Institute for
Sustainable
Process Technology

# HyChain 4

## Integral hydrogen-based supply chain development

# Acknowledgements

The successful launch of this report was made possible through the invaluable support of our partners, implementers, and other stakeholders. The project initiated in March 2020 and thus coincided with the onset of the global Covid crisis. This meant adapting to full online cooperation, digital meetings, and remote project development. The project concluded by the end of 2022, and 2023 was designated as a reporting phase.

The unwavering support of everyone involved played a key role in the project's realization. We, therefore, express our special thanks to everyone listed below, as they made significant contributions to the project development, research, and the formulation of the results and report.

Our valued partners that formed the consortium are: Deltalinqs, Dow, HyCC, Nobian, OCI Nitrogen, Port of Rotterdam, Provincie Zuid Holland, Stedin, TNO, Vopak, and Yara.

The research was carried out by: John Kerkhoven, Rob Terwel, and Tuuli Tiihonen from Kalavasta, Gregor Brandt, Jan van Schijndel, Jaron Davelaar, Nort Thijssen, and Rutger de Mare from Quo Mare, Bastiaan Knoors, and Cas Thoonsen from Royal HaskoningDHV, and Sebastiaan Hers from TNO.

The project furthermore benefitted greatly from the support of Martijn Verwoerd and Emiel Langenhuizen from Smart Delta Resources.

From ISPT Andreas ten Cate, Carol Xiao, Christa de Ruyter, Lotte van der Velde, and Marleen Roozen contributed to this project.

- **The Authors**

# Foreword

The industry needs to reduce its greenhouse gas emissions drastically. Hydrogen and electricity are both carbon free energy carriers. This means that there are no greenhouse gas emissions when using hydrogen and electricity.  And if hydrogen and electricity are produced without emitting greenhouse gas emissions, it is zero greenhouse gas emissions over the total supply chain.

Today hydrogen is produced from fossil fuels, emitting carbon dioxide, and used as a feedstock. The Netherlands is the second largest producer and consumer of hydrogen from natural gas in the EU, after Germany. However, in future hydrogen needs to be produced from renewable energy sources, amongst others via water electrolysis using renewable electricity. And in future hydrogen will not only be used as feedstock, but also as carbon free energy carrier and reducing agent. This requires investments in all parts of a hydrogen supply chain; in production, transport, storage and use in different sectors.

In all parts of the supply chain alternative technology choices and competition is possible. Large scale water electrolysis in the Netherlands may compete with import from South Europe, Africa or the Middle East. Hydrogen import via pipeline can compete with ammonia or liquid hydrogen import by ship. Industry investments are required for the use of hydrogen that can compete with other options to reduce greenhouse gas emissions, such as direct electrification or Carbon Capture and Storage.

So industry has to deal with a complex investment decision making process, with a lot of uncertainties and many stakeholders. The HyChain 4 project addresses this complex issue, not by focusing on delivering exact answers, but by delivering a model tool and dataset that can be used by companies and industry clusters to explore different hydrogen supply chains and options. Such a tool is invaluable in maintaining the leading position of Dutch industry and making it more sustainable at the same time. Next to this, it will contribute to develop a world class clean hydrogen supply chain and hub in the Netherlands, that builds on the unique position of the Netherlands; good offshore wind resources, a very extensive gas infrastructure that can be repurposed for hydrogen, excellent hydrogen storage facilities in salt caverns and several depleted gas fields, innovative industry clusters, especially in the chemical and petro-chemical industry and world leading ports.

With a little help of HyChain 4 the Netherlands will be able to scale up and speed up clean hydrogen, to empower an innovative and sustainable industry!

- **Em. Prof Ad van Wijk (profadvanwijk.com)**
  Professor Future Energy Systems at faculty TPM, TU Delft
  Guest Professor Energy & Water at KWR water research
  Holds several supervisory and advisory board positions, a.o. member advisory board Dii desert energy.

# Summary

## Objective, scope, and approach

The HyChain project aims to provide a deeper understanding of drivers and mechanisms that steer the development of new hydrogen value chains. There is a chicken-and-egg problem in synchronizing the investment decisions in the hydrogen value chain. Industry only invests if there is reliable technology and carbon-neutral fuel and feedstock. The supply-side only invests if there is a market for green hydrogen. The infrastructure operators need to understand the scale and location of the required infrastructure for their investments. This HyChain project aims to develop the practices and services to support joint decision making with individuals as well as groups of stakeholders in a public-private setting to support hydrogen supply chain development.

This project delivers datasets, tools, and practices to support joint evaluation and investment decision-making. A robust mathematical optimization model for industrial investments and infrastructure needs for industrial regions in the Netherlands is developed that allows for systematic assessment of transformation pathways that accounts for the interdependency.

The platform supports multi-stakeholder informed decision making to arrive at the most attractive investments needed for development of the hydrogen economy as an integral part of the energy transition challenge of the industry. In addition, a sustainable service model is developed that secures long-term access and maintenance of the tools and data. This is expected to accelerate the deployment of hydrogen value chains and implementation of the hydrogen economy in The Netherlands and across Europe.

## Results

In this project an integral hydrogen supply chain model for optimal energy system investments in supply, energy infrastructure and industrial demand side technologies was developed. The decision support tool covers the hydrogen system, and for balanced assessment also includes the electricity system as well as carbon capture and storage in the Netherlands. Here the scope includes the Dutch system as well as energy imports, and detailed site-level representation of two large industrial clusters in Zeeland and the Rotterdam area. The model was developed in close cooperation with industrial stakeholders and cluster representation for validation and verification. The model was applied in joint stakeholder sessions to establish the value for decision support for individual stakeholders as well as joint fact-finding and development of a common understanding of trade-offs involved with these uncertainties and implications for the investment strategies for hydrogen supply chain development and industrial GHG emission reduction. A service model was developed to make the model available for stakeholders to support the analysis of future hydrogen supply chain development.

## Conclusions

An integrated investment optimization model for the hydrogen supply chain for the Dutch industry in the South-West of the Netherlands (SWNL) and the Rotterdam-Moerdijk region (PoR) was developed. The model allows for long-term optimal investment modelling of system decarbonisation over the course of the energy transition, presenting optimal multi-stakeholder investments across energy supply, infrastructure, and industrial demand on a year-by-year basis.

The HyChain Model was applied in a series of case assessments in a multi-stakeholder setting with project partners representing regional authorities, industry, energy, and network operators. The cases were designed to explore the impact of uncertainties in energy policy, technical potential for new markets and infrastructural dependencies.

Some of the findings in these case assessments may be taken to serve as an illustration of the potential of the HyChain Model:

- Accelerated GHG emission reduction through target setting as observed in recent years, bringing the 2030 GHG emission reduction targets forward to 2027, left case results largely unaffected in comparison to the reference case that was predominantly driven by the EU ETS prices.
- Promotion of green hydrogen production in industry as proposed in the Fit-for-55 package, resulted to drive increased green hydrogen investments at the expense of blue hydrogen investments in both industrial clusters and higher costs.
- Potential for hydrogen as feedstock, exploring the potential for hydrogen deployment in synfuel and syn-naphtha production, rendered to be high in comparison to demand for hydrogen as an energy carrier in the Rotterdam area.
- An imposed CCS phase-out by 2045 results in a significant reduction of the attractiveness of CCS investments in SWNL (South-West of the Netherlands?), while such is not the case for the PoR area. In the first case higher CO2 emissions result from notably 2030 onward, while in the latter case investments in alternatives by the end of the evaluation period predominantly drives up overall costs.
- Delayed regional power grid reinforcement in PoR in the coming decade may limit electrification efforts and predominantly induces increased (blue) hydrogen deployment, lowered CO2 emission reductions and increased EU ETS exposures in the 2030 – 2040 timeframe.

The workshops allowed for joint fact-finding and development of a common understanding of trade-offs and implications for the investment strategies for hydrogen supply chain development and industrial GHG emission reduction. This experience suggests significant benefits may be attained, both for individual stakeholders as well as joint stakeholder efforts in the Dutch Hydrogen supply chain development.

The consortium experienced that there is substantial interest in the availability of the HyChain Model for transition planning in industry and the Cluster Energy strategies, as well as the future role of industry in the Dutch society in terms of the material output and the economic contribution. The service model developed in this project builds on early arrangements to support the Cluster Energie Strategie 2.0 for SDR and Rotterdam-Moerdijk and offers a solid basis for future governance, maintenance, development, and deployment of the HyChain Model.

# Contents

# Introduction

## Background

Hydrogen may play a vital role in large-scale renewable energy systems and for decarbonization pathways for the industry. The Hydrohub Innovation Program of ISPT has a single mission: Large-scale electrolysis-based production of sustainable, low cost, hydrogen as a driver for circular industrial chains.

To reach large-scale adoption of hydrogen all stakeholders along the value chain need to make informed investment decisions that are interdependent and have a collective impact. There is a need for a better understanding of how decisions are connected and rely on each other. Further there is a need for reliable public and public-private datasets, reference sources and tools to keep exploring these investment decisions as time progresses.

This project is related primarily to the TKI program line 4 – Hydrogen as it focuses on the deployment and position of industrial-scale water electrolysis and the implications of value chain development in industrial regions and in The Netherlands as a whole. This project also supports the other program lines. It fits most closely with the agenda of MMIP8 Electrification and is related to MMIP13 System Integration. This project supports the SDG's 7, 9, 12, 13 and 17 - see Figure 1.

