Deliverables

HyDelta

WP 7B – D7B.4
Innovation roadmap

A roadmap on transport and storage of H_2 and H_2-carriers for five sectors in the Dutch economy

Status: Final

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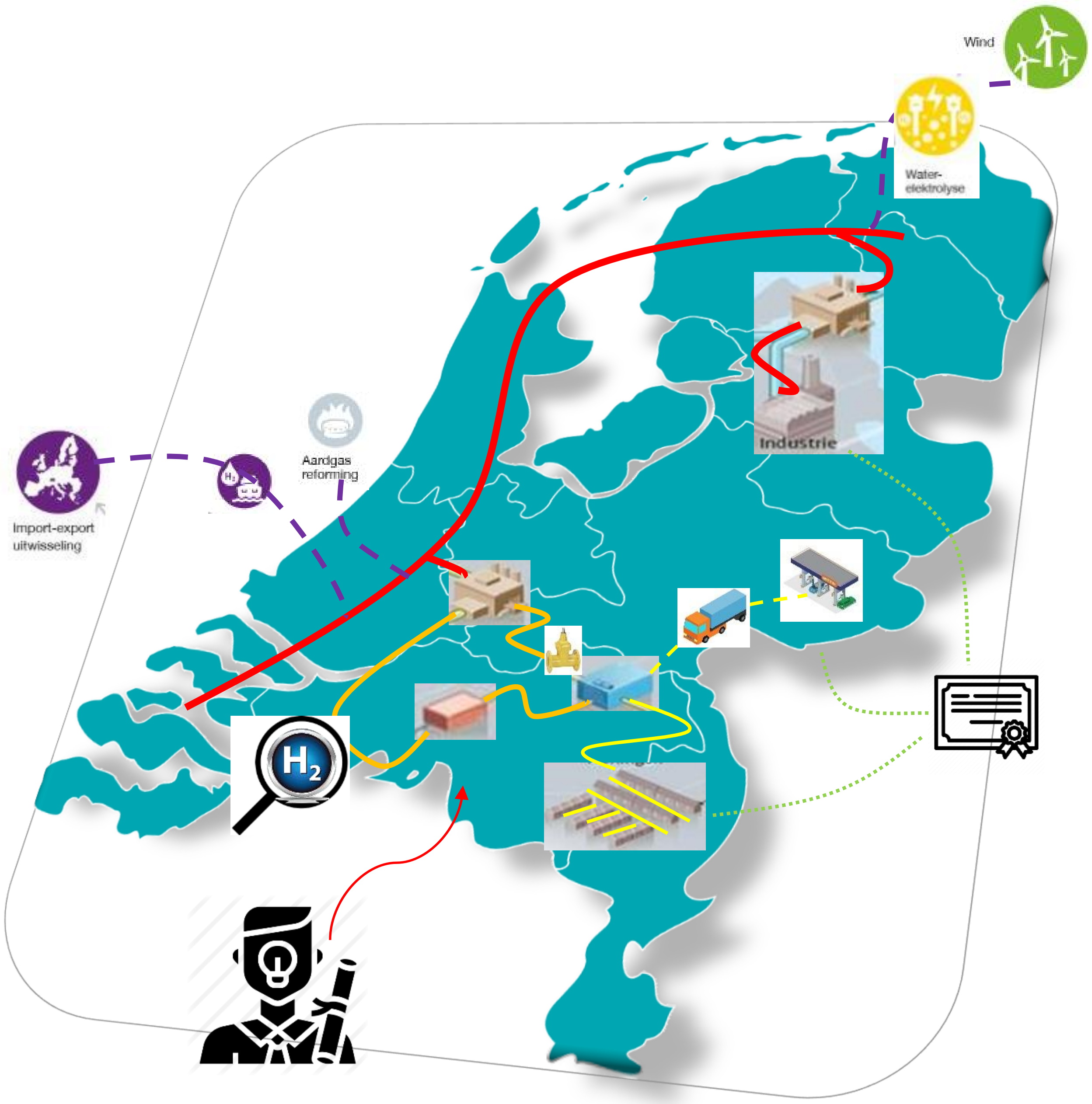

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DOCUMENT SUMMARY

Document history

Version	Date	Author	Affiliation	Summary of main changes
1	16-Feb-2022	Sara Wieclawska, Twan van Leeuwen	TNO	First version
2	10-May-2022	Sara Wieclawska, Twan van Leeuwen	TNO	Updated after comments from Expert Assessment Group

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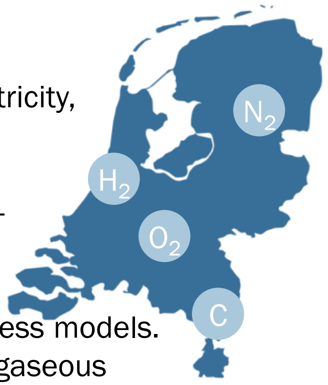
Dissemination level

Dissemination Level		
PU	Public	×
R1	Restricted to • Partners including Expert Assessment Group • Other project participants including Sounding Board • External entity specified by the consortium (please specify)	
R2	Restricted to • Partners including Expert Assessment Group • Other project participants including Sounding Board	
R3	Restricted to • Partners including Expert Assessment Group	

INTRODUCTION

A roadmap on transport and storage of H_2 and H_2-carriers for five sectors in the Dutch economy



The Netherlands currently imports and partially produces coal, crude oil and natural gas in order to provide for electricity, heat, fuel and chemicals. The coal, crude oil and natural gas provide the molecules (carbon, nitrogen, hydrogen and oxygen) which can be turned into the desired service (electricity, heat) or molecule (fuel, chemicals). In a sustainable future, the source of these molecules, is renewable.

In order to get to this sustainable future, value chains for the sustainable alternatives need to be developed. Examples are value chains for hydrogen-for-mobility or value chains for sustainable ('green') ammonia for the production of fertilizers.
These value chains start with producers (or import) and end with 'end-users'. Between the producer and end-user there are multiple parts that need to be in place: transport, storage and sometimes chemical transformations. All with the right technology, capacity, safety, regulations and business models. To make matters more complicated: some chains have multiple options (will the product be made centrally or decentral? Will it be stored in liquid or gaseous form?)

Given the variety of hydrogen import supply chains that can be developed towards the Netherlands and NW Europe, it is of importance to have a thorough understanding of the technological and economic performance of these import chains to be able to make informed strategic, policy and investment decisions (see HyDelta D7 B.3). Subsequently, potential hydrogen value chains have been developed and modelled for five types of end-uses, providing insight in the 2030 cost breakdowns (see HyDelta D7 A.2). Once produced and arrived, it is crucial to know how to store and distribute the hydrogen in the Netherlands. That is why this document, the HyDelta 7 B.4(?) Innovation Roadmap study, aims to provide more insight in the context and required developments for transport and storage of hydrogen for five sectors in the Netherlands. The sectors studied are the high temperature heat, fertilizer, methanol, built environment and mobility sector.

In order to do so, this document will focus on the following research question and three sub-questions:

What developments are required for transport and storage innovations for the large scale production and import/export of hydrogen in the NL?

1. **End users**: where will we need hydrogen & what are logical first end users?
2. **Infrastructure**: what technological developments do we need regarding storage and transport?
3. **Regulation**: what regulatory bottlenecks or drivers need to be tackled/in place?

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2. Conclusions

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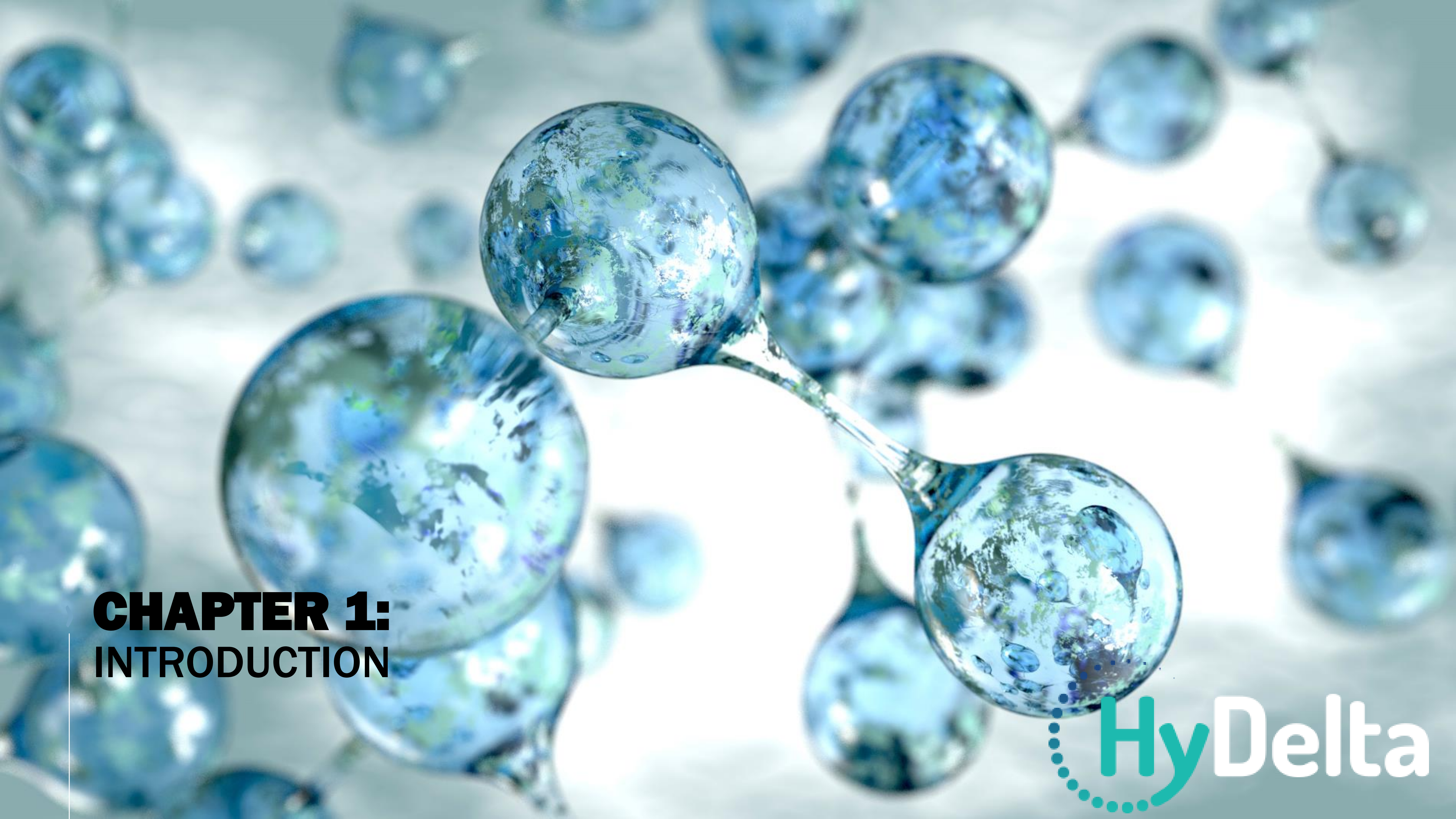
2.2. Technology is available
2.3. Regulation has to be in place as soon as possible

