Long-term Cost Optimization of a Low-carbon Hydrogen Network for Industrial Decarbonization

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Agenda

- Introduction
- Research Gap and Objectives
- Methodology
- Case Study
- Results
- Conclusion

Introduction

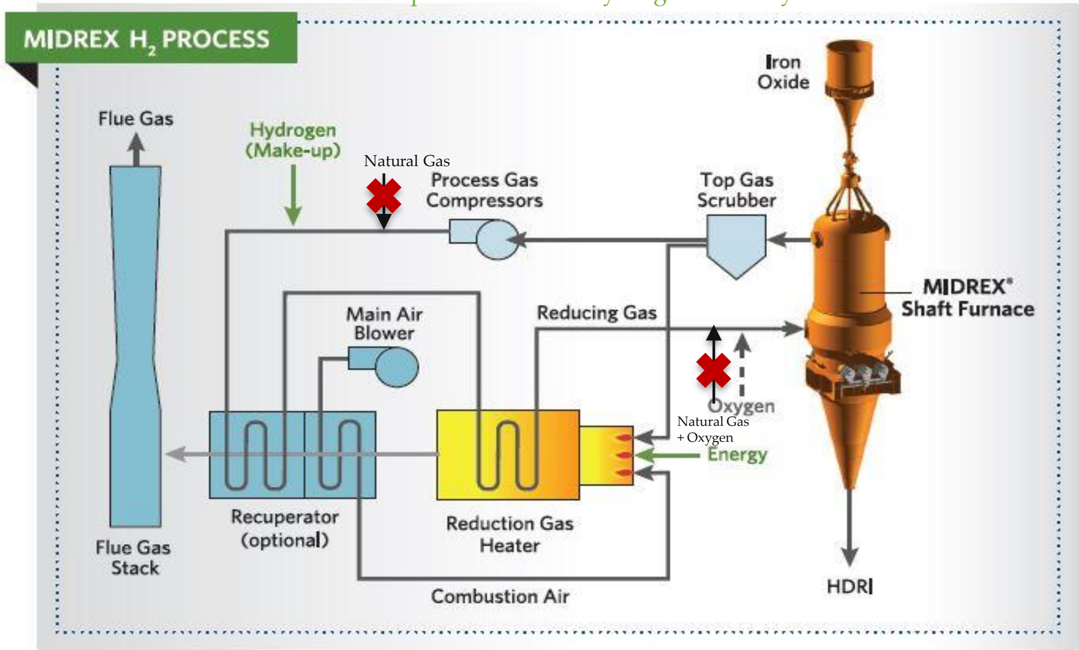
Role of hydrogen in transition pathways

- ❑ **Electrification** → the most efficient way : **residential, commercial, transport, and some industries**

- ❑ Mixed decarbonization routes for a full cross-sector green transition → **clean molecules**

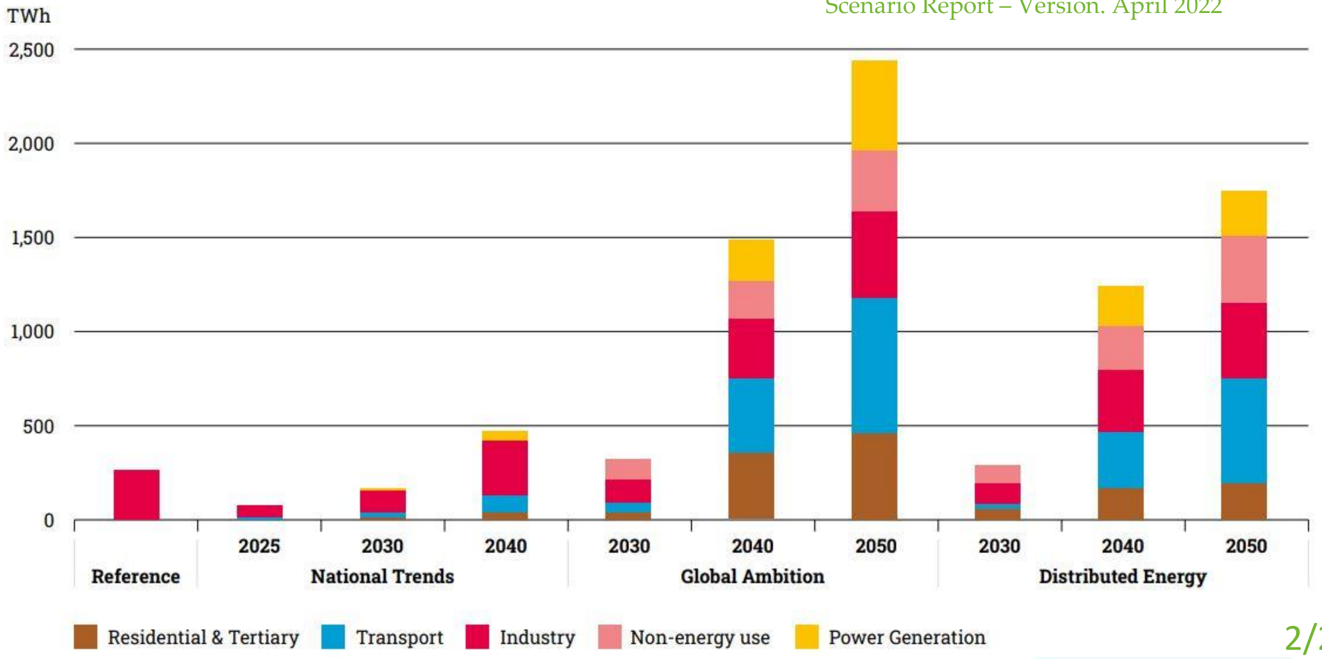
  - **Industry:** Fossil fuel-based feedstocks in the hard–to–abate industries
  - **Transport:** long-distance transport routes (heavy-duty trucks, shipping, aviation)
  - **Power sector:** long-term/short flexibility in the power system with a high share of renewables

Source: MIDREX H2, Ultimate low CO2 ironmaking and its place in the new hydrogen economy



Hydrogen demand per sector for EU 27

Source: ENTSO-E // ENTSOG TYNDP 2022 Scenario Report – Version. April 2022



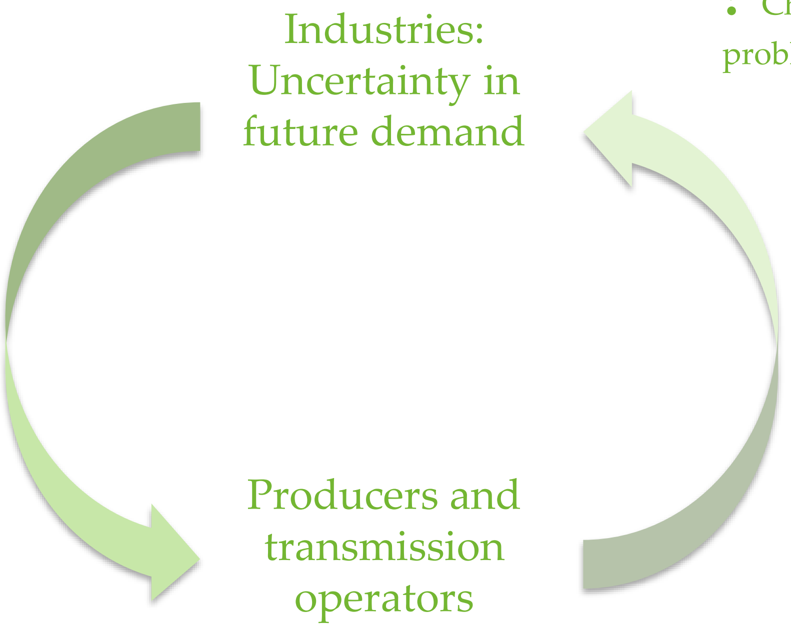
Introduction

Uncertainty in the future hydrogen market

Regulatory Framework and Policy Mechanism: lack of value recognition

! Chicken and egg problem

Without any market interest, investments in **wide-scale hydrogen production** and transmission remain too **risky**



