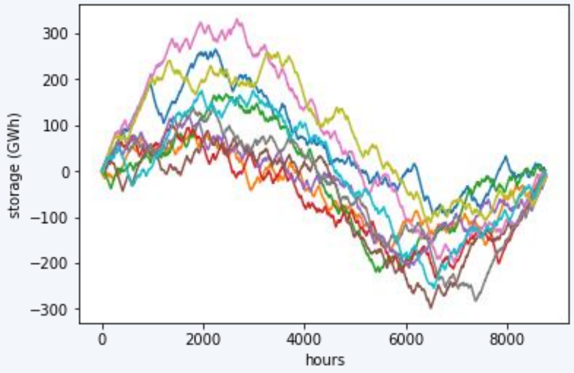




Balancing output after the national backbone

- The required working gas volume for the 10-year period ranges from 250 GWh to 550 GWh
- The storage injection and withdrawal pattern follows an inverse pattern to normal storage operation. In Winter the storage is filled and in Summer it is produced
- It would require ~2 salt caverns of 234 GWh (LHV) at Zuidwending to balance the mismatch between demand and supply





Other balancing options

Besides balancing with a salt caverns three other options exist:

- Line pack of the hydrogen pipeline system. Variation of the pressure in the hydrogen transmission backbone can deliver flexibility to the system.
- Dual fuel burners at end-users. End-use equipment can receive a mixture of natural gas and hydrogen. It is assumed that the hydrogen percentages in natural gas will fluctuate from zero up to the maximum allowable hydrogen content in natural gas.
- Flexible operation of SMR units. Existing SMR units in the network can be ramped up and down based on the hydrogen production of the SMR

Line pack

- Line pack potential has been calculated based on the total dimensions of the foreseen hydrogen backbone
- Calculations show a relatively small working gas volume that can be achieved by using linepack
- The total amount of flexibility equals 27GWh for the entire backbone. The total available linepack scales linear with the allowed pressure variation: a pressure variation of 1 bar would result in a line pack of 2.7GWh

Segment	total length	water volume	Linepack (dp=		10 bar)
	m	m3	Nm3 H2	kg H2	GWh
amsterdam-rotterdam	160.000	105.071	1.050.709	94.438	3,1
eemshaven-amsterdam	207.000	137.322	1.373.218	123.425	4,1
eemshaven-zuidwending	60.000	38.388	383.882	34.503	1,2
emmen-geleen	194.000	161.364	1.613.640	145.034	4,8
emmen-ruhrgebied	183.000	178.912	1.789.123	160.806	5,4
ravenstein-rotterdam	122.000	59.449	594.489	53.433	1,8
rotterdam-zeeland	270.000	116.340	1.163.400	104.566	3,5
zuidwending-emmen	198.000	115.438	1.154.381	103.756	3,5
Eindtotaal	**1.394.000**	**912.284**	**9.122.843**	**819.961**	**27,3**

End-user flexibility

In the direct proximity of the hydrogen production site three potential (large scale) off-takers are present:

- Zeeland Refinery (~0.5 bcm of natural gas to be replaced but indirect processes can run without natural gas)
- Yara Sluiskil (0.6 bcm of natural gas to be replaced which is used for fuel consumption, the other usage as feedstock is not taken into account)
- Opportunity: Power plant @ Elsta

Potential for different end-user appliances to switch to H2

- A large variety of end-use equipment is installed, all having a different sensitivity towards hydrogen addition to natural gas. Consequently, the allowable fraction of hydrogen gases in natural gas depends strongly upon both the type of appliances installed and the natural gas composition distributed.
- Especially, for gas turbines with premixed combustion systems retrofitting for more than 30% of hydrogen is not yet feasible. However, turbine manufacturers are researching retrofit solutions that can handle up to 100% hydrogen

GTS (H-gas)

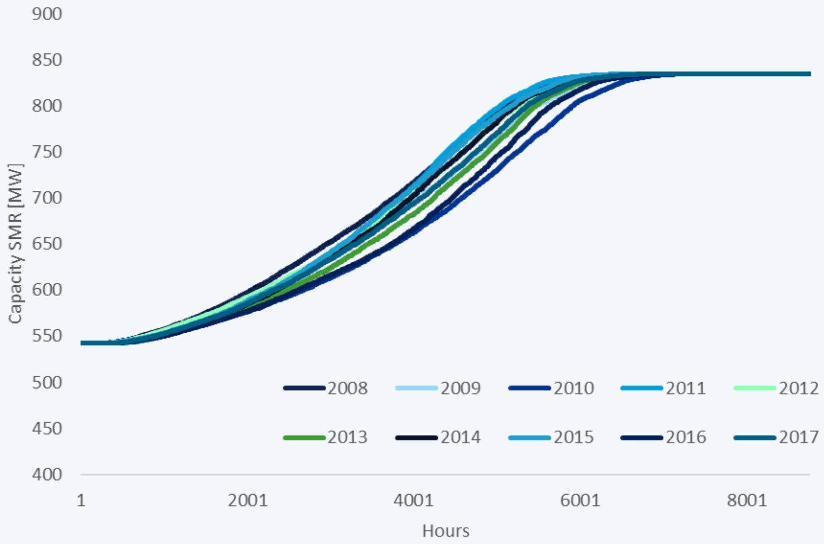
Market	End-use equipment	without retrofit, % hydrogen		With retrofit or additional research, % hydrogen		Reference
GTS network	Gas turbines	0	5	0	30	[5, 10]
	Gas engines	0	5	0	25	[5, 10]
	Industrial burners (indirect heating)	0	20	0	100	[5, 7, 10]
	Industrial burners (direct heating)	0	10	0	100	[5, 7, 10]
	Compression Centrifugal	0	5	0	10	[10]
	Compressor piston	0	5	0	10	[10]