3. Background

3.1. End users: where to deliver the hydrogen?
3.2. Infrastructure: what technological developments regarding storage and transport are needed?
3.3. Regulation what regulatory drivers and/or bottlenecks need to be in place/tackled?

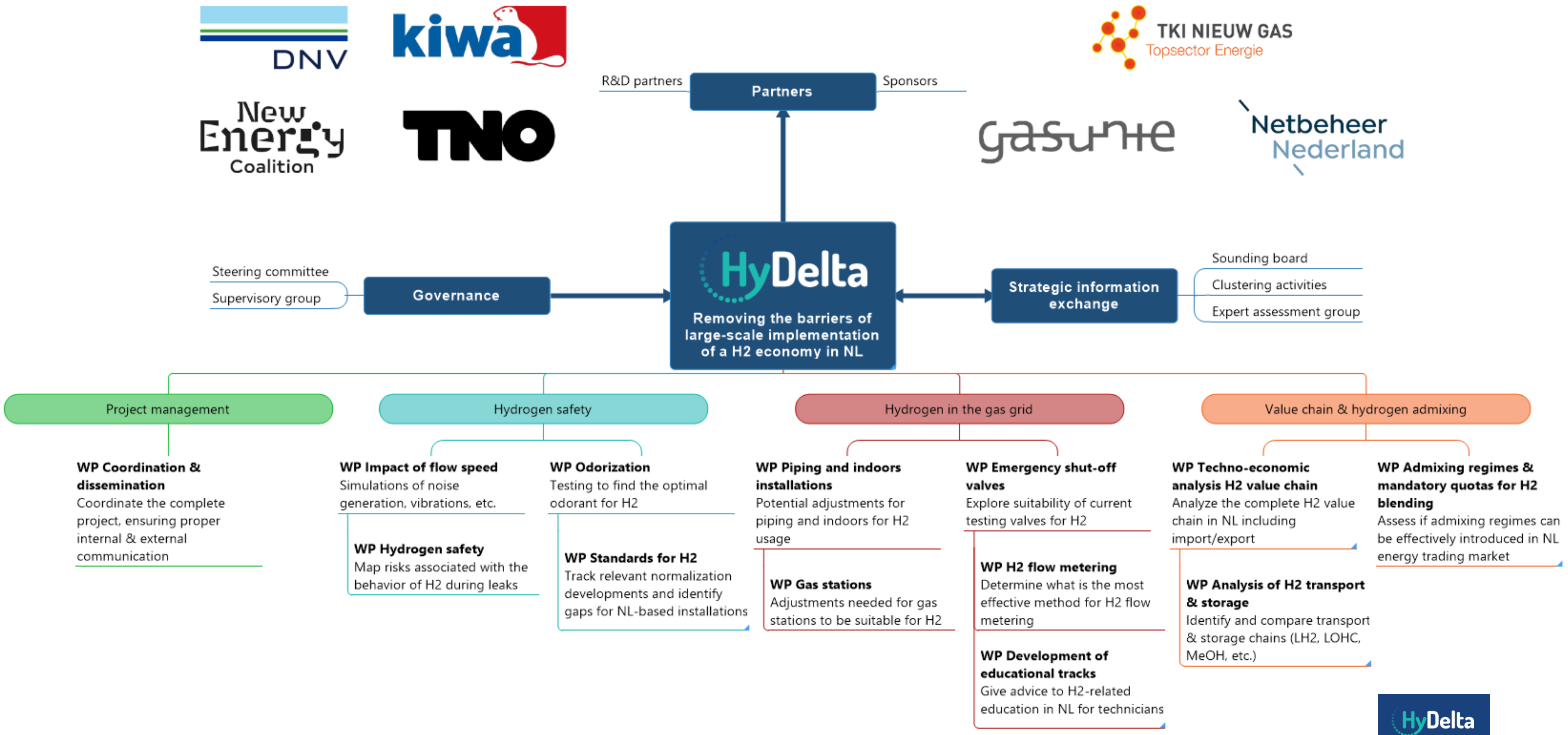


CHAPTER 1:
INTRODUCTION

1.1 AIM OF THE HYDELTA PROJECT

Hydelta is a national programme which aims to accelerate the scale-up of hydrogen in The Netherlands.

The project has multiple partners and three work packages around the themes ‘safety’, ‘transport’ and ‘value chain’ varying from technical analyses to economic analyses. More info on: www.hydelta.nl



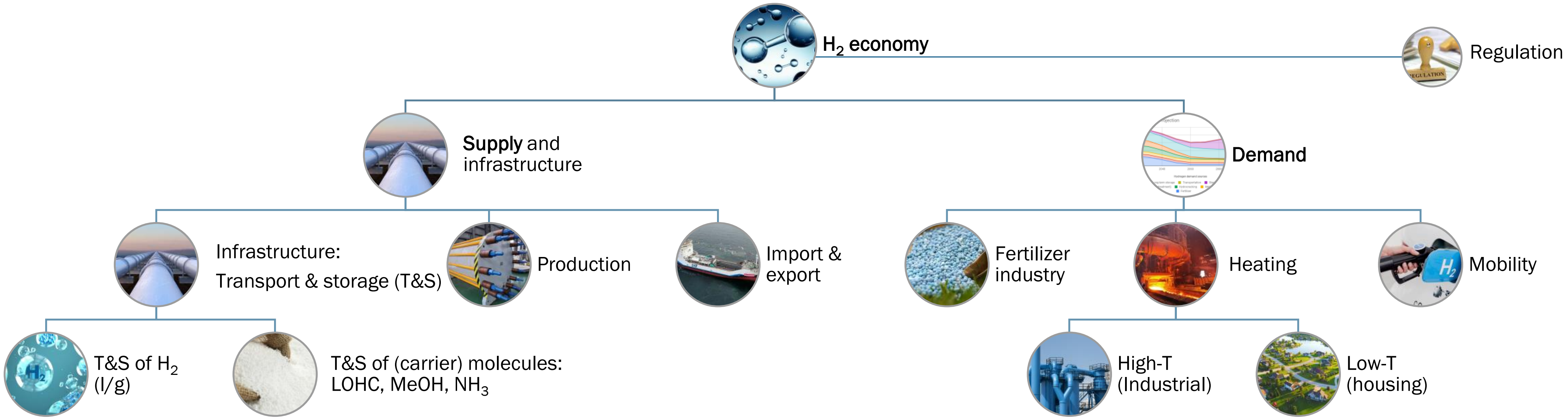
HyDelta

1.2A CONTEXT: ZOOMING OUT

Top down overview of the H_2 economy

Development and innovation for hydrogen storage and transport is an essential part of the hydrogen supply chain. However, it is difficult difficult to isolate and discuss on its own because of dependencies on the rest of the chain. The diagram below aims to create clarity in the different hydrogen topics by providing a top down overview of the hydrogen economy.

The focus of this document is on the 'Transport & Storage' part of the hydrogen supply chain. However, supply and demand parts will be discussed as transport & storage is highly dependent on developments, changes and choices in the supply and demand parts.