Without certain plans for hydrogen production and infrastructure, investments in the **transition to renewable hydrogen consumption** remain too **risky**

Detailed national scenario analyses on the **future hydrogen supply chain** from the **required production and transport capacities to the final demand estimations**

Research Gap and Objectives

Research gaps:

- ❑ Most of the studies → **the role of hydrogen in the energy sector (transport, heat, electricity)**
- ❑ Rare attempts at **industrial decarbonization** following a detailed high **spatial resolution network optimization** model
- ❑ Different **supply scenarios** for the **production and imports of low-carbon hydrogen (derivatives)** are still missing

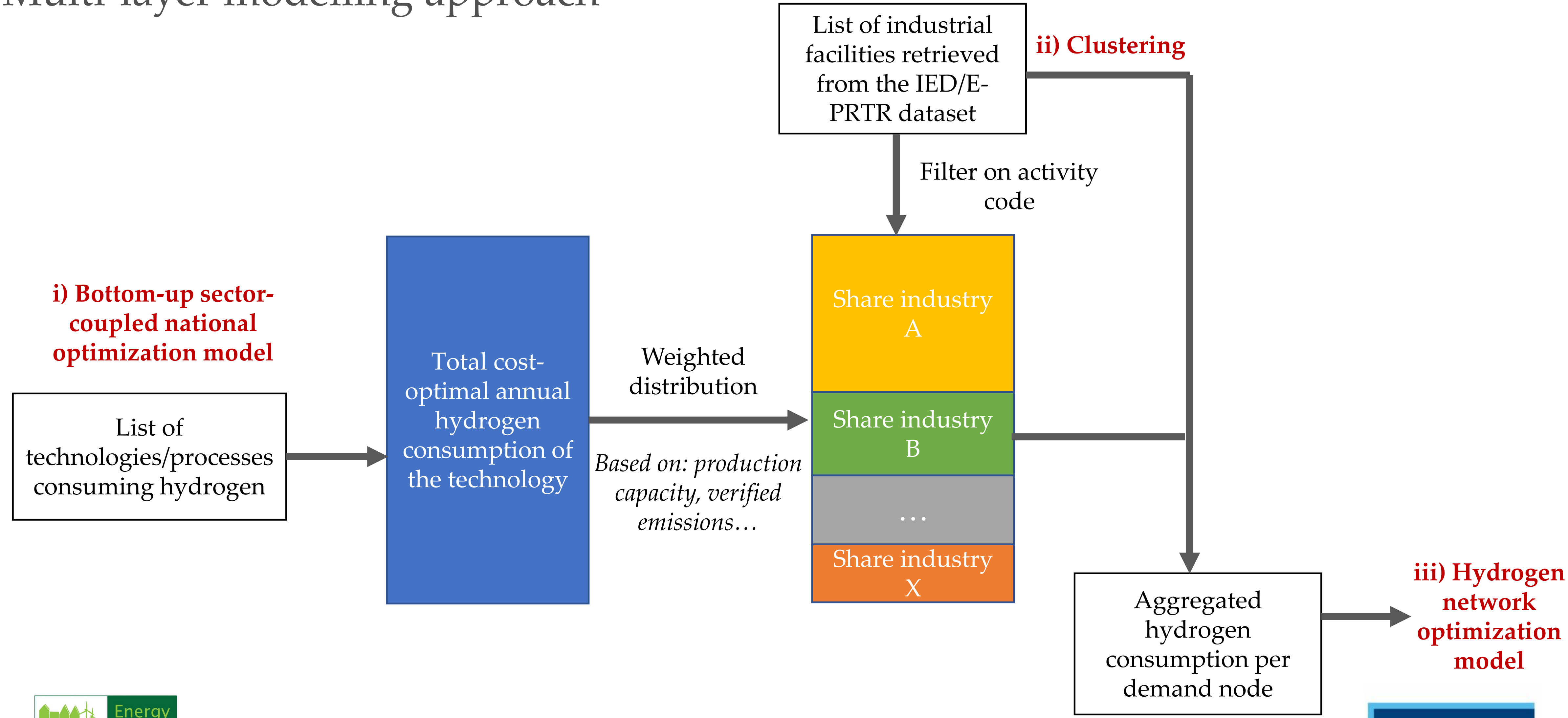
Objective:

Developing a multi-layer modeling methodology for:

i. Future **hydrogen demand estimation** of **industrial facilities**
ii. Geospatial analysis for **grouping industries** in different **demand nodes**
iii. Cost-optimal sizing of the required **future hydrogen network** following the national **gas TSOs' topology**