*Figure 1: Sustainable Development Goals relevant to the HyChain project.*

## HyChain Program

Hydrogen plays an important role in the future renewable energy systems. In a large scale sustainable energy system green hydrogen, produced by electrolysis of water, is a crucial element. The HyChain project is focused on a strategic understanding of the drivers behind global emergence of future renewable hydrogen value chains.

The HyChain project looks at the development of future renewable hydrogen value chains with the Netherlands as a focal point. Industry, consultants and knowledge institutes work together to clarify what is needed to build energy chains based on large-scale affordable production of green hydrogen. The program consists of five parts:

1) Assessment of Future Trends in Industrial Hydrogen Demand and Transport
2) Hydrogen Cost Implications
3) The Technological Value Chain for Hydrogen
4) Dutch Systemic Scenarios for the Hydrogen Supply Chain
5) Public Engagement for the Hydrogen Supply Chain

HyChain 1, 2 and 3 started in 2018 and finished in 2019. HyChain 4 started in 2020 and was finalized in 2023. Building on the results from the previous HyChain projects HyChain 5 started in 2022 and is foreseen to be finalized in 2026.

## HyChain 4

### Motivation for the project

Hydrogen is expected to play a key role in the future economy as carbon-free energy carrier and feedstock. Investments in generation of renewable electricity will require parallel investments in generation of renewable or green hydrogen, while the current reference of conventional hydrogen produced from natural gas may be combined with Carbon Capture and Storage (CCS) for blue hydrogen supply. There is much uncertainty about the rate at which a hydrogen economy can be developed. This requires investments in all stages of the supply chain - production, storage, transportation, and use - and in many sectors. Supply-side investments, e.g., large-scale electrolysis, may compete with import from regions such as Southern Europe with high renewable energy production potential. Also, industry investments are required for hydrogen deployment. These depend on secure supply at an affordable price level, and compete with the alternatives, e.g., direct electrification and CCS.  Furthermore, decisions of parties in hydrogen supply and industrial clusters are connected through infrastructure development and have synergy potential when aligned. Until today the decisions are generally taken on an individual basis with risks of overspending and socializing investment costs. There is a clear need to improve the investment decision making under large uncertainties and in a coherent way in multi-stakeholder settings.

### Objective of the project

Our key solution is to create a tool - consisting of a common dataset and model - that supports multistakeholder informed decision making to arrive at the most attractive investments needed for development of the hydrogen economy as an integral part of the energy transition challenge of the industry. In addition, a sustainable service model is developed that secures long-term access and maintenance of the tools and data. This is expected to accelerate the deployment of hydrogen value chains and implementation of the hydrogen economy in The Netherlands and across Europe.

### Approach

The project approach may be structured into three phases. In the first phase the base model for optimal investment in national hydrogen supply and regional hydrogen supply and demand in the Dutch industrial clusters in the South-West of the Netherlands (i.e. the Smart Delta Resources SDR region in Zeeland) and Rotterdam-Moerdijk was developed on the basis of a series of model scoping sessions with project partners. The second phase of the project involved a series of targeted multi-stakeholder sessions (with project partners representing regional authorities, industry, energy and network operators) on national and regional model validation and verification. This phase was concluded with a series of multi-stakeholder sessions for application of the model to research questions regarding hydrogen supply chain development in the Netherlands. The third phase of the project built on the experiences gained in the multi-stakeholder practices, as well as early support provided to the development of the Cluster Energie Strategie 2.0 for SDR and Rotterdam-Moerdijk. This project phase covered the development of a service model for future governance, maintenance, development and application of the HyChain Model.

## How to read this report

This report covers the project results for HyChain 4. In the first chapter of this report we describe the project approach to develop the HyChain Model. The approach is followed by a chapter going more in depth on the HyChain model description, describing the modelling approach and modelling scope. In the following chapter on Multi-stakeholder Case Analysis, we describe the application of the model to a series of cases on strategic questions in hydrogen supply chain development. The chapter covers the results of the multi-stakeholder case analysis that was carried out for both model validation and verification purposes as well as the purpose to experience model-based joint multi-stakeholder analysis. The final chapter on the Service Model presents an outlook on future use of the tools in transition planning in industrial regions. It illustrates how a service model can be shaped that positions the tool as a strategic repository in a trusted regional setting and covers sustained support on aspects like model use, handling confidentiality in various use cases, secures maintenance and ongoing model development in Dutch industrial clusters.

# HyChain Model Description

## Introduction

Hydrogen may play a vital role in large-scale energy systems for decarbonization pathways of industrial companies and clusters. The HyChain model aims to support joint decision making with individuals as well as groups of stakeholders in a public-private setting. In this project three models are developed to support investment decisions for Dutch hydrogen supply chain development:

- A national model to assess cost-effective hydrogen supply investment decisions to meet hydrogen demand in the Netherlands by either making or buying hydrogen;
- A South-West Netherlands model to assess cost-effective investment decisions in decarbonization strategies in the cluster and to analyse how the hydrogen demand and regional supply in the cluster will develop over time;
- A Port of Rotterdam model to assess cost-effective investment decisions in decarbonization strategies in the cluster and to analyse how the hydrogen demand and regional supply in the cluster will develop over time.

The development of the HyChain model was undertaken in close cooperation with the project partners in a series of plenary sessions and dedicated workshops for regional model development in three iterations of respectively base model development and two sprints for further model refinement, covering model scoping, model validation and model verification. For this HyChain project the TEACOS system/tool is deployed.

## TEACOS

TEACOS stands for Techno-Economic Analysis of Complex Option Spaces and is a long-term decision support tool. The tool generates credible, affordable and competitive transition pathways towards a low carbon energy system.

TEACOS is a generic tool which is suitable for many applications. Figure 2 presents the high-level set-up of the TEACOS framework. The tool consists of four general building blocks covering the structure of the energy system. These building blocks are supply, conversion infrastructure, transport infrastructure and demand. All the data in this model is with temporal and spatial granularity, so that both the aspects of location and timing are captured in the model.

The TEACOS model is of the class of Multi-Period-Mixed-Integer-Linear-Program (MP-MILP) optimization and it is built on the AIMMS advanced optimization engine. TEACOS performs a techno-economic optimization, optimizing the Net Present Value of system considered by selecting the most attractive investments from a set of investment options, resulting in the highest margin or lowest cost over the time

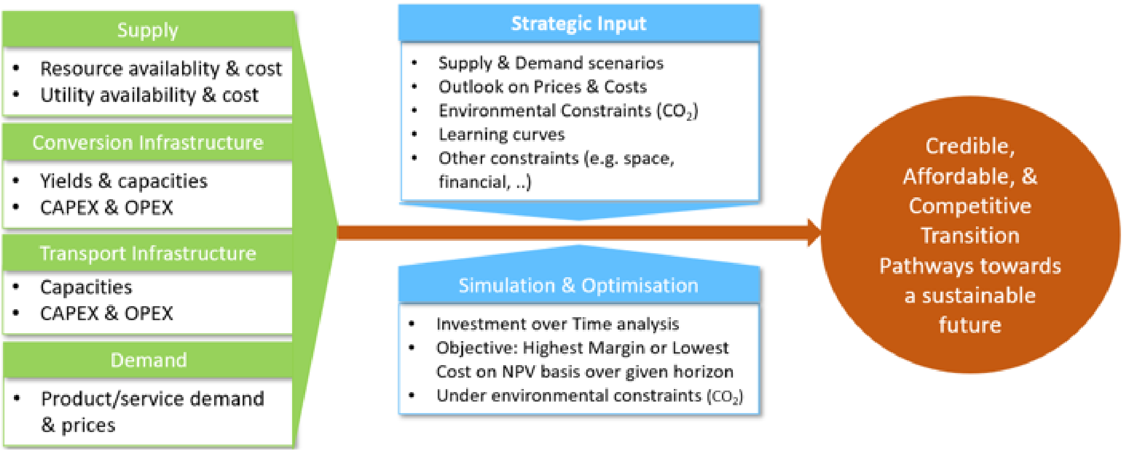

*Figure 2: Set-up of the TEACOS framework*

$$Obj_{NPV} = \sum_t DiscC_t * \begin{pmatrix} SalesPrice_t * NodeFlow_t \\ -Capex_t * ProjectStart_t \\ -FixedOPEX_t * ProjectInUse_t \\ -SupplyCost_t * NodeFlow_t \\ -NodeCost_t * NodeFlow_t \\ -ArcCost_t * ArcFlow_t \\ -StorageCost_t * StorageLevel_t \end{pmatrix}$$

*Figure 3: Objective function in the TEACOS framework, including all costs components by node and timestep. The discount factor is abbreviated with DiscCt*

horizon considered and based on the input assumptions (supply and demand, prices, learning curves), and respecting boundary conditions and environmental constraints like for example CO2 emission targets. The model optimizes over the full time-horizon of the problem and delivers the optimal configuration over time to reach the optimization objective. Figure 3 presents the objective function.

The tool is data-driven and flexible. This means that new insights, initiatives, and updated policies can be incorporated to the model easily. The scenario set-up ensures that different viewpoints can be specified and optimized in the model. Sensitivity analysis can be executed in the model to identify the robustness of transition pathways and tipping-points for the relative attractiveness of the investments.