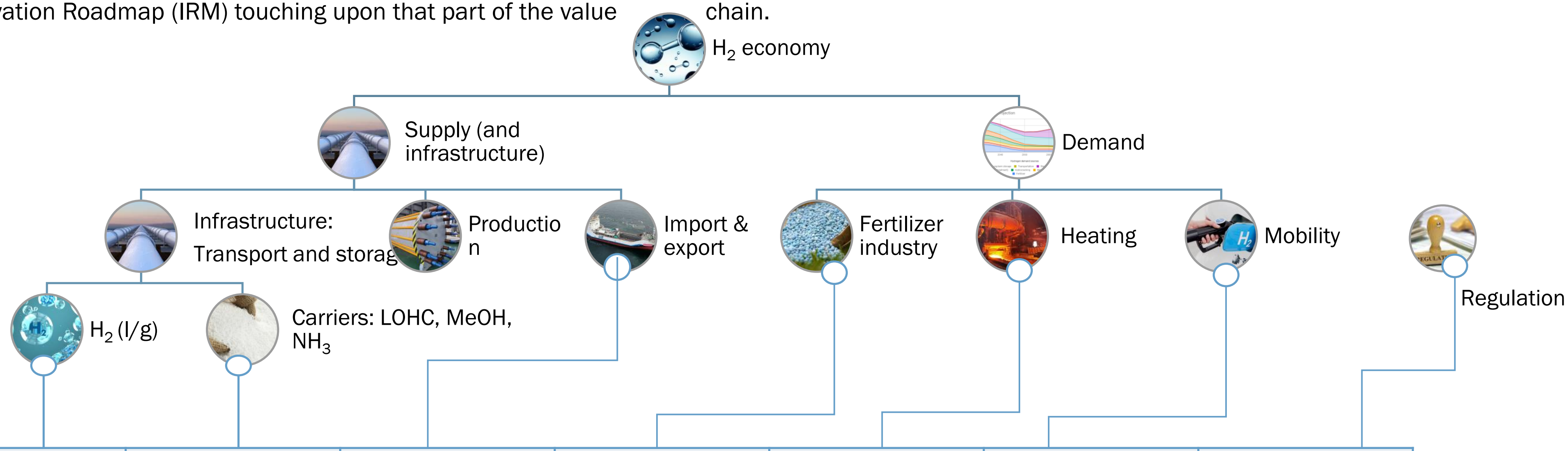


1.2A CONTEXT: ZOOMING OUT

Top down overview of the H_2 economy

A lot has been written already on hydrogen: roadmaps and research reports have been written on the whole system or particular parts of the value chain. This slide gives an overview of ‘innovation roadmap’-type documents that are currently available. This overview is extensive, but not complete: almost monthly new reports see the light of day.

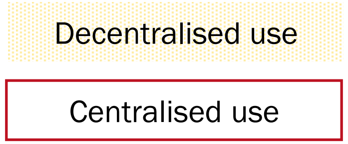
In the table, relevant sources for the different parts of the value chain are indicated, as well as the HyDelta project work package (which have their own reports) and the parts of this Innovation Roadmap (IRM) touching upon that part of the value chain.



IRM	1.2C, 2.2, 3.2	1.2C, 2.2, 3.2		2.1, 3.1	2.1, 3.1	2.1, 3.1	2.3, 3.3
HyDelta Work Package	7B	7B	7B	7A	7A	7A	
External	[1], [2], [5], [6], [8]	[1], [7], [8]	[1], [2], [7]	[3], [4], [12]	[3], [4], [9], [10]	[3], [4], [11]	[5], [12]

External sources consulted:
[1] Roland Berger, 2021, Hydrogen transportation / The key to unlocking the clean hydrogen economy
[2] Guidehouse, 2020, European Hydrogen Backbone
[3] FCHJU, 2019, Hydrogen roadmap
[4] Berenschot & Kalavasta, 2020, Klimaatneutrale energiescenario’s 2050
[5] PWC, 2021, HyWay 27
[6] TNO, 2021, Large-Scale Energy Storage in Salt Caverns and Depleted Fields (LSES)
[7] Guidehouse, 2021, Analysing future demand, supply, and transport of hydrogen
[8] Lanphen, 2019, Hydrogen Import Terminal
[9] BlueTerra, 2018, Toekomstvisie WKK
[10] Consortium Waterstofwijk Hoogeveen, 2020, Waterstofwijk: Plan voor waterstof in hoogeveen
[11] Ministerie van Infrastructuur en Waterstaat, 2020, Visie Duurzame Energiedragers in Mobiliteit
[12] TNO, 2022, Impact ‘fit For 55’ Voorstel Voor Herziening Red Op De Vraag Naar Groene Waterstof In Nederland

1.2B CONTEXT: FROM CARRIERS TO END USERS



How carriers & end user markets are connected

On the previous slide, the different forms of hydrogen –or carriers- where stated as molecules that needed transport & storage.
However, the picture is slightly more complex: these molecules (MeOH, NH3, hydrogen (liquid, gaseous or as LOHC) and electricity) are needed in different 'areas' of demand such industry (refineries, bulk-chemistry) but also for mobility or in the built environment.

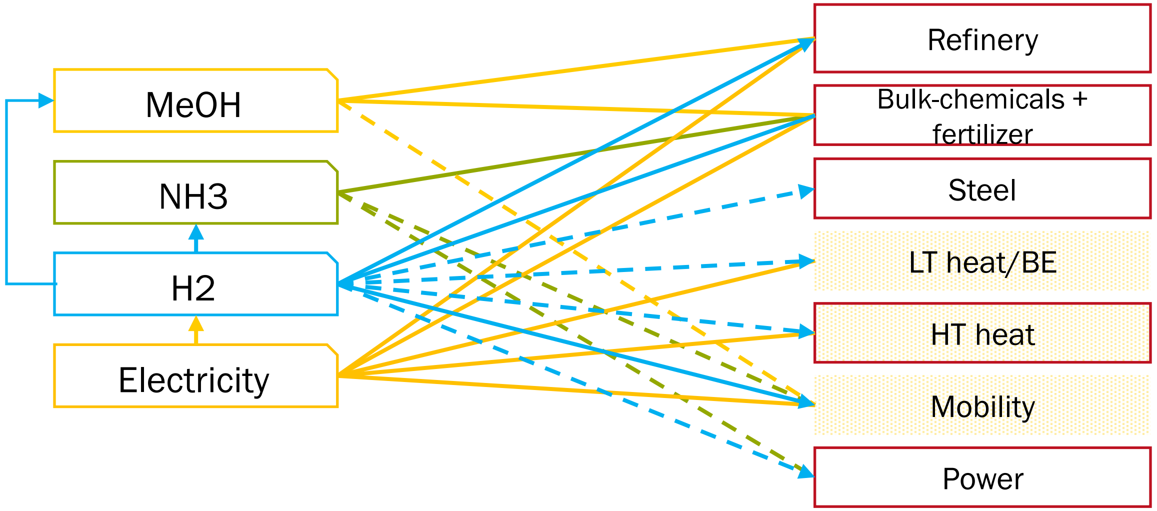
If the molecules are connected to their potential demand-markets (or 'end users'), we get the figure to the right.
In this picture we can see that varying molecules are needed in more than one demand market. Sometimes this is because a demand market (e.g. chemical industry) needs both, or because no choice has been made on which molecule is the most efficient or effective in that particular market.

This figure also indicates that the value chains are very much intertwined: they are more reminiscent of a network than a chain. This causes more complexity on one hand but also brings the potential for interesting collaborations, scale-up potential and efficiency.

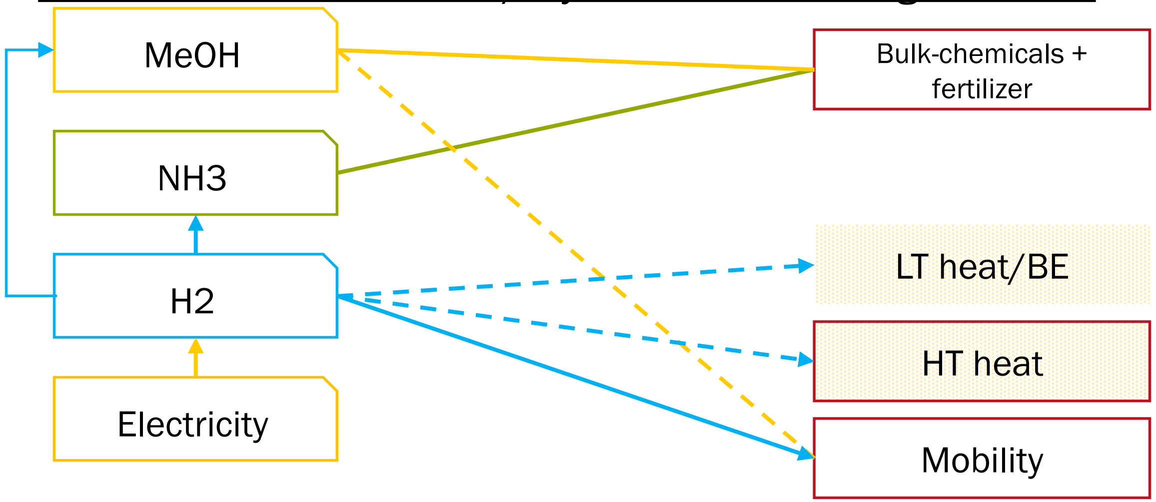
The bottom part of the picture shows the energy carriers-demand combinations taken into account in this document (and in the HyDelta Work Packages 7a & 7b). This was done in scoping sessions / in discussion with the HyDelta steering group based on an estimation where the largest impact can be made in The Netherlands on a medium-to-short timescale.

On the end-use side, we can distinguish roughly between 'central' end-use and 'decentral' end-use. 'Central' end-use being the use of these molecules on e.g. large industrial complexes whilst being on an industrial site / in neighbourhood of one. Or linked to existing (large scale) infrastructure. 'Decentral' end-use can be seen as a more spread out use of the molecules, e.g. for the built environment or mobility. This kind of use typically requires a more branched transport & storage network.