Methodology

Multi-layer modelling approach

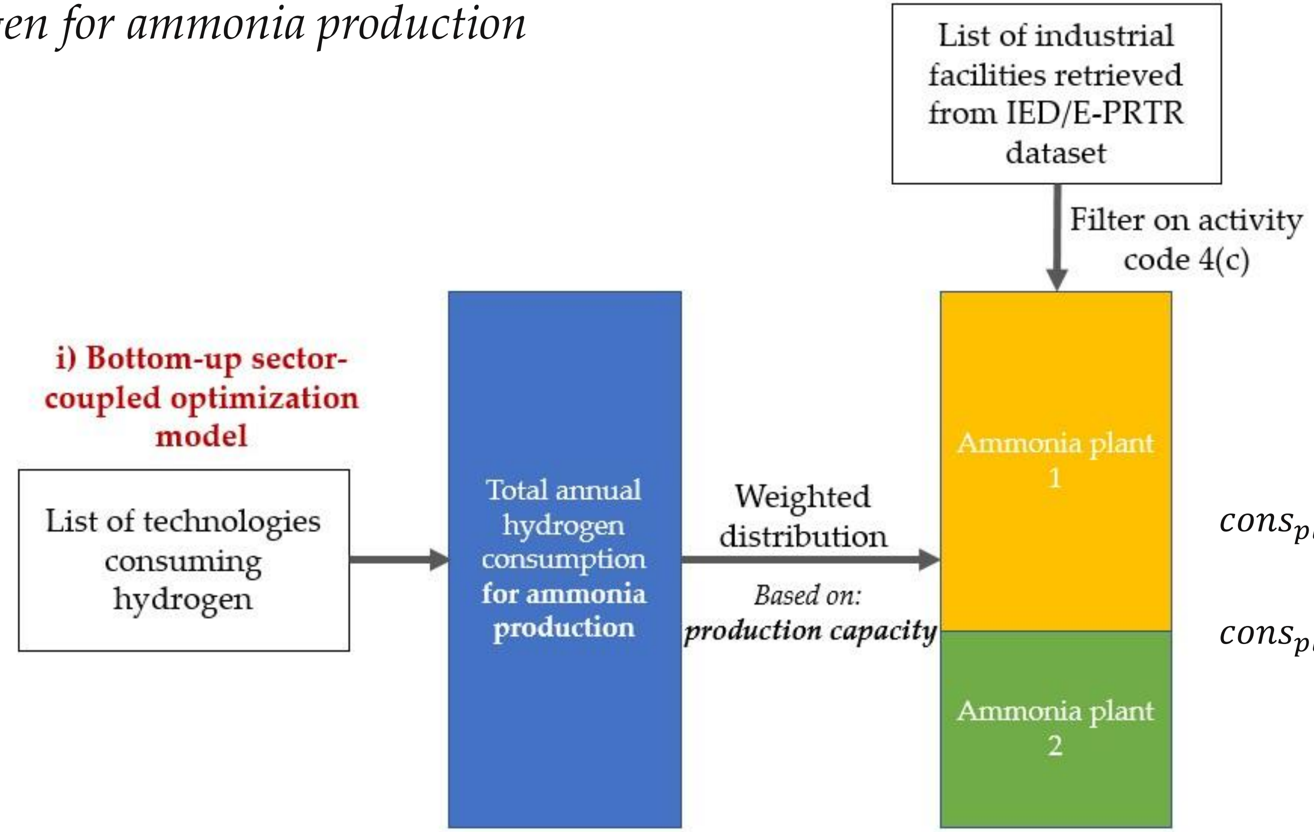


Methodology

Layer 1: demand estimation per industrial facility

Example: hydrogen for ammonia production

- *Steel*
- *Glass*
- ***<u>Ammonia (Haber Bosh process)</u>***
- *Cement & lime*
- …



All facilities producing nitrogen-based fertilizers

~ activity code 4(c) :

Chemical installations for the production on an industrial scale of basic organic chemicals or fertilizers

$$cons_{plant1} = \left(\frac{x}{x+y}\right) \times cons_{haberbosh}$$

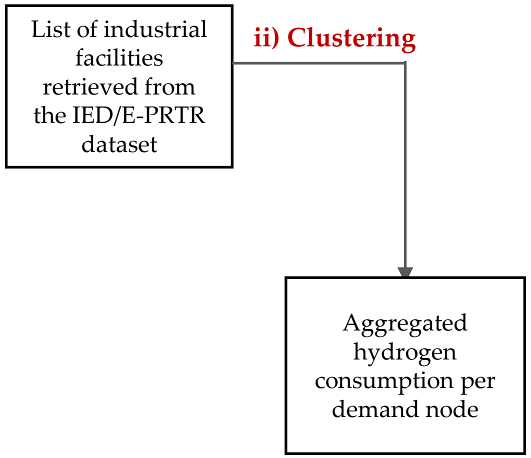
$$cons_{plant2} = \left(\frac{y}{x+y}\right) \times cons_{haberbosh}$$

Ammonia plant 1 – x kton/y

Ammonia plant 2 – y kton/y

Methodology

Layer 2: clustering algorithm



List of facilities with details on annual hydrogen consumption, based on production capacity → How to group these facilities into larger demand zones for the hydrogen grid?

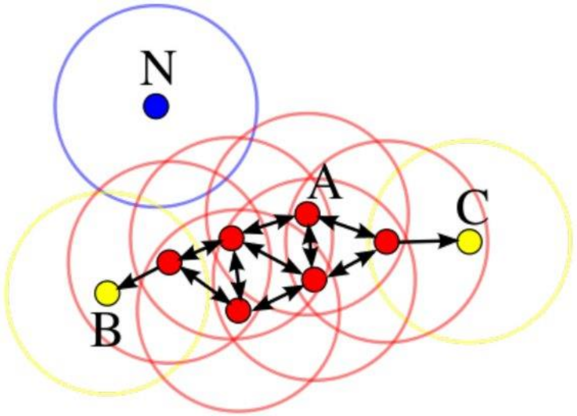
Solution

***D**ensity **B**ased **S**patial **C**lustering of **A**pplications with **N**oise*

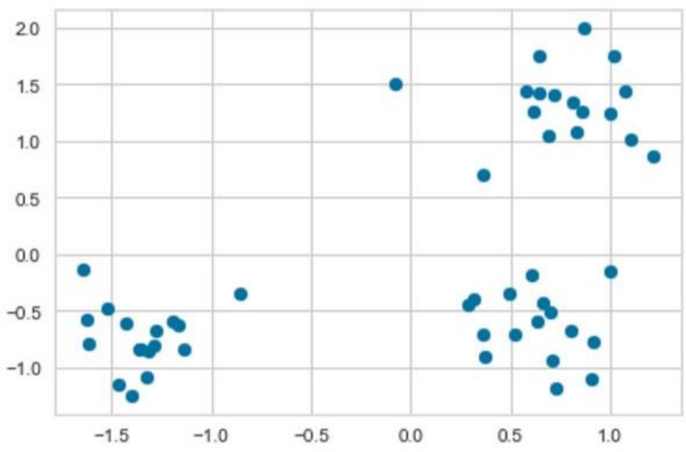
- ✓ *Identify areas of high density*
- ✓ *Distinguish clustered from noise points*
- ✓ *2 degrees of freedom, epsilon (an upper limit to the distance between two neighboring nodes), and #nodes (min number of nodes)*

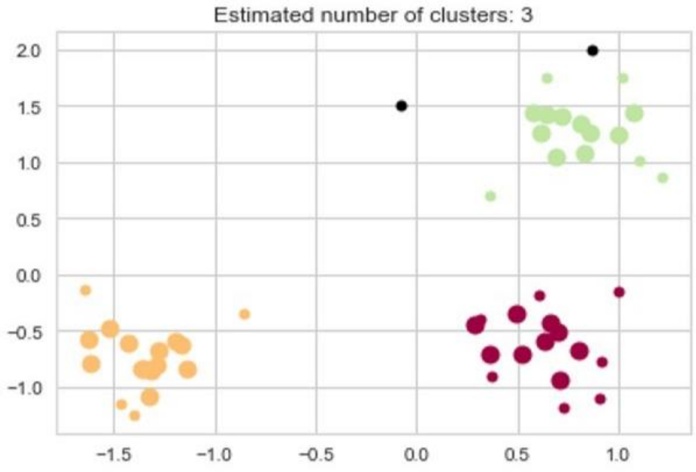
→ List of demand clusters

- Center of the cluster used as a grid node
- Total hydrogen consumption per cluster instead of per facility



Source: DBSCAN - Wikipedia





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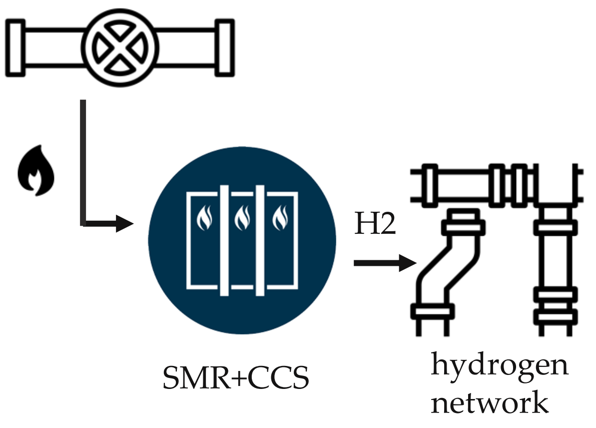
Methodology