## The HyChain Model

In this project the TEACOS framework/tool is used to analyse the hydrogen value chain for the Netherlands, connecting the five industrial clusters, and in more detail two specific Dutch industrial clusters, the South-West Netherlands (Zeeland or SDR region), and the Port of Rotterdam region. Each of these energy system segments is covered in dedicated modules as presented in this section. The model delivers cost-effective transition pathways by identifying cost-optimal investment strategies for all assets (production, infrastructure, and use) in the period 2020-2050 at an annual granularity.

### National Supply Model

The main question for the National Model is: how will the Netherlands meet its hydrogen demand over the time horizon 2020 – 2050? Optimal investment in the Dutch hydrogen supply chain development as driven by Greenhouse gas (GHG) emission reduction targets is the primary objective.

Future hydrogen supply system development may involve national supply chains based on either natural gas or electricity, as well as international supply chains of hydrogen through imports. Each of these supply routes is covered in the hydrogen system scope of the national supply model.

Hydrogen prospects for national production are generally expected to build on the vast offshore potential for renewable electricity in the Netherlands, and as such depend on electricity system development as well.

Both the hydrogen system as well as electricity system is therefore covered by the scope of the national model. In the following both will be briefly presented.

### *Hydrogen System*

The hydrogen system in the National Supply Model is structured to reflect the make-or-buy decision to fulfil the hydrogen demand: either **make** the hydrogen in the Netherlands or **import/buy** the hydrogen from importing countries.

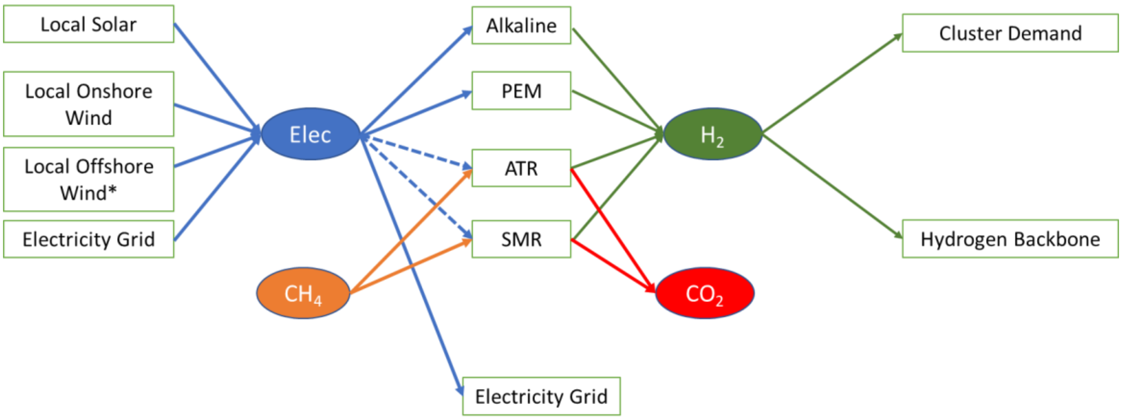

*Figure 4: Schematic overview of all national production options*

Local production in the Netherlands is possible via Steam Methane Reformers (SMR; grey hydrogen), Autothermal Reformers with CCS (ATR; blue hydrogen) and Alkaline or PEM electrolysers (green hydrogen produced from green electricity), as illustrated in Figure 4. The potential of CO2-emission-free hydrogen production in the Netherlands is limited due to spatial constraints, limited availability of renewable electricity (sun, onshore and offshore wind power) and limited $CO_2$ storage capacity.

Import of Hydrogen is possible via multiple routes, as illustrated in Figure 5. Hydrogen import can either be transported via pipelines or shipping in the model. For shipping the hydrogen has to be converted to a hydrogen carrier. $NH_3$, LOHC (Liquid Organic Hydrogen Carrier), $NaBH_4$, Methanol and Liquid Hydrogen are incorporated into the model as hydrogen carriers. For this HyChain project, nine import countries are selected based on location, potential and ambition (as indicated by Kalavasta and HyChain2). The model is flexible to include other countries in potential next phases.

To transport the hydrogen to each industrial cluster in the Netherlands a hydrogen backbone will be built by GasUnie. This hydrogen backbone is incorporated in the model and the time of availability of the backbone is a flexible parameter in the model, see also Figure 6.

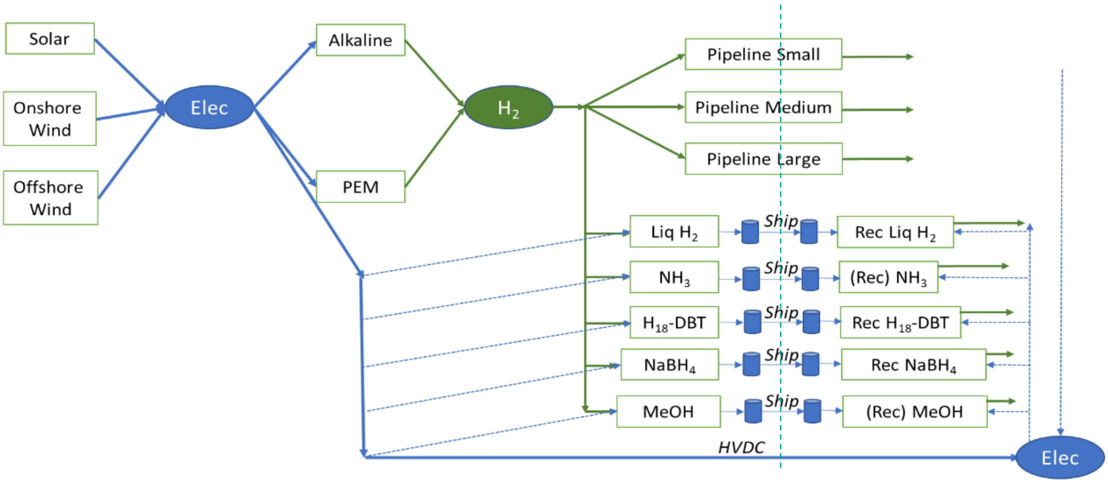

*Figure 5: Generic overview of the import routes*

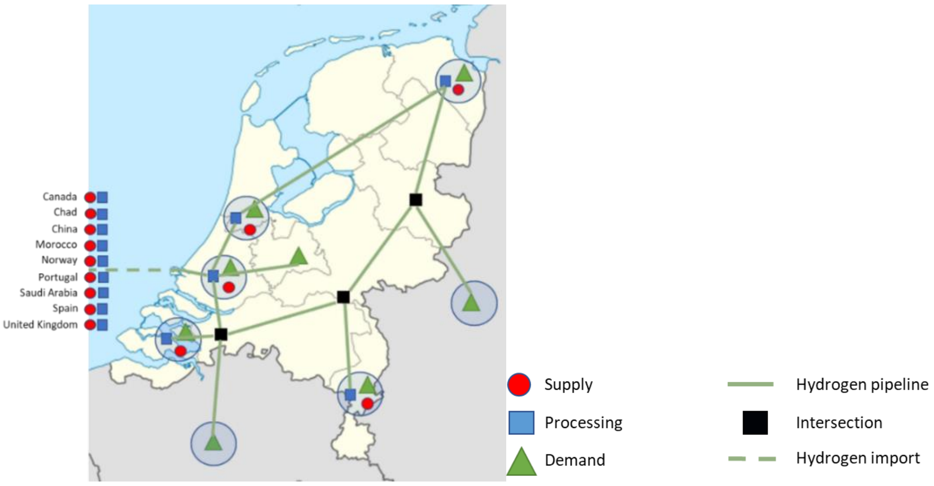

*Figure 6: Overview of the spatial system topology in the national HyChain model*

The hydrogen demand of the Netherlands is input for the National Supply Model. The endogenously determined hydrogen demand is classified in the following categories: food, paper, refining, chemicals, fertilizers, steel, aluminium, other industry, mobility, synfuels, electricity production and a generic category 'other' for other demand, while other hydrogen demand like residential demand from households can be set exogenously. Two geographical components are included in the hydrogen demand:

- Hydrogen demand in the industrial clusters (Eemshaven, Chemelot, Zeeland, Rotterdam, Noordzeekanaalgebied and the 6st cluster); data is based on II3050 scenarios
- Transit to Germany (Ruhr Area) and Belgium (Antwerp); data is based on Kalavasta estimate

In separate detailed models the hydrogen demand for the industrial clusters in the Port of Rotterdam Region and in the South-West of the Netherlands is covered.

### *Electricity System*

Hydrogen production based on electrolysis requires on-site availability of electricity, as determined by electricity supply, transmission infrastructure and demand. The National Supply Model was therefore expanded with the explicit modelling of the electricity market in the Netherlands. This modelling does include both the demand and supply of electricity per cluster and an explicit modelling of the offshore wind parks and other production capacity, while other electricity demand is set exogenously. The 2020 data for the supply of electricity is used as initial capacity for all electricity production options. The model is free to invest in new units and/or retrofits over the complete time horizon, taking into account the electricity supply potentials in this investment strategy. As the power sector will be in flux due to the energy transition much like the industrial sector, future development of the power sector is covered as well. The electricity supply potentials per electricity production technology are defined per industrial cluster and contain the following technologies:

- Biomass-Cofiring (with options for retrofit to 100% biomass and CCS)
- Biomass-Standalone (with option for CCS)
- Sun-PV, Wind-onshore, Wind-offshore[1]
- Natural Gas: NGAS-CCGT (with options for CCS and Oxyfuel), NGAS-GT and NGAS-CHP
- Green Gas: GGAS-CCGT (with options for CCS and Oxyfuel), GGAS-GT and GGAS-CHP
- H2-GT and H2-CCGT
- Waste stand-alone
- Derived-gas technology (blast furnace gases in Noordzeekanaal)

The electricity demand profiles for all clusters in the Netherlands are based on the II3050 report for 2030 and 2050 (Berenschot, Kalavasta, 2020; Kalavasta, 2019). Demand in surrounding countries is based on the Ten-Year Network Development Plan 2020 as developed by the European Network of Transmission System Operators for electricity (ENTSO-E).