Energy carriers coupled to their demand markets / end-users



The energy carrier – demand market combinations taken into account in this document / HyDelta Work Package 7a & 7b



1.2C DUTCH HYDROGEN PLANS 2020 – 2030

How this roadmap relates to the Dutch H_2 plans

Development and innovation for H2 storage and transport is difficult to isolate from the bigger picture. How does this research question fit within currently running initiatives and demonstrations?

The *Meerjarige Programmatische Aanpak voor Waterstof in Nederland 2020 – 2030* shows what theme's, timing and budget. Highlighted in blue are elements that overlap with this roadmap.

	Thema	Timing (wanneer gereed)	Geschat budget (M€)
1	**Van visie naar beleidsvorming**		
1A.	Beleidsvisie waterstof	Begin 2020	Geen
1B.	Studies voor programmaontwikkeling	Doorlopend	Jaarlijks 0,2-0,5
2	**Laten zien in grootschalige praktijkprojecten**		
2A.	Realisatie grootschalige waterstofproductie op GW-schaal	2030	1.000+
2B.	Aanleg van een waterstofbackbone in Nederland en waterstofopslag	Rond 2030	Deels publiek
2C.	Inzet van stuurbare, flexibele elektriciteitscentrales op waterstof	2030	250+
2D.	Demonstratie van 3-5 pilots met waterstof in de gebouwde omgeving	2025	10-20
2E.	Uitrol van mobiliteit op waterstof incl. vulpunten	2025	10-20
2F.	Pilot- en demoprojecten waterstof in de industrie (valt deels onder 2A)	2025-2030	50-100
2G.	Inpassing decentrale duurzame elektriciteitsproductie via waterstof	2025	10-20
2H.	Ontwerp en aanleg testenergie-eiland	Voor 2030	100+
3	**Creëren van de randvoorwaarden**		
	Diverse onderwerpen, uit te werken in de komende jaren (o.a. veiligheid, wet- en regelgeving, gaskwaliteit, standaardisatie)	2020-2021	10-20
4	**Onderzoek voor de langere termijn**		
	Middellange tot lange termijn R&D-agenda ten uitvoer brengen	2020-2030	Jaarlijks 5-10
5	**Ondersteunende en flankerende activiteiten**		
5A.	Certificering van waterstof	2020-2021	Beperkt
5B.	Internationale afstemming en samenwerking	Doorlopend	Beperkt
5C.	Divers: regionale samenwerking, HCA, Digitalisering, MVI etc.	Doorlopend	Beperkt
	TOTAAL *(zeer globale schatting voor de periode 2020-2030)*		**Ordegrootte 1.500 - 2.000**

Source: Waterstof voor de Energietransitie - Een programmatische aanpak voor innovaties op het thema waterstof in Nederland voor de periode 2020 – 2030, TKI Nieuw Gas link

1.3 RESEARCH QUESTION & METHOD

This document aims to provide more insight in the context and required developments for transport and storage of hydrogen in the Netherlands, by answering the following research question and sub questions.

“What developments are required for transport and storage innovations for the large scale production and import/export of hydrogen in the NL?”

1. **End users**: where will we need hydrogen & what are logical first end users?

   Answer: *From a techno-economic and regulation point of view, centralized industrial clusters should pave the way*

2. **Infrastructure**: what technological developments do we need regarding storage and transport?

   Answer: *Technology is available, but large scale hydrogen storage in caverns is the current bottleneck*

3. **Regulation**: what regulatory bottlenecks or drivers need to be tackled/in place?

   Answer: *Regulation regarding sustainable hydrogen certification, standardization and regulation on end user level should be put in place asap*

This document is a reflection of two workshops with stakeholders in the value chain held in February and March 2022. This document is therefore a reflection of the opinions of these stakeholders on the needs of the market, not as a fact-checked or complete roadmap. The workshops were divided in ‘central’ and ‘decentral’ hydrogen markets, which is reflected in the results. The basis for the discussion and the structure lies in the HyDelta WP deliverables of Work Package 3 on the potential distribution of hydrogen in The Netherlands.

CHAPTER 2: CONCLUSIONS

This document is a reflection of two workshops with stakeholders in the value chain held in February and March 2022. This document is therefore a reflection of the opinions of these stakeholders on the needs of the market, not as a fact-checked or complete roadmap.

2.1 INDUSTRIAL CLUSTERS SHOULD PAVE THE WAY

From a techno-economic and regulation point of view

Both centralized and decentralized applications have small scale pilots operational and should continue to research and integrate (green) hydrogen solutions. From a techno-economic and regulation point of view, the industrial clusters should pave the way.

- **Hydrogen is a know commodity in industry**
  - Technical knowhow is available
  - Clustered demand and industrial scale enables economies of scale (centralized industry demand: ~2000 ktpa H_2 divided over 5 locations; compared to dentralized demand of ~1000 ktpa H2 divided over ~3000 locations)
  - Regulation for safety is in place. H_2 is a known commodity in the chemical industry; as industrial gas and raw material
  - ➡ Techno-economic and regulatory feasibility for centralized hydrogen transport and storage is high

- **Hydrogen is a new commodity in decentralized applications**
  - Decentral application are scattered over the Netherlands, which requires many transport movements which is very costly and inefficient
  - The characteristics and requirements of decentral applications (purity, demand patterns, …) will largely determine what type of transport and storage will be required, making the H_2 supply chain more complex
  - 50 hydrogen refuelling stations will be deployed by 2025, but hydrogen in mobility will be supplied largely via (costly) trucks until there is an alternative available (pipeline)
  - Low temperature heating in built environment has better alternatives from an efficiency point of view, therefore H_2 in BE will play a small role on short term
  - Regulation for standardization and safety is being developed, but not yet in place
  - Lessons and experience from large scale hydrogen industrial applications can be used for decentralized applications
  - ➡ Therefore, developing decentral hydrogen applications should continue but faces more techno-economic and regulatory barriers compared to the industry

2.2 TECHNOLOGY IS AVAILABLE

But large scale hydrogen storage in caverns is the current bottleneck

- Hydrogen (-carrier) storage and transport technology is available, bottlenecks are mainly at the (large) scale level.
- Transport via different carriers and transport modalities is technically possible and happens in practice, but is costly and can require new safety regulations.
- There is experience with transport and storage of the hydrogen carriers NH_3, MeOH and LOHC, however, reconversion technology is a bottleneck.
- Gaseous and liquid hydrogen transport already happens in practice. Pipeline transport of compressed gaseous H_2 is a mature but expensive technology (Air Liquide has been operating 200 km pipelines for decades), therefore ongoing studies focus at cost-effectively retrofitting the natural gas grid.
- Storage is a more pressing issue than transport. Especially large scale storage needs development, as e.g. seasonal storage is required for large scale hydrogen application. Worldwide, four pure hydrogen storage facilities in salt caverns are operational, and practical experience with these sites has shown that hydrogen can be safely stored in this way for long periods of time. Effects of more frequent and cyclical injection and withdrawal, and moreover at higher volumetric rates should be researched.
- Direct application of hydrogen on production location is preferable in terms of cost and safety, especially on short term.

The table below summarizes all supply chain elements including the technical feasibility of the studied supply chains in HyDelta 7A

Tehnical feasibility of supply chain elements						
Chain	Transport			Storage		
Fertilizer	Pipeline (H_2)	Rail (NH_3)		Caverns (H_2)	Tanks (NH_3)	Tanks (H_2)
Methanol	Pipeline (H_2)			Caverns (H_2)	Tanks (MeOH)	
Mobility	Pipeline (H_2)	Trucks (LOHC)	Trucks (H_2)	Caverns (H_2)	Tanks (LOHC)	
Built environment	Pipeline (H_2)	Trucks (LOHC)	Trucks (H_2)	Caverns (H_2)	Tanks (LOHC)	Tanks (H_2)
HTH	Pipeline (H_2)	Trucks (LOHC)		Caverns (H_2)	Tanks (LOHC)	

Carrier	Reconversion
Ammonia	NH_3 > H_2
Methanol	MeOH > H_2
LOHC	LOHC > H_2
Liquid H_2	lH_2 > gH_2
Gaseous H_2	

2.3 REGULATION SHOULD BE IN PLACE ASAP

Business cases and large scale investments wait on clarity in regulation

Industry and businesses take a wait-and-see approach due to lack of clarity regarding hydrogen related regulation. Uncertainty about e.g. the future tax treatment of green hydrogen and standardization makes it impossible for companies to determine their business cases. Transport, storage and end use of hydrogen comes with a large set of regulations, and even more specific regulatory requirements per type of end use.