Layer 3: hydrogen network optimization model

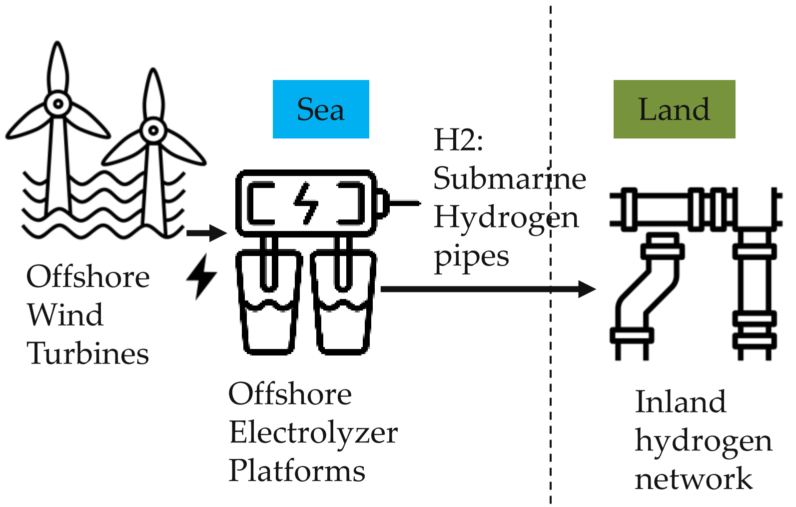
Aggregated hydrogen consumption per demand node → **iii) Hydrogen network optimization model**

Different low-carbon/green hydrogen production scenarios

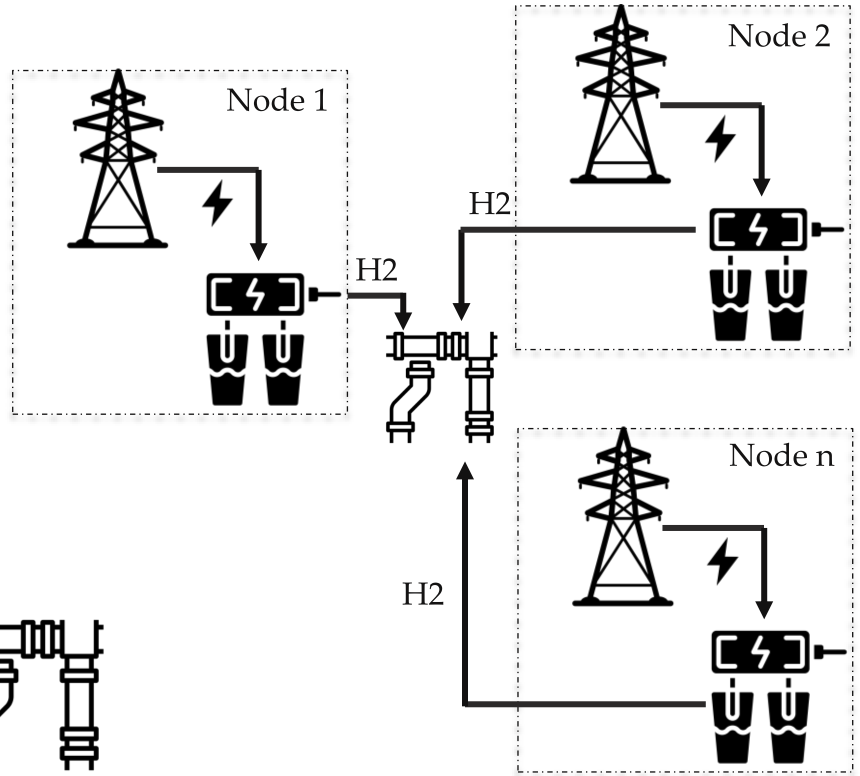
I. Blue hydrogen scenario



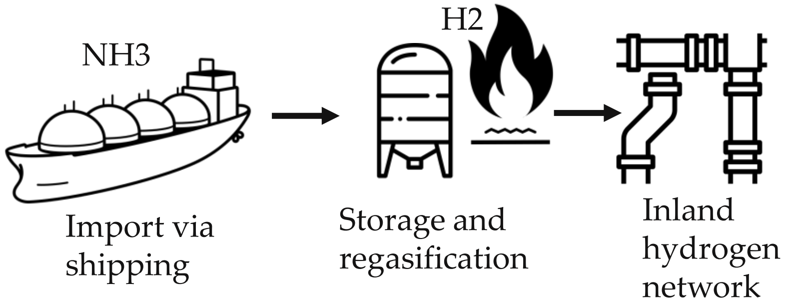
II. Offshore scenario



II. Decentral inland scenario



Possibility of **importing hydrogen derivatives** in **all the scenarios** from overseas and **reconverting** to pure gaseous hydrogen



Methodology

Layer 3: hydrogen network optimization model

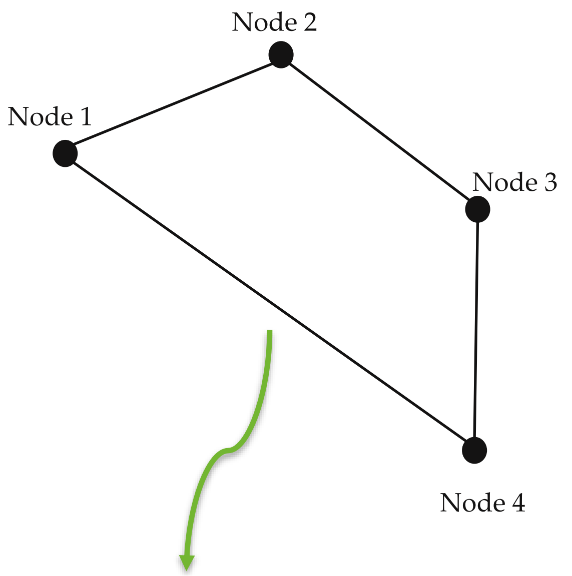
- High spatial resolution following a nodal approach

- Demand nodes → resulted from the clustering algorithm

- Supply nodes → depending on the given scenarios
  - Offshore zones
  - Coastal regions: interconnector between offshore zones and inland zones
  - Terminals: import zones for hydrogen derivatives
  - Interconnection with neighboring regions/countries
  - Industrial zones with steam methane reforming capacities

- High temporal hourly resolution

- Multi-year investment periods



A connection among each pair of regions can be chosen and installed from the given candidate pipe (for e.g., DN500, DN900, DN1200):

CP1: C_1 GW capacity
CP2: C_2 GW capacity
…
CP3: C_n GW capacity

A binary variable is defined for each candidate pipe

Methodology

Layer 3: hydrogen network optimization model

What do we minimize/maximize in this model?