## South-West Netherlands Regional Model

The objective of the South-West Netherlands model is two-fold:

- Identify robust and optimal investment strategies for decarbonization (hydrogen-use, electrification, CCS) for the industry in South-West Netherlands at site-level as well as cluster level, considering infrastructure boundary conditions.
- Determine hydrogen demand in South-West Netherlands over time

Industrial sector in the region includes Dow Chemicals Terneuzen, YARA and Zeeland Refinery. In the following, coverage of the industrial sector and energy infrastructure is presented.

### *Industry*

In the South-West Netherlands Regional model, Dow Chemicals Terneuzen, YARA and Zeeland Refinery are modelled in detail, on process unit level. To illustrate the level of detail of this modelling a flow scheme of the modelled YARA -, Dow – and Zeeland Refinery sites is presented in Figure 7, Figure 8 and Figure 9.

For each of the processing units, the current annual average mass flows are taken as a starting point. In addition to this, decarbonization options are included per site, taking into account hydrogen-use, electrification and CCS. The regional model can replace fossil-based units for carbon-neutral alternatives (including CCS), thus optimizing the transition pathway of each industrial site in the South-West of the Netherlands. In selecting processes, the model takes into account environmental constraints ($CO_2$ reductions), policies and pricing (e.g. gas price, electricity price, hydrogen price and $CO_2$ penalty).

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[1] The offshore wind potentials are deduced from the modelled offshore wind parks and search areas.

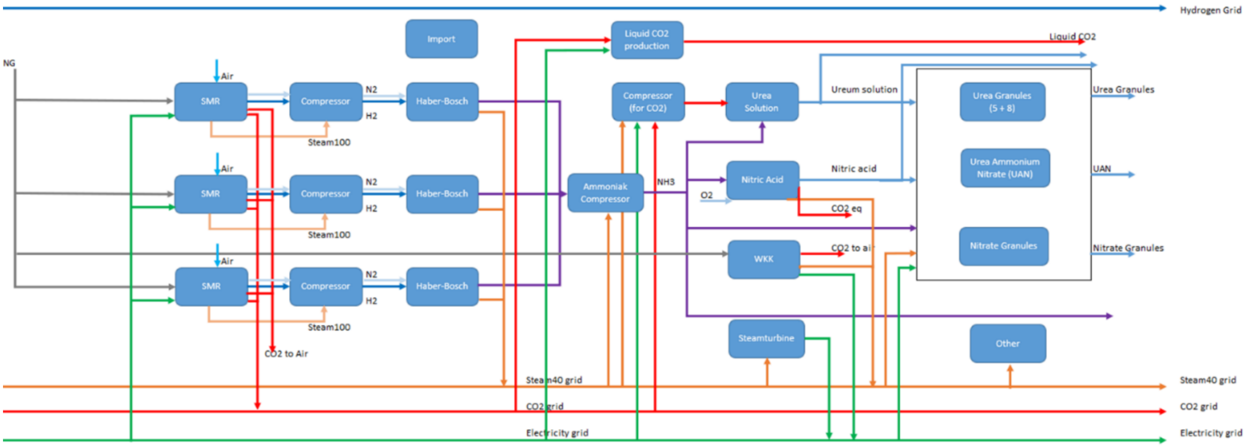

*Figure 7: Flowchart of the YARA site as covered in the South-West Netherlands regional model.*

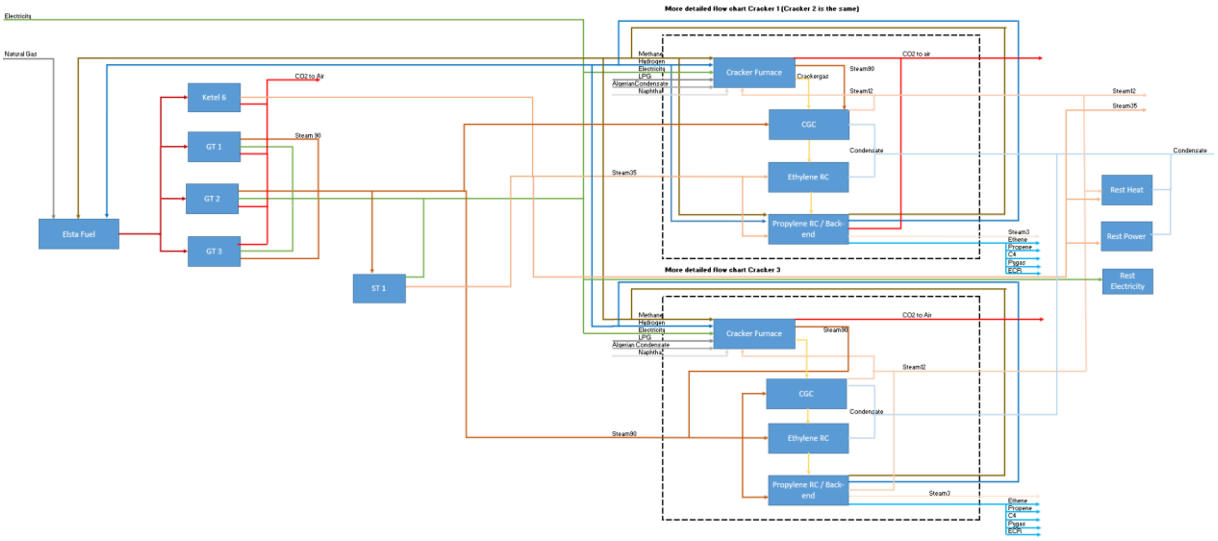

*Figure 8: Flowchart of the Dow Chemicals Terneuzen site as covered in the South-West Netherlands regional model.*

Regional hydrogen demand outside the modelling scope of the industrial cluster may be set exogenously (in this report based on the II3050 scenarios), classified by the same categories as in the National Supply Model. The II3050 scenarios also contain the categories electricity production, chemicals, fertilizer and refining. Due to the explicit modelling of Dow, YARA, ZR and Sloe Centrale in the model this hydrogen demand is established endogenously, and as such output from the model.

### Infrastructure

In the South-West Netherlands model regional interdependencies are incorporated, including natural gas, hydrogen, electricity and CO2 infrastructure. In the model we include limitations for all infrastructures.

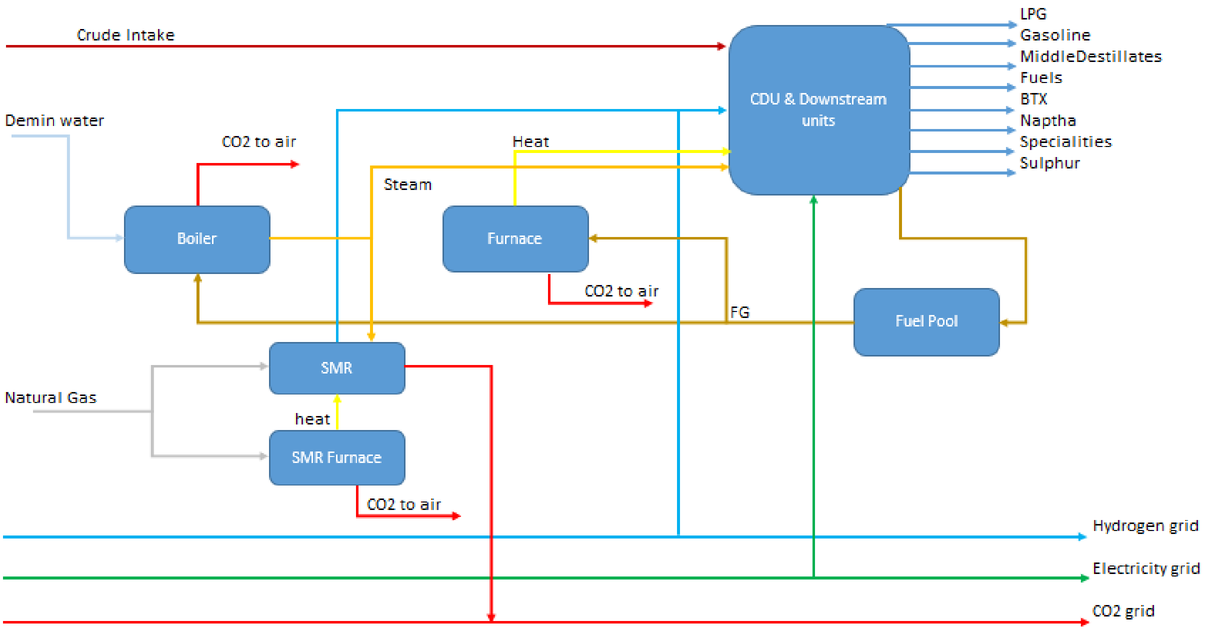

*Figure 9: Flowchart of the Zeeland Refinery site as covered in the South-West Netherlands regional model*

Capacities of existing infrastructure and investments for new or reconversion (gas pipelines to hydrogen pipelines) infrastructure options are included. Also, for expansion of the electricity network and CO2 'export/CCS' options.