We summarized three main bottlenecks that need to be solved to further accelerate the hydrogen economy:

1 Development of sustainable hydrogen certification

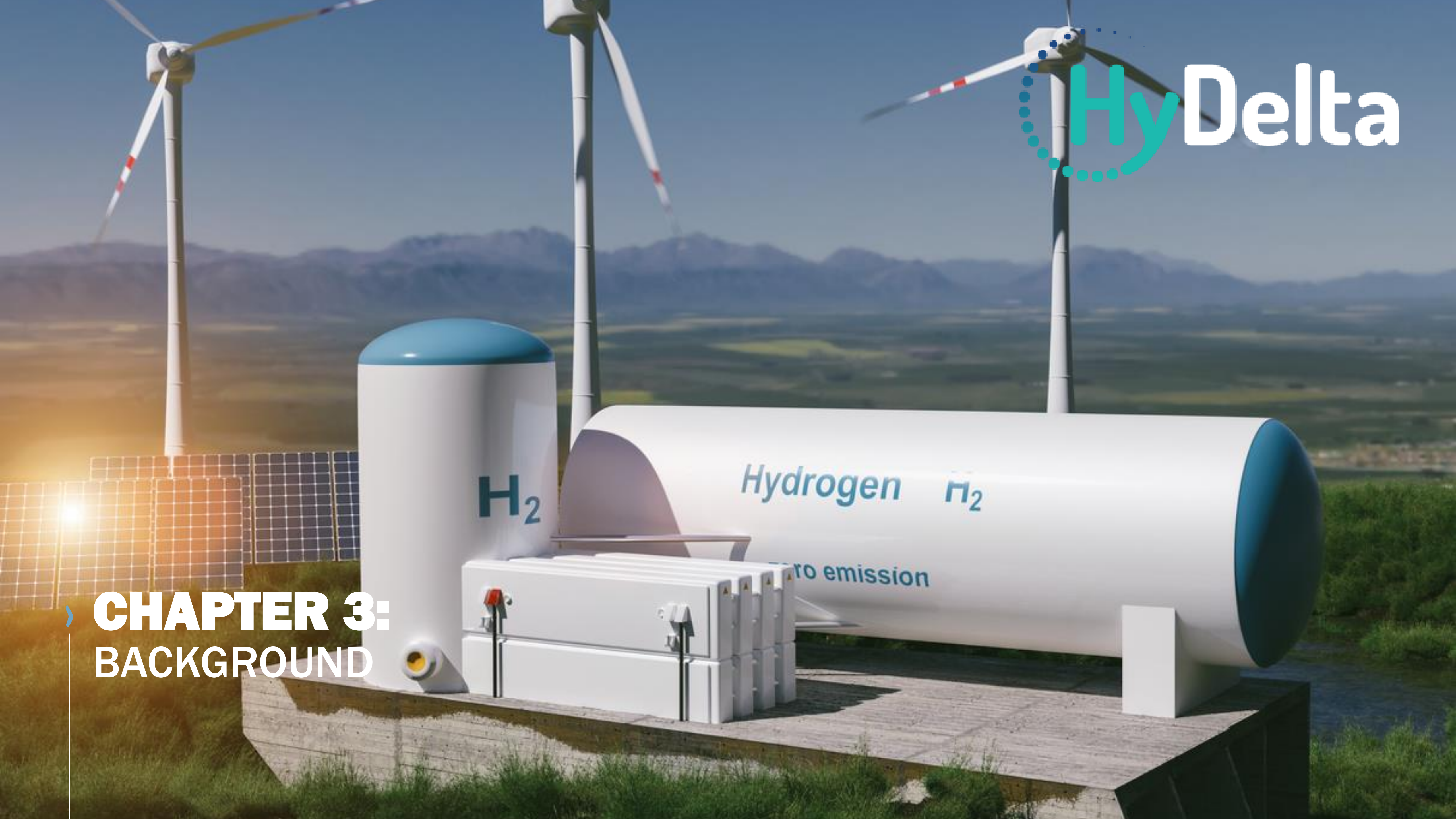
- Certification will provide markets with financial clarity, enabling investors to determine their hydrogen business cases
- For a level playing field, there is a need for an EU-wide Guarantee of Origin system for green and low-carbon hydrogen
- National development of a *Waterstofbeurs*[3] could accelerate and facilitate national hydrogen trade

2 Standardization

- Standardization could accelerate faster roll out of the hydrogen economy, providing clarity on requirements for technology, safety, management etc.
- There is a need for a directive entity to steer and facilitate the standardization and regulatory discussion and manages the outcomes
- A logical order could be first standardization for the transport and distribution equipment, than for gas stations and lastly for end user equipment.

3 Regulation on end user level

- Different types of end users require different regulation. Hydrogen for heating requires new regulation, whereas industrial applications and passenger transport already has quite some regulation in place.
- Security of supply regulation for hydrogen is yet to be developed



CHAPTER 3:
BACKGROUND

3.1 END USERS

Distinguishing between end users: centralized large scale vs. decentral applications

Hydrogen can be used and applied in many applications, therefore the transport and storage requirements can vary largely. Some users demand a large base load, whereas others can have fluctuating peak demand. To simplify and structure this, we looked at the different clusters that could potentially use hydrogen, and distinguish between **central industrial clusters** and **decentral end users.** Below and on the following slides more details are provided.

Central industrial clusters

The Dutch industry is divided in six large industrial clusters; Rotterdam-Moerdijk, Noord-Nederland, Noordzeekanaalgebied Chemelot, Smart Delta Resources and finally the sixth cluster. All these clusters are different and have their own industry, but what they share is large scale industrial processes, experience with handling (complex) chemicals and commodities and technical expertise. For these central industrial clusters, we focus on the following potential hydrogen applications:

- HTH High temperature heat (>250°C)
- NH_3 Fertilizer industry
- MeOH Methanol

Decentral end users

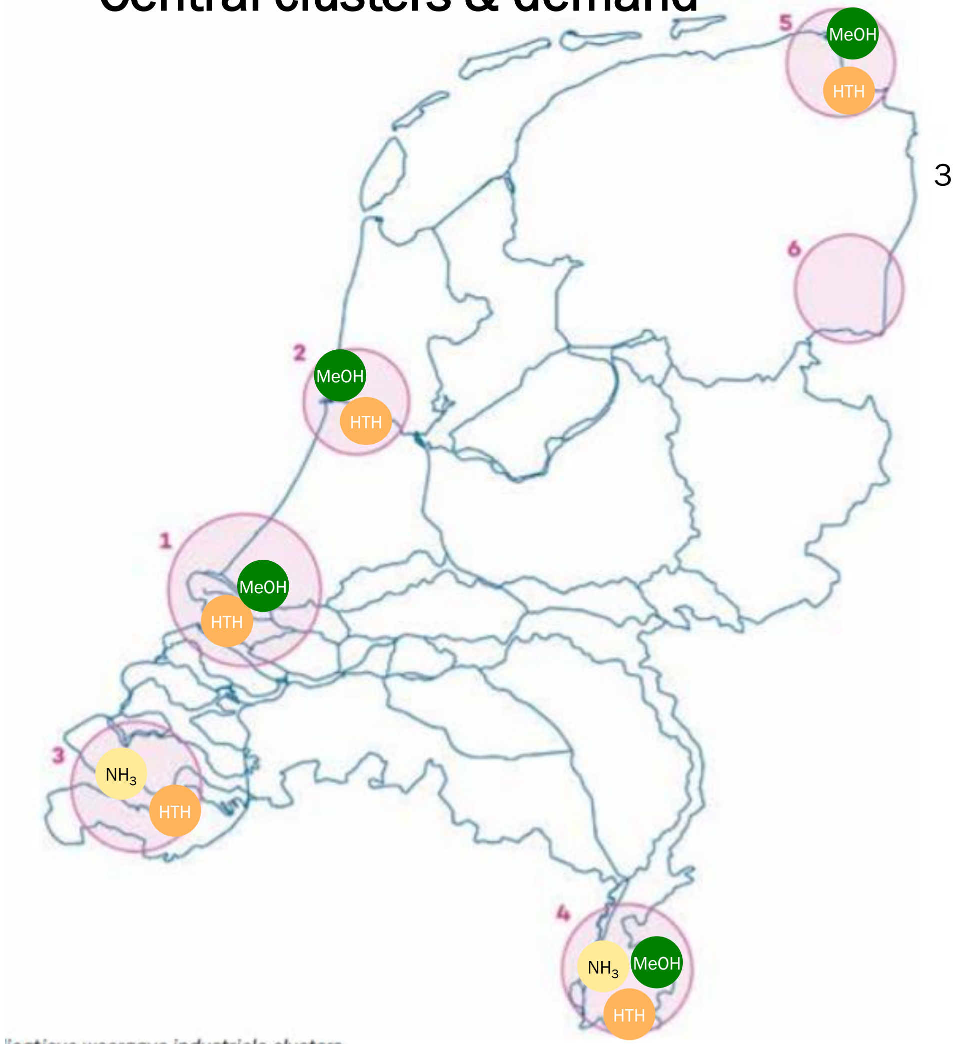
As opposed to the central industrial clusters, hydrogen also knows potential decentralized end users. Again, many of these applications can have different requirements in terms of volumes, quality and profiles. However, one aspect that they do share is operation at relatively small scale, the novelty of their application and demand largely scattered over the country. For the decentral clusters, we focus on the following potential hydrogen applications:

- DHTH Decentral high temperature heat
- BE Built environment
- M Mobility

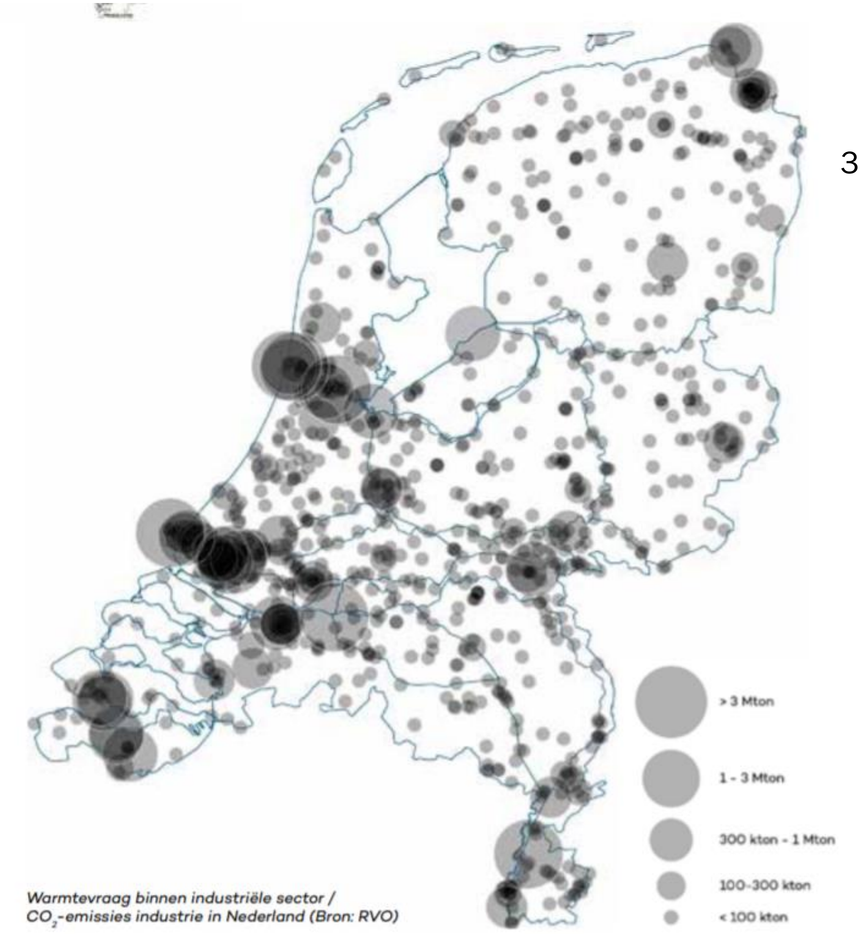
3.1 END USERS: CENTRAL CLUSTERS

Central clusters & demand

	Legend	Demand	H_2 demand
HTH	HTH market (see heatplot)[1,4]	100 PJ*	883 ktpa H_2
NH_3	Fertilizer market[2]	1300 ktpa NH_3	126 ktpa H_2
MeOH	Methanol market[2]	100 PJ MeOH/y	900 ktpa H_2



icatieve weergave industriele clusters



[1] NEC 7A
[2] BlueTerra, Toekomstvisie WKK, Link
[3] RVO – Ruimtelijke verkenning Energie en Klimaat
[4] Coalitie waterstof vier pijlers, link

*Total heat demand in industry clusters~ 100PJ.
Total industrial heat demand in 2030 is estimated at ~400PJ

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3.1 END USERS: CENTRAL CLUSTERS

Feedstock & heating demand per cluster

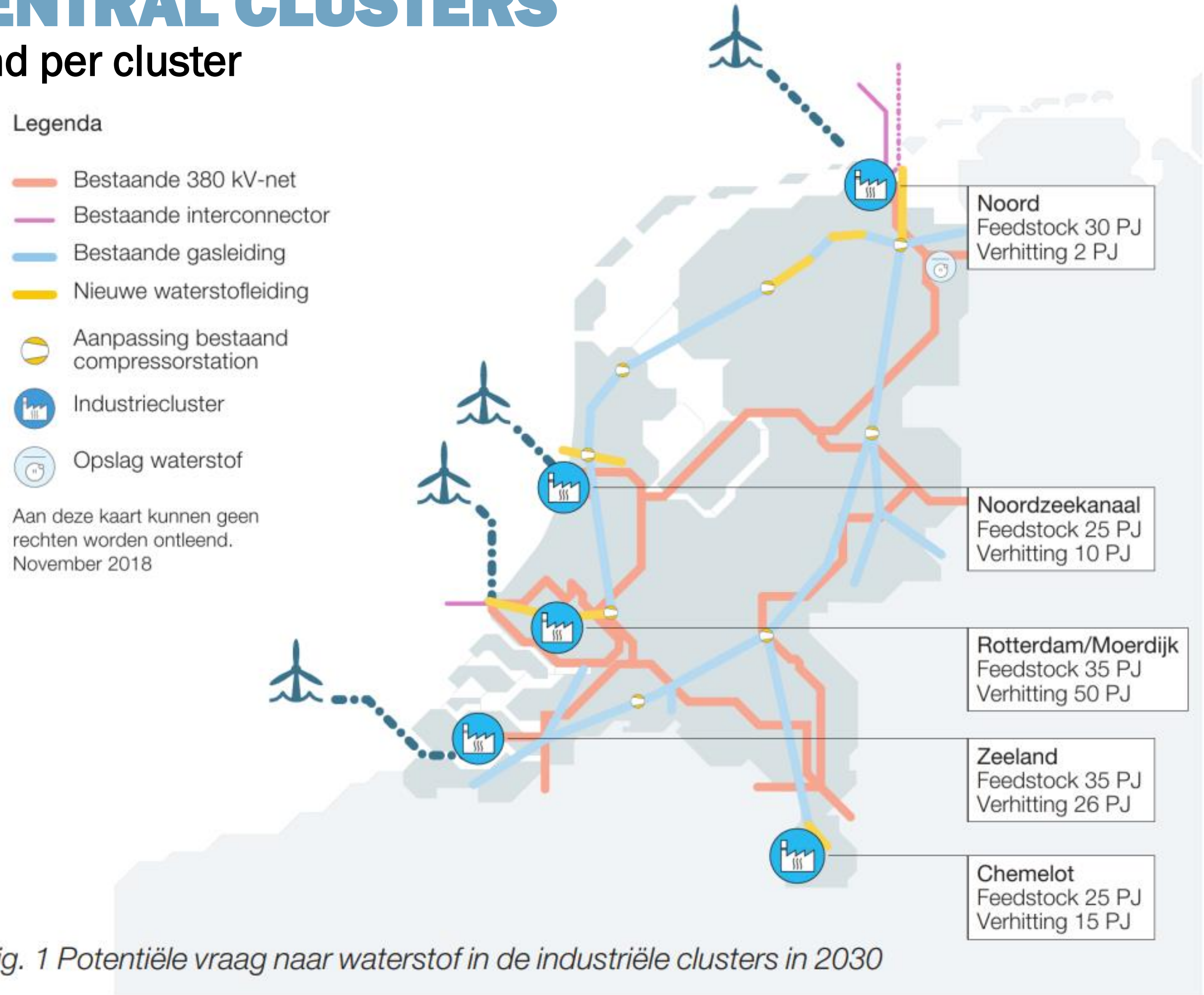


fig. 1 Potentiële vraag naar waterstof in de industriële clusters in 2030

Source: Coalitie waterstof vier pijlers, [link]

3.1 END USERS: DECENTRAL

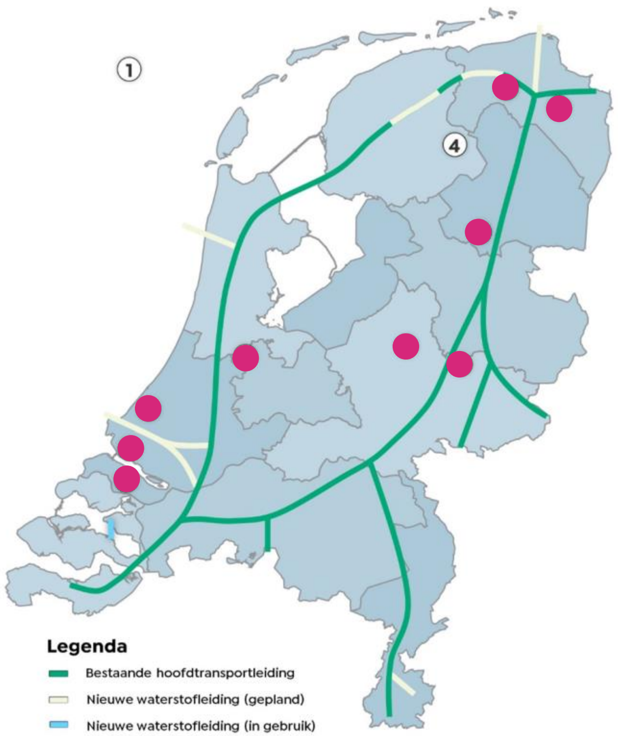
Decentral applications & demand

	Legend	Total demand	Scale
M	Mobility[1]	146 ktpa H_2	0.146 ktpa H_2 per HRS for 1000 HRS
BE	Built environment[1]	642 ktpa H_2	0.286 ktpa H_2 per NBH for 2244 NBHs
DHTH	Decentral HTH[1]	357 ktpa H_2	7 ktpa H_2 per plant for 51 plants

Mobility

2

Built Env.