Flexible use of SMR

- In the vicinity of the electrolyzer both Zeeland Refinery and Yara Sluiskil have SMR units operational
- The estimation is that:
  - the unit at Zeeland Refinery produces baseload ~116.000 m^3/h using imported natural gas
  - The unit at Yara Sluiskil produces baseload ~400.000 m^3/h using imported natural gas
- SMR's are able to ramp-down to 40-65% of designed load. However, other downstream by-product restrictions on steam or CO2 delivery might limit the ramp-down potential

Balancing output before the national backbone

- 400 MW electrolyser can supply around 150 MW base load demand
- The flexibility can be delivered by using 835 MW of SMR capacity with a minimum load of 65%
- The same result can be achieved by using dual fuel end-user equipment
- The flexibility is derived from the natural gas grid



Path forwards

- The balancing capacity of the existing SMR and industrial equipment will limit the amount of large scale renewable hydrogen produced from offshore wind that can be integrated in a regional network
- Therefore, the challenge is to coordinate between the developers of electrolyzer capacity and the providers of flexibility.
- Opportunity: H_2 import terminal
- Avoided cost potential by :
    - Avoidance of CO_2 (green H2 vs. grey H_2)
    - Decreasing in net congestion

Oxygen utilization

- Total production: 112 kNm^3/h (@ 1 GW)
- Potential off-take Air Liquide: max. 60 kNm^3/h
  - Annual revenue: ~10 million EUR (@5000 full load hours; 30 EU/ton)
  - O_2 CAPEX:
    - ~40 million EUR on-site
    - ~50 million EUR off-site piping (~50 km @ 1 million EUR/km)
- Opportunity: O_2 in ATR process of DOW (pipeline across the Schelde required(!))

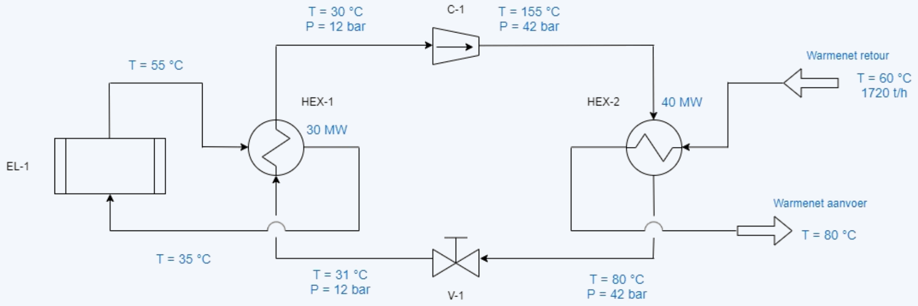
Cooling

- 300 MW cooling capacity
  - Option 1: 100 dry coolers: 21 million EUR (+/- 50%) CAPEX
  - Option 2: 9 seawater coolers: 20 million EUR (+/- 50%) CAPEX
    - Should not be a problem in the Westerschelde

District heating

- 43 million EUR CAPEX (+/-50 %) for heat pump installation
- ~7000 full load hours/year @ 30 MW heat recovery and 1 GW electrolyser
- No profit expected due to regulatory aspects

- Ammonia heat pump cycle
- COP: 4
- 10 MW electric



Permit overview

- Environmental Permit:	Extended procedure (6 mo), BAT and EIA notification
- Water Permit:	Extended procedure, aquatic hazard tests
- Deviating from zoning plan:	High risk facility, only allowed on specific locations
- Nature permit:	Low N-emissions in user phase, partial exemption construction
- Environmental safety:	Emergency plan, domino effects & prevention policy required
- Building permit:	Normal procedure (8 weeks)

Permitting is not expected to be a critical issue if there is no significant on-site H_2 storage

Risks, strategy and planning

Risks in permitting process:
- Spatial planning: locations allowing type of activity (cat. 5.2) are sparse + safety contours
- Environmental effects: sound, nature (partial exemption, government plans). Court appeals
- Engineering: information is required in time for environmental and safety studies

Strategy: Combine permits for zoning plan deviation, environment, water and nature in 1 application (longer procedures, larger risks), followed by building and other permits (shorter procedures, smaller risks)

Planning: 1-1,5 years without court appeals (+2 years)

Theme	Q1	Q2	Q3	Q4	Q5
Preparation	NRD EIA				
Engineering		Parallel engineering and permitting to provide required input			
Environment + safety		Studies, prepare application and EIA		Permit procedure	
Building				Studies, prepare application	Permit procedure

Key findings – HAZID/ENVID

- No major risks identified
- Impact of supporting infrastructure in the larger environment (pipes and cables) could be significant. Address this as soon as possible
- Ensure sufficient space between components (H_2 and O_2)
- Use European Industrial Gases Association (EIGA) standards for a safe design

Attendees HAZID session: Air Liquide, Ørsted, Zeeland Refinery, Witteveen+Bos

Attendees ENVID session: Dow, North Sea Port, Province of Zeeland, Witteveen+Bos

Feedback from interviews with financial parties

- Project financing very challenging at this point. Key dealbreaker for banks is market exposure
- Revenues need to be fully covered by contracts in order to be able to attract loans.
- Finance of Invest NL / regional fund essential
- Technical risks acceptable
- Start smaller to gain experience and figures
- Electrolyser manufacturers do not have the capacity for a 1 GW scale project

Green hydrogen policy – RED II

- Hydrogen is fully renewable if produced **simultaneously** with contracted renewable power generation
- Contracted renewable power must be **additional** capacity
- Green hydrogen production must **not cause grid congestion**