To have a full overview of regional supply and demand for electricity, supply of electricity from the Sloe Centrale, Nuclear Plant Borssele, offshore wind parks, onshore wind parks and solar parks are included. In addition to this, other electricity demand for the different regions within the South-West Netherlands is included. (see Figure 10). The import and export via the grid is also included to have a full overview of the electricity balance in the region (see 'Inlet' and 'Outlet' in Figure 10).

The full load hours of offshore, onshore and solar parks are taken into account. This means that if the renewable electricity sources do supply the industrial companies in the cluster, balancing units (Sloe Centrale, Nuclear Plant Borssele) do have to supply electricity if there is no wind or sun. In practice, the seasonal production profile of wind and solar in the Netherlands largely complement each other, while peak production of wind and solar seldomly coincide. This means that the required balancing electricity depends on the relative contributions of offshore/onshore wind parks and solar parks.

The existing gas network and new hydrogen and CO2 networks are modelled in the same level of detail as the electricity infrastructure, see also Figure 11 (CO2 network is not included due to confidentiality).

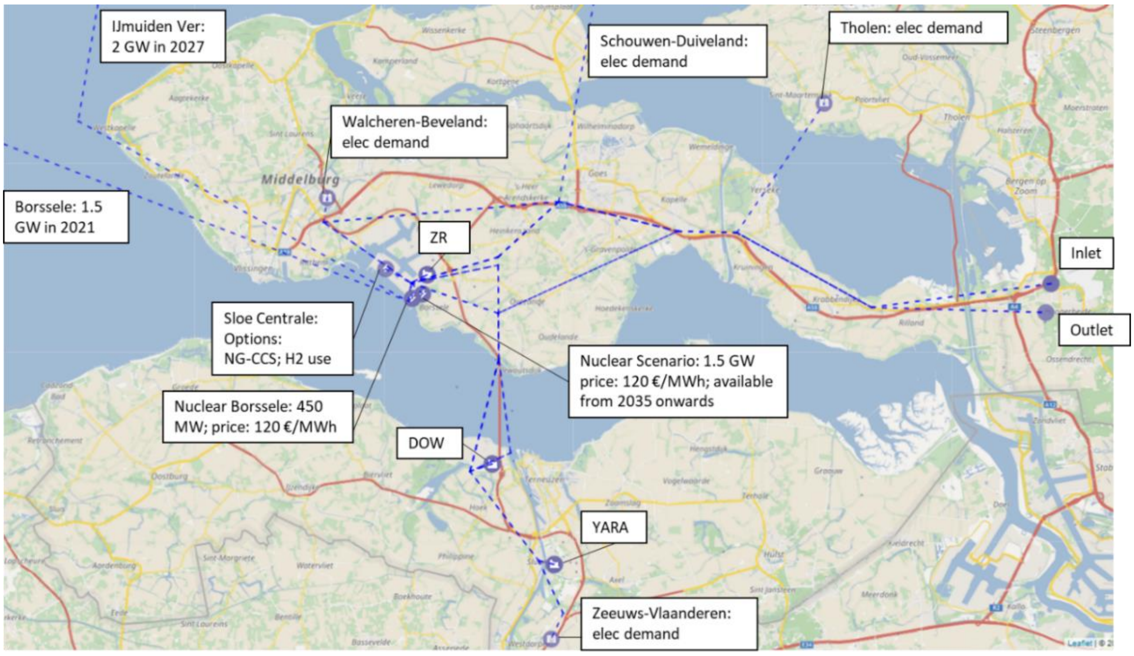

*Figure 10: Overview of supply and demand for electricity in the South-West Netherlands regional model*

*Figure 11: Overview of gas and hydrogen infrastructure in the South-West Netherlands regional model*

## Port of Rotterdam Regional Model

The objective of the Port of Rotterdam model is two-fold:

- Identify robust and optimal investment strategies for decarbonization (hydrogen-use, electrification, CCS) for the industry in the Port of Rotterdam, considering infrastructure boundary conditions and interdependencies.
- Determine hydrogen demand in the Port of Rotterdam area over time.

Over 36 companies and 14 electricity producers are covered in the model, representing approximately 98% of the current $CO_2$ emission in the Rotterdam Port area (including Moerdijk). Though the initiatives for blue hydrogen production, low-carbon hydrogen from refinery gases (H-vision[2]), and green hydrogen production (conversion park), imply quality differences in hydrogen supply, the implementation for now assumes a singular quality as a first step (as hydrogen quality is technically less critical for industrial applications compared to fuel cell requirements). Accordingly, technical quality differences are not captured in the current framework, while differences in the role of blue versus green hydrogen that result from positioning in the merit order (i.e. differing cost characteristics) are.

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[2] The H-vision consortium develops routes to convert residual gases (refinery gases) into CO2 for capture and low-carbon hydrogen for heating to reduce emissions of the heavy industry in the Port of Rotterdam. More information here: https://www.h-vision.nl/.

In the following, a description of what is covered for the industrial sector, the power sector and energy infrastructure is presented.

### *Industrial energy demand*

In the Port of Rotterdam model, 36 companies are modelled at site level. The data used for 35 companies is based on the Energy-mix Study (or E-mix Study) by Deltalinqs and TNO[3] (Port of Rotterdam, Stedin, Deltalinqs, 2022), while data for Shell Moerdijk was based on inhouse expertise and team analysis.

In this E-mix data, five (brownfield) strategies per company are included, all with their own energy-mix, potential CAPEX and CO2 emission:

- The *As Is* Strategy, which corresponds to the current E-mix of a company.
- The *Business as Usual* or BaU Strategy (2030 plan), including decarbonization options (energy efficiency improvements, CCS) which are feasible before 2030.
- The *CCS Strategy* (available from 2031 onwards).
- The *Hydrogen Strategy* (available from 2031 onwards).
- The *Electrification Strategy* (available from 2031 onwards).

An illustration of the energy-mix and CO2 emission per strategy for company x is given in Figure 12.

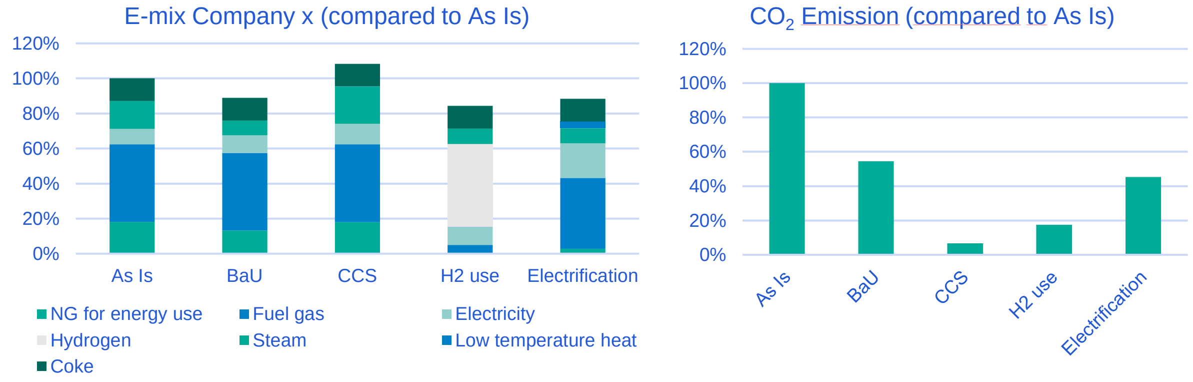

*Figure 12: Illustration of the energy-mix (left-hand side) and CO2 emission per strategy (right-hand side) for some company x.*

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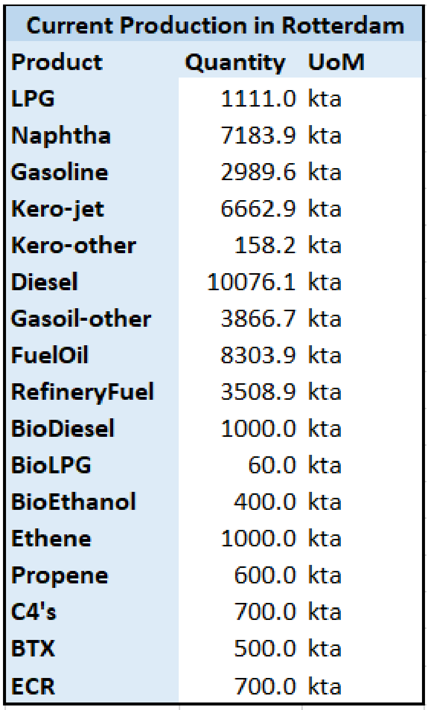
[3] Available at https://www.deltalinqs.nl/stream/rapportageenergiemixstudie.

*Industrial feedstock demand*

The previous subsection presents the modelling approach to assess the vital role that hydrogen may play in decarbonizing the energy-mix in the Port of Rotterdam. Hydrogen in combination with circular carbon may also be deployed as syngas feedstock to produce synthetic fuels and base chemicals that serve as feedstock to other industry. Therefore, a synfuel module has been developed as part of the Port of Rotterdam model. In contrast to the industrial energy strategies, it involves a greenfield approach.