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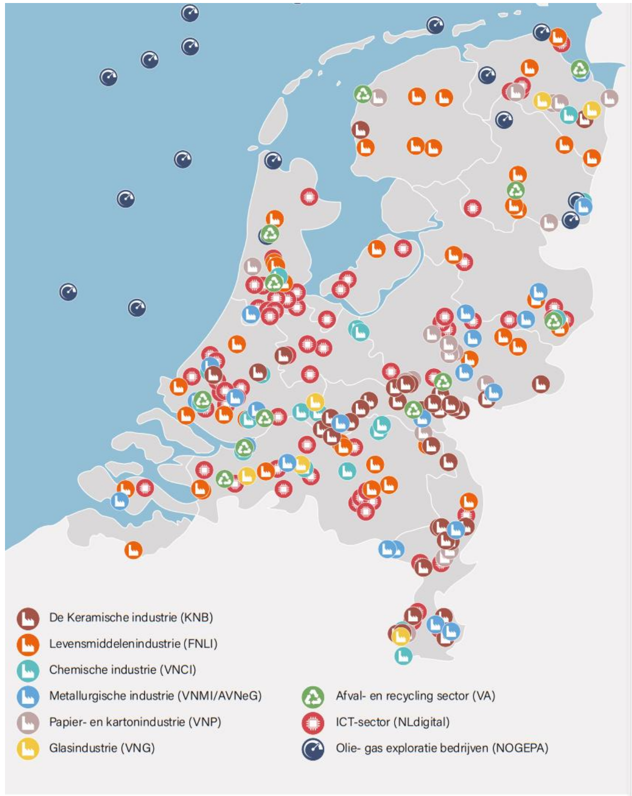
Decentral heat



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[1] NEC 7A
[2] Waterstofnet - https://www.waterstofnet.eu/nl/nieuws/overzicht-waterstoftankstations-benelux
[3] NBN - https://www.netbeheernederland.nl/dossiers/waterstof-56
[4] FNLI – Klimaattransitie door de Nederlandse industrie – Het zesde cluster

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3.2 TECHNOLOGY & SUPPLY CHAINS

Drawing conclusions for a large set of possible supply hydrogen chains

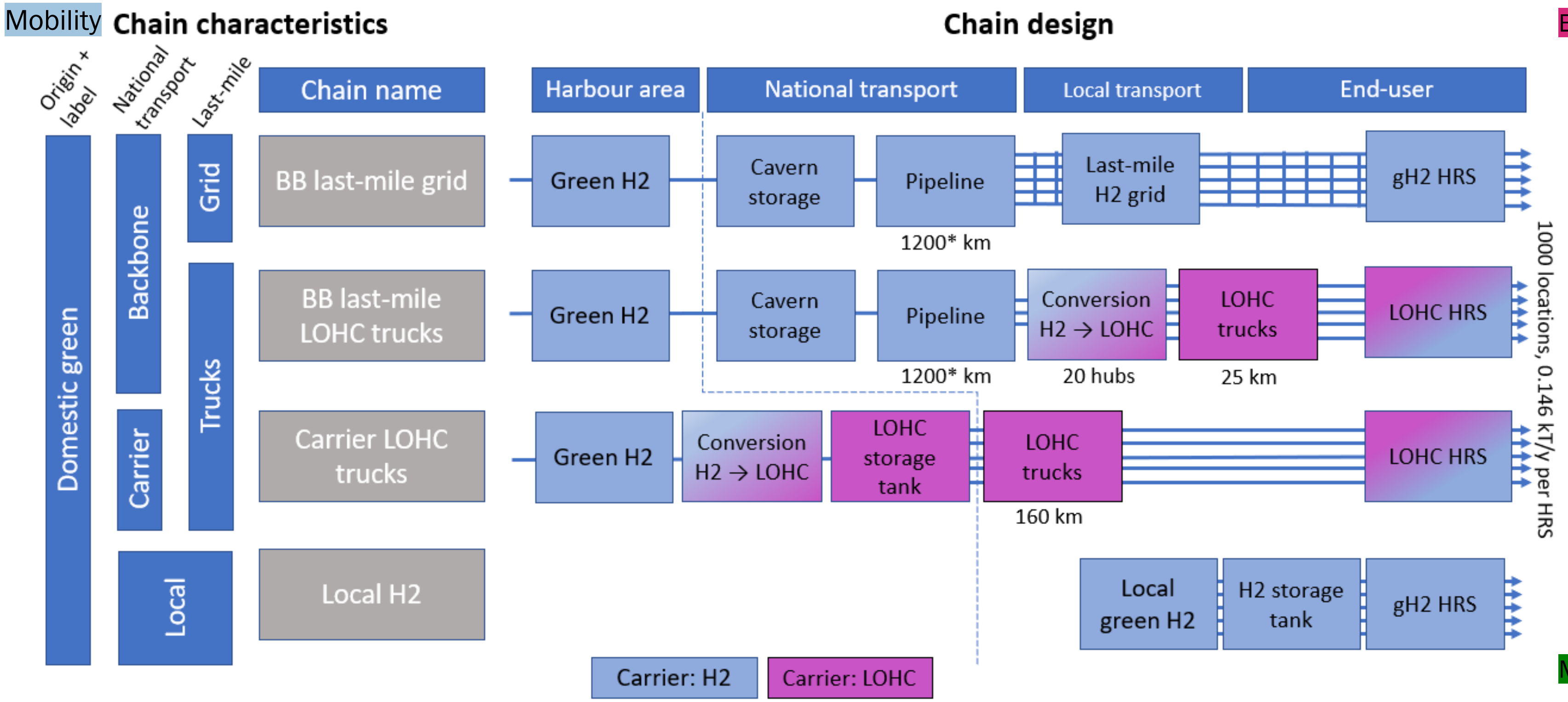
Previous HyDelta deliverables (see HyDelta D7 A.2) have looked into the distribution and storage supply chain once the hydrogen is supplied in Rotterdam. This has resulted in a large set of possible supply chains per type of end user.

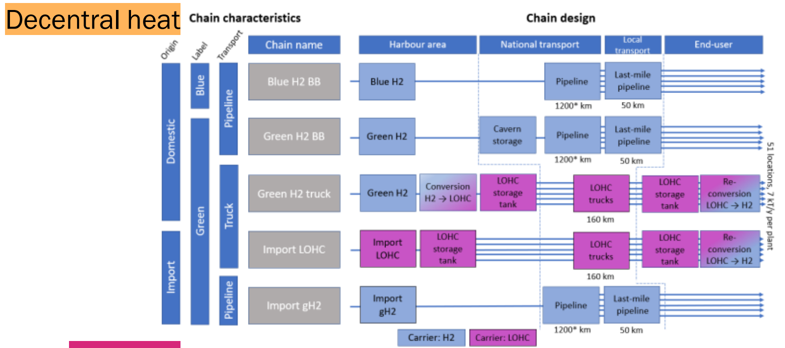
One of the goals for this roadmap has been to assess the technical readiness or maturity of these supply chains. In order to prevent an incomprehensible overview of the maturity of all these individual supply chain options, we have looked at all the technical elements relevant for transport and storage. Since we look at different hydrogen carriers, we have also included the reconversion element.

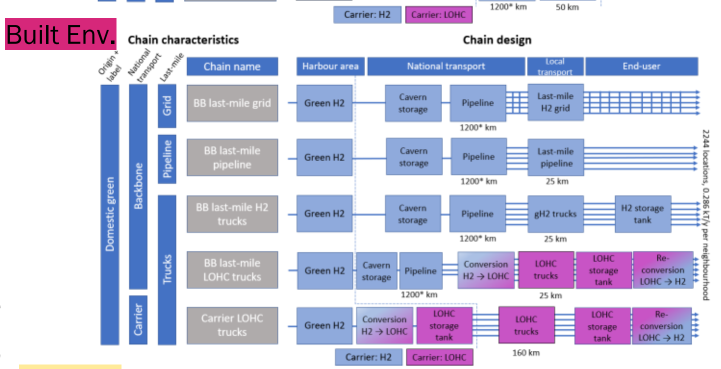
On the next slides, you will find a quick look into all the supply chains (3.2A), the complete overview of all transport and storage elements combined with an assessment of their maturity (3.2B) and lastly a summary of the need of innovation and research (3.2C).

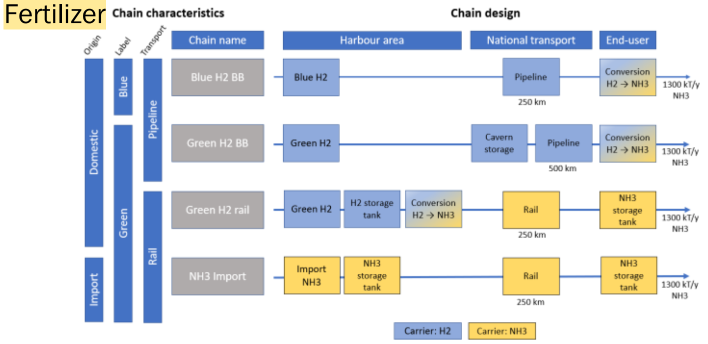
3.2 A OVERVIEW OF ALL SUPPLY CHAINS

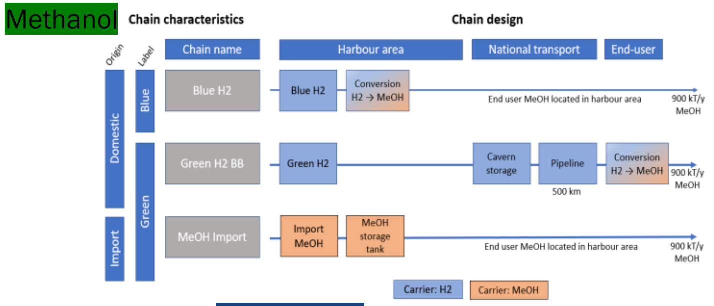
Overview of chain design characteristics