Objective function: $Cost^{tot} = \boxed{Cost^{prod}} + Cost^{imp} + Cost^{trans}$

- Production cost components depend on the scenario

I. Blue hydrogen scenario

$$Cost^{prod} = \sum_{y \in Y} \Big((1+D_y)^{-y} . \underbrace{\textstyle\sum_{s \in S} C_{s,y} \,.\, cap^{new}_{s,y} + F_{s,y} \,.\, cap^{tot}_{s,y}}_{\text{CAPEX and OPEX SMR+CCS}} + \underbrace{\textstyle\sum_{t \in T} \sum_{e \in E} P^{da}_{gas,t,y} \,.\, cons^{gas}_{s,t,y}}_{\text{Variable cost for gas consumption}}\Big)$$

II. Offshore scenario

$$Cost^{prod} = \sum_{y \in Y} \Big((1+D_y)^{-y} . \big(\underbrace{C_{w,y} \,.\, cap^{new}_{w,y} + F_{w,y} \,.\, cap^{tot}_{w,y}}_{\text{Costs of offshore wind turbine}} + \underbrace{C_{ofe,y} \,.\, cap^{new}_{ofe,y} + F_{ofe,y} \,.\, cap^{tot}_{ofe,y} + V_{ofe,y} \,.\, p^{H2}_{ofe}}_{\text{Costs of offshore Electrolyzer}}\big)\Big)$$

III. Decentral inland scenario

$$Cost^{prod} = \sum_{y \in Y} \Big((1+D_y)^{-y} . \underbrace{\textstyle\sum_{e \in IE} C_{ie,y} \,.\, cap^{new}_{ie,y} + F_{ie,y} \,.\, cap^{tot}_{ie,y}}_{\text{CAPEX and OPEX of inland Electrolyzer}} + \underbrace{\textstyle\sum_{t \in T} \sum_{e \in IE} P^{da}_{elec,t,y} \,.\, cons^{elec}_{ie,t,y}}_{\text{Variable cost of electricity purchase in the day-ahead electricity market}}\Big)$$

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Methodology

Layer 3: hydrogen network optimization model

What do we minimize/maximize in this model?

Objective function: $Cost^{tot} = Cost^{prod} + \boxed{Cost^{imp}} + \boxed{Cost^{trans}}$

$$Cost^{imp} = \sum_{y \in Y} \left((1 + D_y)^{-y} \cdot \sum_{y \in Y} \left(\sum_{n \in N^{imp}} \left(\sum_{t \in T} (p^{imp}_{a,t,y} \cdot imp^{a}_{t,y}) + C_{conv,y} \cdot cap^{new}_{conv,y} + F_{conv,y} \cdot cap^{tot}_{conv,y} \right) \right) \right)$$

Import price — CAPEX and OPEX ammonia tank and regasification

$$Cost^{trans} = \sum_{y \in Y} \left((1 + D_y)^{-y} \cdot \sum_{(n,\acute{n}) \in P} \sum_{cp \in CP} \left((C_{cp,y} + C^{comp}_{cp,y}) \cdot z_{n,\acute{n},cp,y} \cdot L_{n,\acute{n}} + (F_{cp,y} + F^{comp}_{cp,y}) \cdot \sum_{y_k = y_0}^{y} z_{n,\acute{n},cp,y_k} \cdot L_{n,\acute{n}} \right) \right)$$

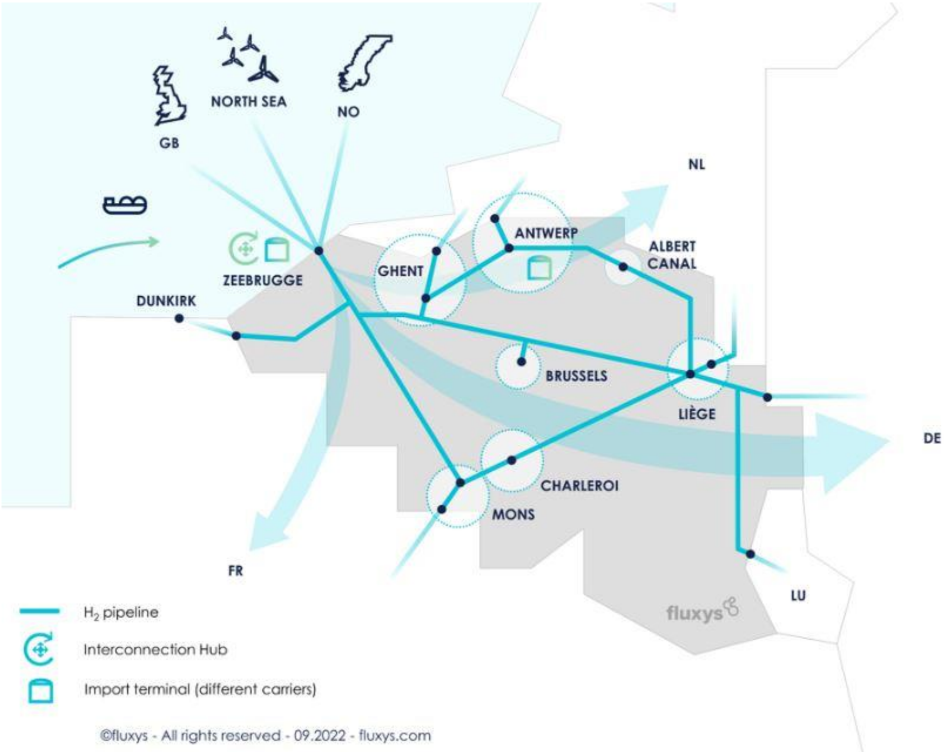
CAPEX pipelines and compressor stations — OPEX pipelines and compressor stations (including the electricity price)

Compressor investment and operational cost are calculated based on the required compression capacity per km of the hydrogen pipeline

Case Study

Fluxys roadmap

Belgium – Fluxys (2040)



Source: Hydrogen: Preparing to build the network (fluxys.com)

A hydrogen infrastructure proposal by the gas TSO based on the **identification of potential industrial demand and supply clusters and their market interest**

No analysis and quantitative information on:

- Required **hydrogen volumes per each cluster**
- Required **pipeline capacities** among each pair of industrial zone considering **different supply scenarios**

Input to our model: boundary condition in terms of **potential connections** among regions within Belgium