Figure 13 presents the current production of both fuels and base chemicals, based on the incorporation of four of the five refineries of Rotterdam in the E-mix data. This production is the baseline situation for the synfuel routes. The topology for the possible synfuel routes consists of the following six building blocks (see also Figure 14):



| Current Production in Rotterdam | | |
|---|---|---|
| **Product** | **Quantity** | **UoM** |
| **LPG** | 1111.0 | kta |
| **Naphtha** | 7183.9 | kta |
| **Gasoline** | 2989.6 | kta |
| **Kero-jet** | 6662.9 | kta |
| **Kero-other** | 158.2 | kta |
| **Diesel** | 10076.1 | kta |
| **Gasoil-other** | 3866.7 | kta |
| **FuelOil** | 8303.9 | kta |
| **RefineryFuel** | 3508.9 | kta |
| **BioDiesel** | 1000.0 | kta |
| **BioLPG** | 60.0 | kta |
| **BioEthanol** | 400.0 | kta |
| **Ethene** | 1000.0 | kta |
| **Propene** | 600.0 | kta |
| **C4's** | 700.0 | kta |
| **BTX** | 500.0 | kta |
| **ECR** | 700.0 | kta |

*Figure 13: Current production of base chemicals in the Port of Rotterdam regional model (source: CBS data and TNO MIDDEN report)*

- Refineries: production of RFG (Refinery Fuel Gas for H2 production)
- H2 Manufacturing: production of H2 via electrolysis in the conversion park, H-vision, NH3 cracking and LOHC(Liquid Organic Hydrogen Carriers) reconversion
- Bio-refinery: production of bio kerosine, renewable diesel, renewable LPG and CO2
- CO2 capture: production of CO2 via Direct Air Capture (DAC), industrial CCS and CO2 imports
- Syngas-park: production of green methanol, synthetic naphtha, LPG, Kero and Marine fuel via syngas (CO-H2)
- Sustainable Base Chemicals Complex: production of green ethene and propene via synthetic naphtha, LPG and green methanol imports.

In the model demand profiles can be defined for the synthetic fuels and green base chemicals, based on projections of how the fuel/chemical market and policies will develop. Given the optionality in the synfuel routes, the model can optimize the investment portfolio to satisfy the demand. Combined with the growth in synthetic fuel demand, also the decline in the current fuel market can be specified. Refineries in the Port of Rotterdam and Shell Moerdijk can scale down to be aligned with this decreasing demand. Via this synfuel route option space, the hydrogen demand (and CO and CO2 demand) for synthetic fuels and green base chemicals will be an output of the model.

Other regional hydrogen demand in the Rotterdam Port area, such as for mobility, shipping, etc, that is outside the modelling scope of industry, is quantified based on the II3050 scenarios, classified by the same categories as in the National Supply Model.

Note that the II3050 scenarios also contain the categories on electricity production, industry and synfuels. However, due the explicit modelling of the industrial companies, the electricity producers and the synfuel options space, this hydrogen demand not used from II3050 but generated by the model.

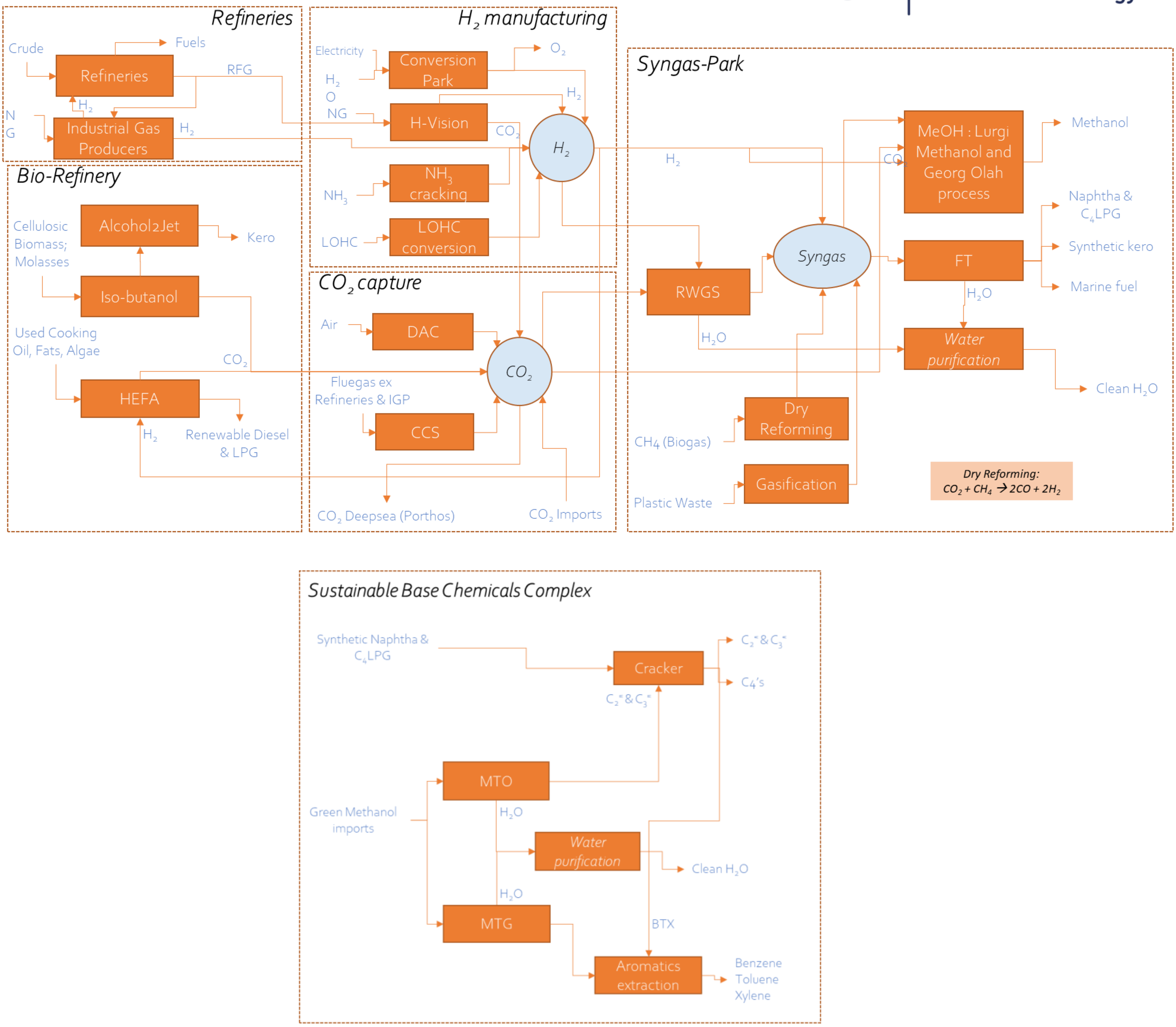


*Figure 14: Topology for the possible synfuel routes as covered in the Port of Rotterdam Regional Model*

### *Power production*

Fourteen electricity producers in the Port of Rotterdam are included in the model. An overview of all modelled electricity producers covered in the model is presented in Figure 15. Data on power, current production and CO2 emission was compiled by team analysis, based on KEV data and NEA data. The electricity producers can switch off their production to reduce CO2 and do have one explicit decarbonization option in the model: adding hydrogen to the feed. Other decarbonization options, such as CCS, are not (yet) included in the Port of Rotterdam model.

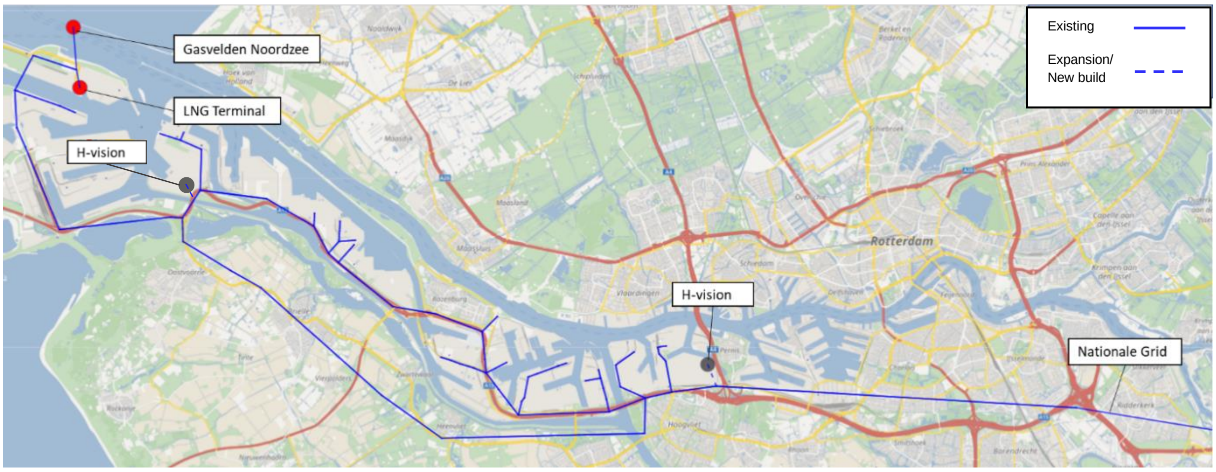
In the Port of Rotterdam model regional interdependencies are incorporated, covering the four main commodities natural gas, hydrogen, electricity, and CO2.