HyDelta

3.2 B TECHNICAL MATURITY OF INFRASTRUCTURE

Chain options from 7A NEC work and indications

Tehnical feasibility of supply chain elements						
Chain	Transport			Storage		
Fertilizer	Pipeline (H_2)	Rail (NH_3)		Caverns (H_2)	Tanks (NH_3)	Tanks (H_2)
Methanol	Pipeline (H_2)			Caverns (H_2)	Tanks (MeOH)	
Mobility	Pipeline (H_2)	Trucks (LOHC)	Trucks (H_2)	Caverns (H_2)	Tanks (LOHC)	
Built environment	Pipeline (H_2)	Trucks (LOHC)	Trucks (H_2)	Caverns (H_2)	Tanks (LOHC)	Tanks (H_2)
HTH	Pipeline (H_2)	Trucks (LOHC)		Caverns (H_2)	Tanks (LOHC)	

Carrier	Reconversion
Ammonia	NH_3 > H_2
Methanol	MeOH > H_2
LOHC	LOHC > H_2
Liquid H_2	lH_2 > gH_2
Gaseous H_2	

Chain element	Notes	Further reading
Pipeline H_2	Technically possible and already operational. Risk: Large scale requires hydrogen backbone. Research needed on tech & safety aspects.	[1], [3]
Rail NH_3	Possible and NH_3 transport happens at large scale on a global level. Risk: transport of additional large quantities NH_3 will require new safety & risk assessments. Due to these safety concerns (toxicity, flammability, explosivity) it is questionable whether authorities would permit the transportation and use of ammonia in populated areas.	[3]
Trucks LOHC	Benzyltoluene is easy and safe to store, transport and handle. It has good viscosity characteristics under ambient pressure and temperatures (even in cold conditions), much like diesel. This similarity enables the use of existing infrastructure, such as trucks, trailers and vessels, as well as storage containers.	[3]
Trucks H_2 (g/l)	Possible, operational at small scale. Increase in quantities road transport of stored H_2 will require new risk assessments. Compressed gaseous H2 trucks and liquid H2 trucks are operational. Liquid H2 truck transport from Rotterdam to London happens for supplying Londen busses.	[3], [4]. [5]
Caverns H_2	Worldwide, four storage facilities for pure hydrogen in salt caverns are already operational, and practical experience with these sites has shown that hydrogen can be safely stored in this way for long periods of time. Risk: many challenges remain to be addressed though, in particular in relation to the integrity and durability of wellbore materials and interfaces, because injection and withdrawal are expected to occur much more frequently and cyclically, and at higher volumetric rates than is currently the case.	[2]
Tanks NH_3	NH_3 is a global commodity, therefore standards already exist. Mature infrastructure for storage and transport is in place, due to the widespread use of ammonia as a chemical feedstock.	[3]
Tanks MeoH	Due to its key role for material synthesis in the chemical industry, its production, transport and storage, including safety aspects, are well-established, efficient and safe.	[6]
Tanks LOHC	See *Trucks LOHC*	[3]
Tanks H_2	Liquified H2 storage is mature	[3]
Reconversion NH_3	The ammonia cracking process (reconversion) is at a very early stage of technological development. It has high energy needs and requires additional purification steps to make the hydrogen usable, making up more than one third of its overall cost.	[3]
Reconversion MeOH	Methanol is easily turned into hydrogen through a catalytic process, using a fuel reformer.	[7]
Reconversion LOHC	The dehydrogenation of LOHC requires very high temperatures, significantly pushing up energy costs.	[3]
Reconversion lH_2	Liquefaction is a relatively well-established technology at small scale, does not require complex reconversion and provides high purity hydrogen to the end user. It is already used in certain special applications today, such as in the aerospace industry, and in some refueling stations.	[3]

- [1] Waterstof voor de Energietransitie - Een programmatische aanpak voor innovaties op het thema waterstof in Nederland voor de periode 2020 – 2030, TKI Nieuw Gas link
- [2] Large-Scale Energy Storage in Salt Caverns and Depleted Fields (LSES) – Project Findings, TNO, 2020
- [3] Roland Berger, 2021, Hydrogen transportation / The key to unlocking the clean hydrogen economy
- [4] Hydrogen Road Transport Analysis in the Energy System: A Case Study for Germany through 2050, Reub et al, 2021
- [5] Transport for London: hydrogen bus project Bringing hydrogen to London's streets, Air Products, 2017 link
- [6] Renewable Methanol Report, The Methanol Institute, 2018, link
- [7] Methanol and Hydrogen, Danish Technological Institute, 2009

3.2 C NEED FOR RESEARCH AND INNOVATION

Transport[1]

Research into using NG infrastructure for blending H_2:

- Which pipelines and receiving stations are suitable for use in a hydrogen transport network, what adjustments are required (technical, organizational, legal), and what would costs be of large-scale conversion. The *Meerjarige Programmatische Aanpak voor Waterstof*[1] made an overview of the suitability of the natural gas grid for H_2 – NG blends
- Embrittlement of materials (pipes)?
- How long will the natural gas odorization stay in the pipes?
- Long term effects for equipment in Dutch households?
- Development of electrochemical hydrogen purification should be further developed/scaled up with cost reduction and less sensitivity to contamination by choosing other membranes.

Research into using NG infrastructure for 100% H_2:

- Are connecting pipe pieces still suitable at higher volume flows? Will noise be a problem?
- How are ignition risks of H_2 leakages compared to natural gas?
- Demonstrations should provide practical experience

Storage[1,2]

Research into using salt caverns for large scale H_2 storage:

- Inventory of suitable salt caverns in the North and East of the Netherlands, including infrastructure, such as salt industry, water, natural gas pipelines and high-voltage grid
- Making a salt cavern physically suitable for H_2 storage (follow up on Zuidwending pilot); four new salt caverns will provide space for stocks of green hydrogen. The first storage can be filled in 2026. Construction should start in 2023 or 2024.

Research into using depleted gas fields for large scale H_2 storage:

- To what extent is large-scale storage of H_2 in gas fields necessary and desirable? Can chemical reactions occur between hydrogen and the reservoir? How much hydrogen loss would occur? How is the microbial activity per gas field in the Netherlands? What is the sealing effectiveness and corrosion resistance to hydrogen of materials used in the gas fields? How much pillow gas would be needed? Recent demonstration projects in Argentina and Austria with injection of up to 10% of hydrogen in a mix with natural gas into a depleted gas field have shown that hydrogen can be safely stored without adverse effects to installations and the environment. However, not all hydrogen was recoverable due to diffusion, dissolution (into formation water), and conversion to methane.

[1] Waterstof voor de Energietransitie - Een programmatische aanpak voor innovaties op het thema waterstof in Nederland voor de periode 2020 – 2030, TKI Nieuw Gas link
[2] Update aardgasbuffer Zuidwending, Gasunie, 2021 link

3.3 REGULATION

Regulatory bottlenecks hinder the implementation of large scale hydrogen

This roadmap looks at the required developments for large scale transport and storage of hydrogen in the Netherlands. Apart from the discussed technical developments, regulation plays a crucial role. Currently, industry and businesses take a wait-and-see approach due to lack of clarity regarding hydrogen related regulation. Uncertainty about e.g. the future tax treatment of green hydrogen and standardization makes it impossible for companies to determine their business cases. And moreover, transport, storage and end use of hydrogen comes with a large set of regulations, and even more specific regulatory requirements per type of end use.

On the next slide the main bottlenecks regarding regulation are summarized.

3.3 NEED FOR REGULATORY DEVELOPMENT

Regulation[1,2]

Sustainable hydrogen certification:

- Develop and pilot an EU-wide Guarantee of Origin system for green and low-carbon hydrogen
- RED II should be updated to improve the preconditions for green hydrogen. As for now, no energy tax or excise duty is levied on hydrogen, whereas this does happen with electricity and mineral products used for hydrogen production. The market demands clarity about future tax treatment in order to determine business cases. A point of attention is avoiding double taxes on both raw material and end product.
- Development of a *Waterstofbeurs*[3] to accelerate and facilitate national hydrogen trade

Standardization

- Accelerate standardization practices to facilitate faster roll out of the hydrogen economy, e.g. with regard to the development of new technology, innovative systems, management and safety/security, as well as accelerating market and public acceptance
- Standardization should happen first for the transport and distribution equipment, than for gas stations and lastly for end user equipment.
- There is a need for a directive entity that steers the standardization and regulatory discussion and manages the outcomes on behalf of the whole hydrogen economy. This could be a role for NWP[4]. This entity could also facilitate possible synergies between the different hydrogen markets

Protocol for the conversion of natural gas to hydrogen

- Clarity on market regulation and the roll of national public network operators
- Regulatory requirements for supplier of last resort (SoLR), storage/delivery setup and verification

Regulation end user level

- For the different types of end users, different regulation is required. Regulation for industrial applications is already in place, as well as for passenger mobility. For application of hydrogen in other transport modalities, built environment and industrial heating new regulation at end user level should be developed and put in place.
- A recent report from the Hoogeveen pilot[5] presents an elaborate legal study highlighting all different laws and regulations that need to be in place/adapted.

Insurance

- In new applications hydrogen processers or end user should be able to insure themselves for accidents.

[1] Waterstof voor de Energietransitie - Een programmatische aanpak voor innovaties op het thema waterstof in Nederland voor de periode 2020 – 2030, TKI Nieuw Gas link
[2] HyDelta workshops #1 & #2
[3] Een Waterstofbeurs voor het Klimaat, 2021 link
[4]Nationaal Waterstof Programma link
[5] Waterstofwijk: Plan voor waterstof in Hoogeveen, 2020, link