✗ The interconnection and potential trade with neighboring countries

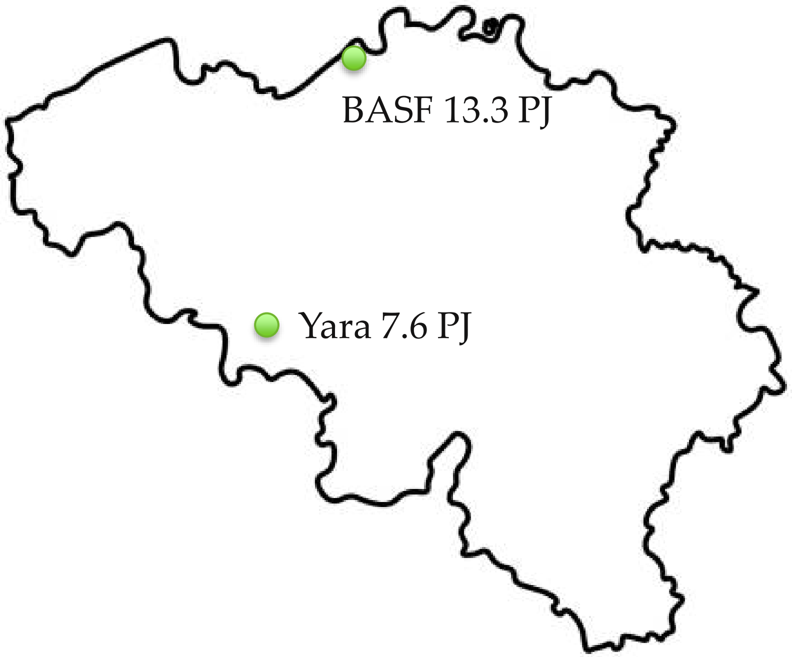
Case Study

Demand estimation: TIMES – BE model

Example: hydrogen for ammonia production

2 ammonia production plants in Belgium (~ E-PRTR database):
- Yara Tertre, 400 kton/year (36%)
- BASF Antwerp, 700 kton/year (64%)

Total annual hydrogen consumption from TIMES BE model for ammonia production (Haber boch process): 20.9 PJ
- Yara Tertre, 7.6 PJ (36%)
- BASF Antwerp, 13.3 PJ (64%)

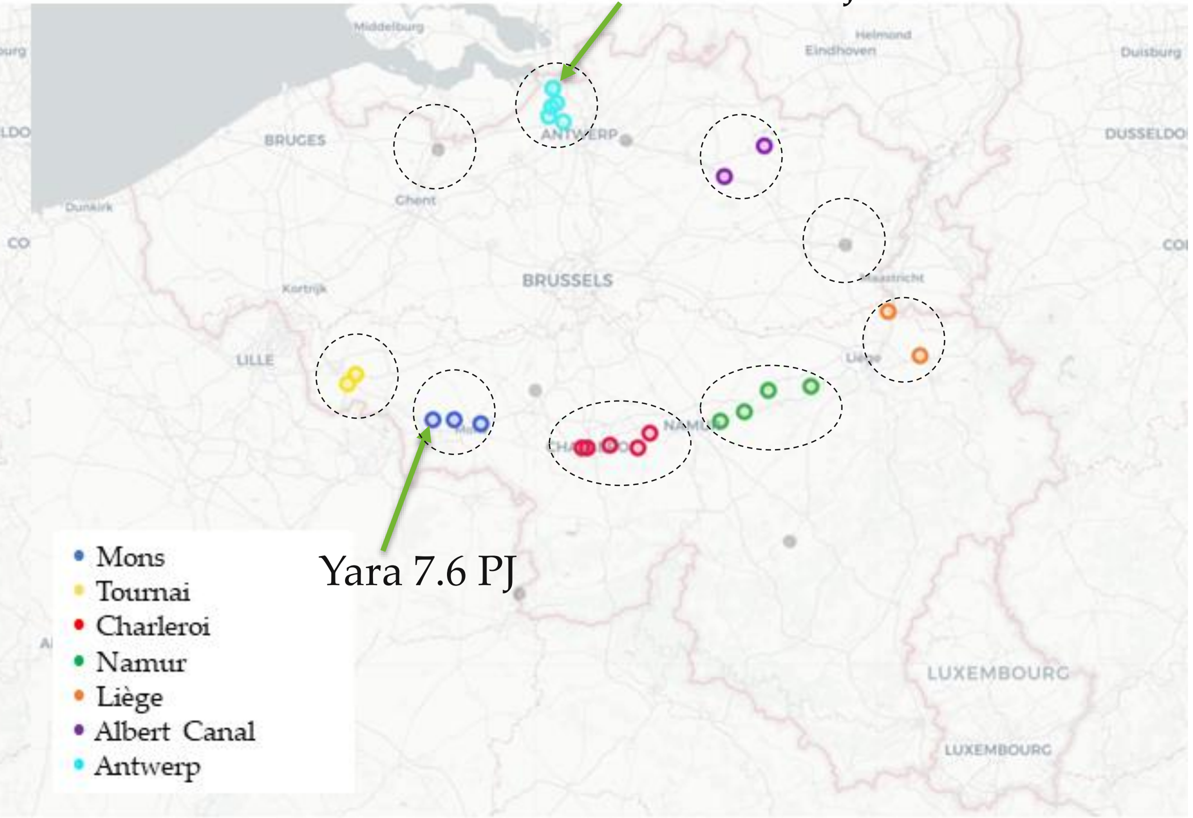


Case Study

Clustering application (Demand nodes)

All industrial activities are assumed to stay in Belgium

BASF 13.3 PJ



Yara 7.6 PJ

Ghent: ArcelorMittal
Genk: Aperam Stainless Belgium

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Case Study

Network optimization (Supply nodes and pipelines)

Blue hydrogen → Antwerp and Ghent (existing SMR capacities

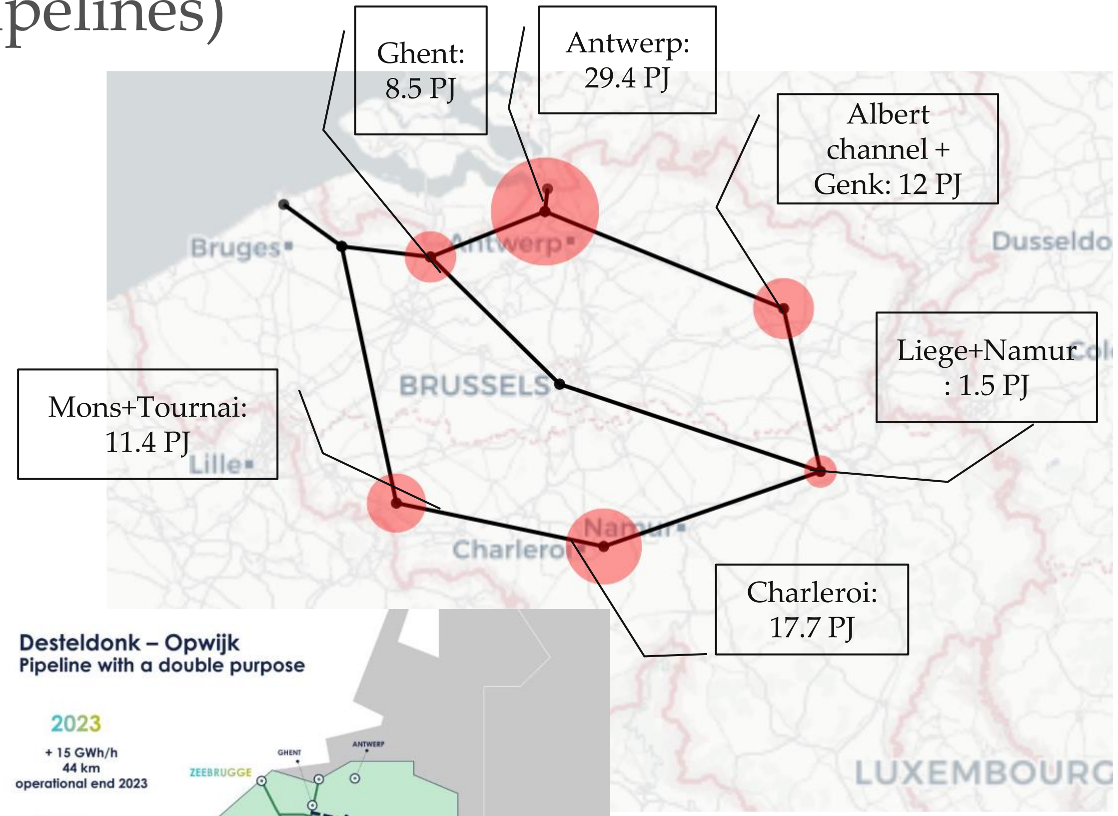
Offshore → Princess Elisabeth Zone connected to Zeebrugge (45 km)