| Producent | Centrale | Plaats | TEACOS Name |
|---|---|---|---|
| Uniper | Centrale Maasvlakte | Rotterdam (Maasvlakte) | E01 |
| Onyx Power | Onyx Power | Rotterdam (Maasvlakte) | E02 |
| Uniper | Maasvlakte UCML | Rotterdam (Maasvlakte) | E03 |
| Uniper | Centrale RoCa | Rotterdam | E04 |
| Uniper | Centrale RoCa | Rotterdam | E05 |
| Uniper | Centrale RoCa | Rotterdam | E06 |
| Eneco/Castleton Commodities International | Enecogen | Rotterdam (Europoort) | E07 |
| Eneco/Castleton Commodities International | Enecogen | Rotterdam (Europoort) | E08 |
| Rijnmond Power Holding | Rijnmond Energie | Rotterdam (Vondelingenplaat) | E09 |
| Air Liquide | PerGen | Rotterdam (Botlek) | E10 |
| Air Liquide/Eneco | EuroGen | Rotterdam (Botlek) | E11 |
| Castleton Commodities International | Maasstroom Energie | Rotterdam (Vondelingenplaat) | E12 |
| Europoort Utility Partners | Europoort Utility Partners | Rotterdam (Europoort) | E13 |
| Afvalverwerking Rijnmond | AVR Rozenburg | Rozenburg | E14 |

*Figure 15: Power assets included in the Port of Rotterdam regional model.*

### *Infrastructure*

In Figure 16 we show the gas infrastructure as included in the model. Three potential import options are included for Natural Gas: National Grid, LNG import and production via the North Sea. Industry, electricity producers and possible locations for H-vision[4] are potential consumers of natural gas. Capacities of the existing network are included per segment in the model, considering the number of pipes per segment and the diameter of each pipe.



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[4] The H-vision consortium develops routes to convert residual gases (refinery gases) into low-carbon hydrogen for heating. The HyChain study assumes central processing, but practice is under development and will be different. More information here: www.h-vision.nl.

*Figure 16: Network topology for natural gas in the Port of Rotterdam regional model.*

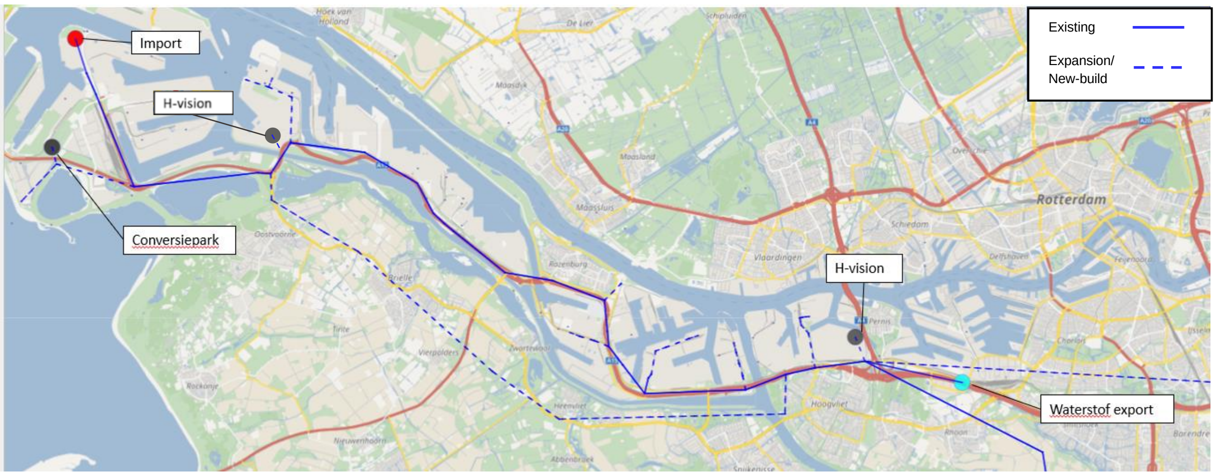

*Figure 17: Network topology (both existing and potential new build) for hydrogen in the Port of Rotterdam regional model.*

Figure 17 shows the hydrogen infrastructure of the model. Three potential supply points for hydrogen are included: import of hydrogen, production of hydrogen via electrolysis (PEM/Alkaline) in the conversion park and H-vision[5]. Industry and electricity producers are potential consumers of hydrogen. In the model multiple types of pipelines with different diameters are included as investment options, each with their own cost per kilometre. Both newly built pipelines and reconversion of gas pipelines is possible. Capacities of the existing network are included per segment in the model.

Multiple supply options of electricity are included: electricity production via the fourteen modelled electricity producers in Rotterdam, electricity from offshore wind parks (Hollandse Kust Zuid, IJmuiden Ver and potential expansions based on VAWOZ) and import from national grid, see also Figure 18. Consumers of electricity are industrial companies, H-vision, and the electrolysis units in the Conversion Park. Capacities of the electricity network are currently not included in the model, due to its complexity and a lack of data. The goal of the electricity network in the model is to show how the use develops over time.

For the CO2 infrastructure the model is aligned with the Porthos and Aramis initiatives. In the Port of Rotterdam area there is an existing connection to OCAP/Linde, see also Figure 19.

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[5] The hydrogen infrastructure of H-vision was not modelled explicitly during the HyChain project. This has no influence on the results of the scenario analysis.

*Figure 18: Network topology for electricity in the Port of Rotterdam regional model.*

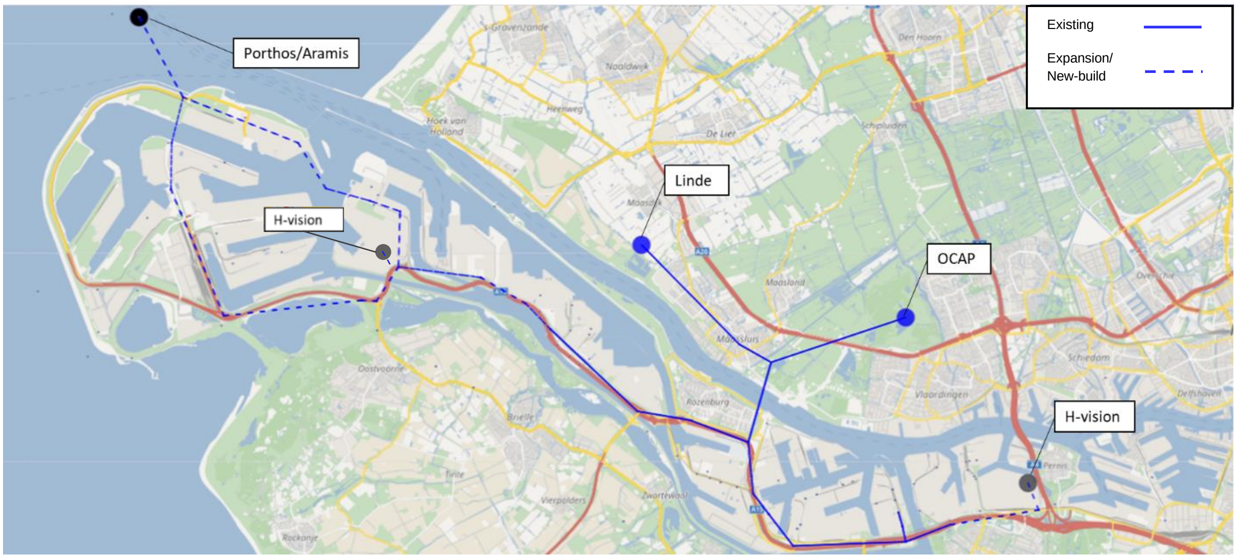


*Figure 19: Network topology (both existing and potential new build) for CO2 in the Port of Rotterdam regional model.*

Producers of pure CO2 are the industry, electricity producers and H-vision. OCAP/Linde are consumers of pure CO2 and the Porthos/Aramis initiatives are able to store CO2 in gas fields in the North Sea.

## Interaction concept National and Regional Models

In the HyChain project a prototype for the interaction between the national and regional models was developed. Though module was implemented, it was not fully tested in the case analysis as the analysis focussed on regional aspects. The overview in Figure 20 describes the interaction module between the national and regional models. A common price set is key for a proper interaction between the models. From the national model the make/buy strategy for hydrogen is generated for each of the industrial clusters in the Netherlands. From this strategy a hydrogen levelized cost merit order curve and import/export profile based on HyChain2 is determined for each cluster and used as input in the regional models. With this input the transition pathways in the Port of Rotterdam and the South-West of the Netherlands are calculated.