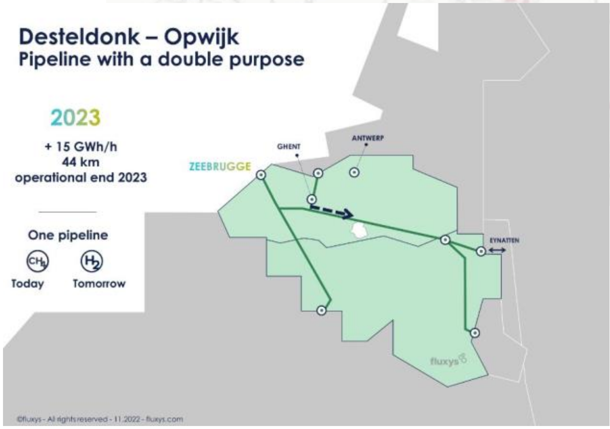
Decentral inland → electrolysis capacities are located in demand clusters themselves

✗ Belgium as a transit country to Germany

Assumptions:
Most of the pipes → newly installed

Candidate pipes and compressors	Construction	CAPEX (M€/km)	OPEX (% CAPEX)
Pipe DN500	New	2.5	0.9
	Repurposed	0.25	0.9
Pipe DN900	New	2.75	0.9
	Repurposed	0.5	0.9
Compressor DN500	New	0.09	1.7
	Repurposed	0.09	1.7
Compressor DN900	New	0.32	1.7
	Repurposed	0.14	1.7





Source: [Fluxys increases transmission capacity with the second Desteldonk-Opwijk pipeline and takes a first step in realizing hydrogen ambitions]

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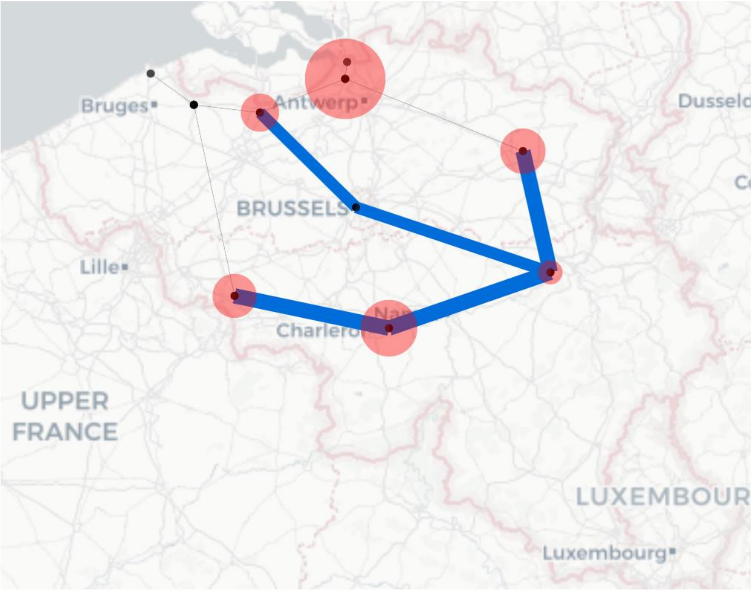
Results

Future hydrogen backbone in each scenario

Repurposed pipe, DN 900 (3.6 GW)

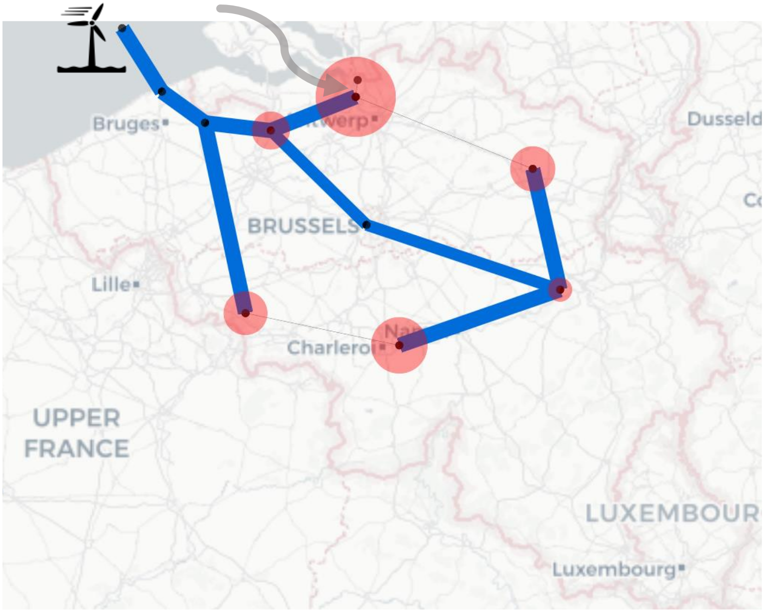
New pipe, DN 900 (4.7 GW)

Ammonia import limited to 50% of the demand



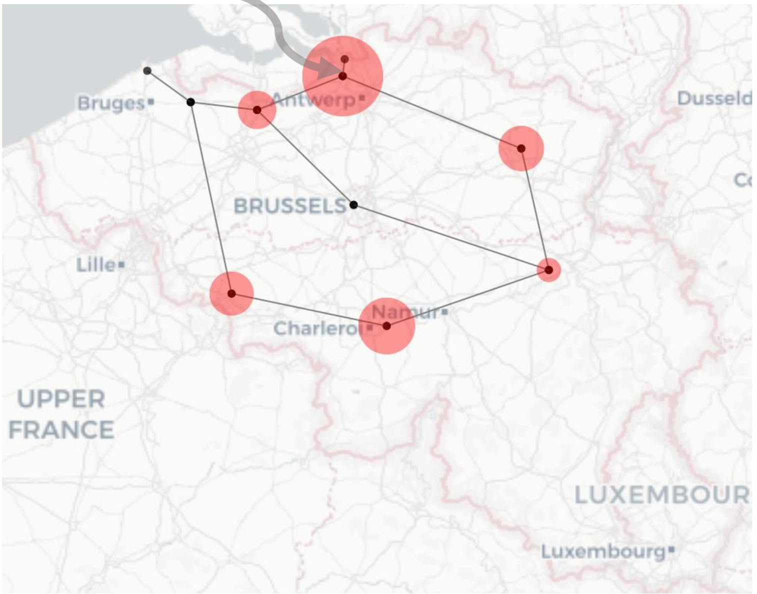
I. Blue hydrogen scenario

Ammonia import: 50.4 PJ



II. Offshore scenario

Ammonia import: 1.4 PJ



II. Decentral inland scenario

Total electricity in decentral scenario consumption: 30.6 TWh
Total renewable electricity produced in 2021: 25 TWh

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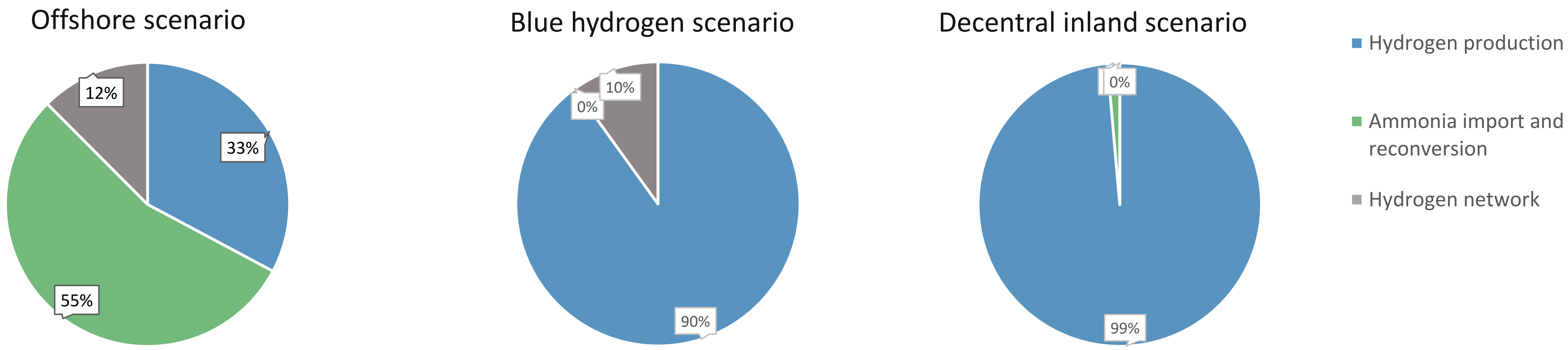
Results

The total cost of hydrogen production and transport in each scenario

(considering costs for the whole model time horizon including the salvage values)



Total cost ~ 1.72 bn EUR-2025

Total cost ~ 1.67 bn EUR-2025

Total cost ~ 1.72 EUR-2025

Offshore scenario:
1) network-intensive scenario
2) Import-intensive scenario (green block is mostly due to regasification and storage)

Conclusions

- Regionalization methods → high spatial demand estimation (after a system-level net zero perspective) → hydrogen network analyses
- Belgian case: DBSCAN clustering algorithm verifies the gas TSO's proposal for industrial hydrogen demand clusters (identifying areas with a high density of facilities)
- Belgian case: the cost-optimal configuration of the future hydrogen network varies based on different supply scenarios
- Offshore scenario → the most network-inessive scenario and slightly higher (total production, import and transport cost)
- Belgian case: longer refurbished pipeline trajectories are more cost-optimal than shorter newly installed pipe segments (Ghent – Liege vs Antwerp – Albert Channel)
- Belgian case: no hydrogen network investments in the decentral scenario with very high additional electricity demand → can the future grid cope with this additional demand?

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Thank you!

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Back-Up Slides

Network Optimization Model

Input parameters and assumptions

Technology	Investment (M€/GW)		Fixed O&M (M€/GWa)		Variable O&M (M€/GWh)		Lifetime (y)		Conversion efficiency (%)		Availability factor (%)	
year	2025	2040	2025	2040	2025	2040	2025	2040	2025	2040	2025	2040
SMR + CCS	1613	1413	50	50	-	-	20	20	69	69	90	90
Ammonia reconv + storage	3150	3150	72.6	72.6	-	-	30	30	84	84	92	92
Offshore wind	1875	1625	72.5	57	-	-	30	30	-	-	Time series **1**	Time series
Offshore electrolyzer + platform	870	670	32	23	0.002 **2**	0.002	20	20	69	72	96	96
Inland electrolyzer	653	463	9.8	6.7	-	-	20	20	69	72	96	96

1. The hourly time series for offshore wind → renewable ninja considering a hub height of 80 m
2. The variable cost of offshore electrolyzer → water desalination process

TIMES – BE Processes

TIMES technology	Main activity	Main activity code
Steel - Hydrogen DRI source for H2 shaft	Metal ore (including sulphide ore) roasting or sintering installations	2(a)
Steel - Blast Furnace with Hydrogen injection	Installations for the production of pig iron or steel (primary or secondary melting) including continuous casting	2(b)
Steel - Finishing Heat_Hydrogen (H2)		
Ammonia - Haber Bosh Process (Refurbished)	Chemical installations for the production on an industrial scale of basic organic chemicals OR fertilizers	4(a)(i), 4(c)
Ammonia - Harber Bosh Process (BY)		
Chemical: HVC - Methanol Syntesis (New)	NA	NA
ICH – Other Chemicals Boiler High Temperature Heat	NA	NA
Glass- Flat with hydrogen	Installations for the manufacture of glass, including glass fibre	3(e)
Glass- Hollow with hydrogen		
Glass- Fiber with hydrogen		
Cement - Process Heat Kiln H2 and plasma substitution (New)	Opencast mining and quarrying OR Installations for the production of cement clinker and lime in rotary kilns or other furnaces	3(b), 3(c)(i), 3(c)(ii), 3(c)(iii)
Lime - Process Heat Kiln H2 and plasma substitution (New)		3(b), 3(c)(i), 3(c)(ii), 3(c)(iii)

E-PRTR Industrial Database

Industrial Companies	Main Activity Code	TRILATE Cluster
ARCELORMITTAL BELGIUM - GENT	2(a)	Gent
APERAM GENK	2(b)	Genk
APERAM STAINLESS BELGIUM SA	2(b)	Charleroi
INDUSTEEL	2(b)	Charleroi
THY MARCINELLE sa	2(b)	Charleroi
CARMEUSE sa - Carrière de Moha	3(b)	Namur
CARMEUSE sa - Carrière d'Aisemont	3(b)	Charleroi
CCB sa - Carrière de Gaurain-Ramecroix	3(b)	Tournai
HOLCIM Belgique sa - Usine d'OBOURG	3(c)(i)	Mons
CBR sa - Site d'Antoing	3(c)(i)	Tournai
CBR sa - Site de Lixhe	3(c)(i)	Liège
LHOIST INDUSTRIE sa - Site de On	3(c)(ii)	NA
CARRIERES ET FOURS A CHAUX DUMONT WAUTIER SA	3(c)(iii)	Namur
DOLOMIES DE MARCHE-LES-DAMES sa	3(c)(iii)	Namur
CARMEUSE sa - Site de Seilles	3(c)(iii)	Namur
3B-FIBREGLASS sprl	3(e)	Liège
AGC GLASS EUROPE VESTIGING MOL	3(e)	Albert Canal
AGC GLASS EUROPE - Site de Moustier (ex-GLAVERBEL sa)	3(e)	Charleroi
GERRESHEIMER MOMIGNIES sa	3(e)	NA
SAVERGLASS MD Verre	3(e)	Mons
YARA TERTRE sa-nv - CETPROBEL sa	4(c)	Mons
BASF ANTWERPEN	4(a)(i)	Antwerp