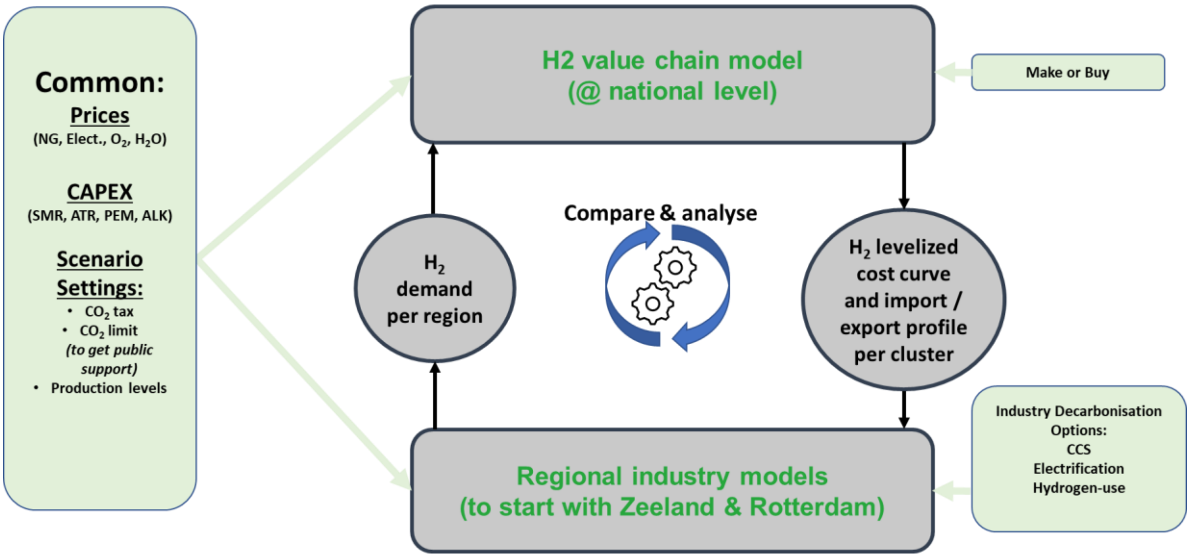


*Figure 20: Interaction module between the national and regional models*

The corresponding hydrogen demand/export for these regions is then checked with the profile generated by the National Supply Model. In case they are the same the system has converged. If not the regional profile (with calculated merit order cost profiles) is given back as input boundary conditions to the national model. The national model will then regenerate regional(cluster) import/export profiles + levelized cost merit order curve. These steps can be executed iteratively until convergence is reached.

## Conclusions

With the HyChain Model an integrated investment optimization model for the hydrogen supply chain for the Dutch industry was developed, in context of alternative decarbonization pathways via direct electrification and CCS as well as associated infrastructure. The model was developed for the Netherlands and two large Dutch industrial clusters, with full coverage of hydrogen and electricity supply chains at national-, regional- and site-level. The model allows for long-term optimal investment modelling of system decarbonisation over the course of the energy transition, presenting optimal multi-stakeholder investments across energy supply, infrastructure and industrial demand on a year-by-year basis.

# Multi-stakeholder Case Analysis

## Introduction

With the models of the HyChain4 project various case studies have been carried out to show how the models give insights in the development of use of hydrogen and in support of coordinated decision making in industrial transformation. The cases explore interdependencies that require multi-stakeholder decision making and show no-regret/robust hydrogen supply chain investments. For this exercise a multi-stakeholder analysis was performed with the project partners in two plenary workshops; we first carried out a case-definition and scoping workshop and a after that a case analysis workshop was done.

The scoping workshop covered a walk-through of the models along with a series of illustrative model results from current base scenario settings and a series of variations of scenario settings (energy price projections, CO2 emission reduction caps per cluster vs. caps per company, electrolyser development limited by green electricity development, and impact of delays in high-voltage infrastructure development) was presented as a starting point for discussion on scenario variations to be assessed for the following workshop on case analysis. In the final stage of the workshop cases for the case analysis were selected:

- Case 1: Accelerated GHG Emission Reduction (both PoR and SWNL)
- Case 2: Promotion of Green Hydrogen Production (SWNL only)
- Case 3: Potential for Hydrogen as Feedstock (PoR only)
- Case 4: CCS Phase-Out (both PoR and SWNL)
- Case 5: Delayed Regional Power Grid Reinforcement (PoR only)

Each of the selected cases was analysed in detail and runs were presented in the case analysis workshop for plenary discussion. Based on comments and input from the workshop a refinement was done and clarification was given. The main results are presented and discussed in this chapter. This chapter is structured by regional analysis, starting with the reference case for the region at hand, and followed by the presentation of the case results. The chapter is closed off with a concluding section.

## Baseline Reference Cases – Assumptions and Results

This section presents the Reference Case assumptions regarding GHG emission policy and commodity pricing. It then shows how these baseline scenarios display in the main results as Reference Case for the two industrial clusters. The results are collected in a dashboard that is used as the standard format to present all results throughout this section.

### GHG Emission Reduction Policy Assumptions

The GHG emission reduction targets for industry assumed in the Reference Case and case analysis are based on current policies. The EU Climate Law adopted on 24 June 2021 imposes a legally binding GHG emission reduction target of 55% with respect to GHG emissions in 1990, while for 2050 a net-zero GHG emissions target is imposed for 2050. For the latter, we assume a 100% reduction for industry. The CO2 in scope consist of end-of-pipe emissions (industry and power), i.e. the so-called Scope 1 emissions. Scope 2 emissions, relating to emissions resulting from the electricity deployed for industrial electrification are not considered. Scope 3 emissions, i.e. emissions relating to deployment of industrial products are only considered in terms of cost-driven (not cap-driven) deployment of renewable feedstock. The targets are imposed as a (back-stop) emission cap in the case analysis, while ETS cost of GHG emissions may drive emissions to levels below the target.

## Commodity Price Assumptions

Price assumptions for the future prices of commodities have a significant impact on the optimal investment decisions as assessed with the HyChain Model. Commodity prices are based on price assumptions for relevant markets or market segments. These are not explicitly modelled but provided as input scenarios. They cover natural gas markets, foreign electricity markets, the market for green electricity and the market for European emission allowances as established by the EU Emissions Trading System.

### *Natural gas price assumptions*

Price assumptions for natural gas in the case analysis are based on the World Energy Outlook (WEO) 2022 (International Energy Agency, 2022). While the European natural gas prices were on the rise in 2021 due to relatively low volumes in the European storages followed and spiked in 2022 due to the situation in the Ukraine, the WEO projects that the European natural gas prices will gradually decline to more moderate levels in future years as international LNG supplies replace the former Russian supplies.

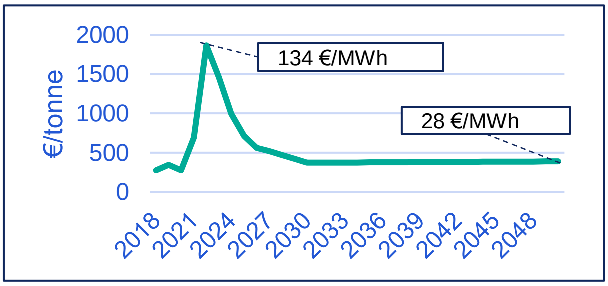


*Figure 21: Natural gas price profile.*

### *Electricity import price assumptions*

Price assumptions for electricity prices in this analysis are based on energy market simulations with TNO's I-ELGAS model, matching the aforementioned natural gas price development. Import prices for electricity in this case decline from last year's highs to a level of around 50 €/MWh.

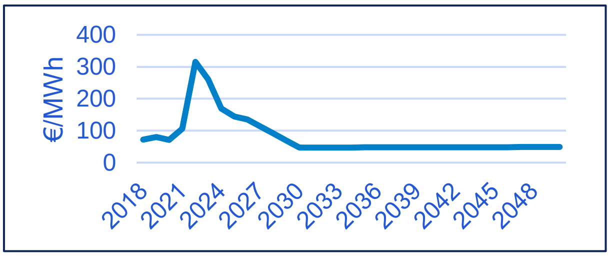


*Figure 22: Electricity import price profile.*

### *Green electricity price assumptions*

Price assumptions for green electricity are based on declining Levelized Cost Of Electricity (LCOE) for green electricity production, driven by learning curves for renewable electricity technologies.

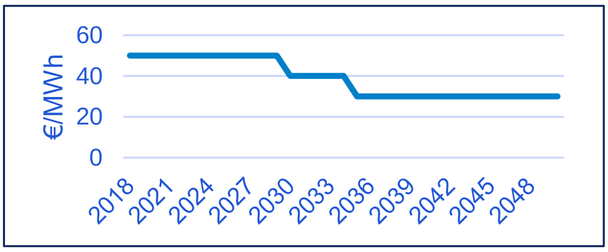


*Figure 23: Green electricity profile.*

### *Hydrogen import prices*

Price assumptions are based on the declining price levels based on declining cost of import as assessed in the HyChain2 project and TNO studies and accounted for in the HyChain Model.

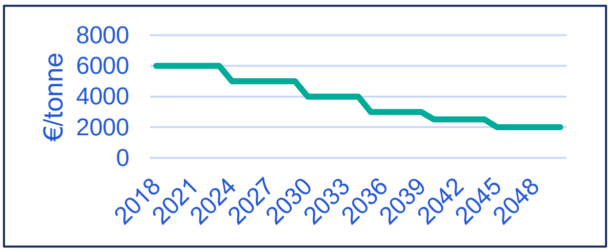


*Figure 24: Hydrogen import price profile.*

### *EU ETS prices*

The EU ETS prices are based on the price scenario for advanced economies in the Net Zero Report (International Energy Agency, 2021), reaching up to some 250 €/tonne by 2050.

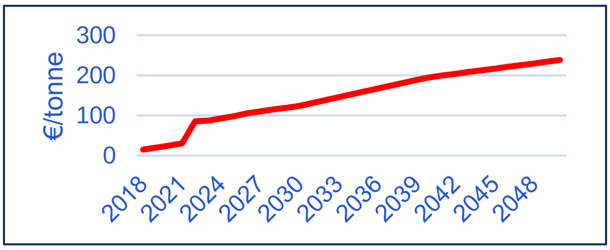


*Figure 25: EU ETS price profile.*

## Reference Case for the South-West Netherlands region

For SWNL, investments in decarbonization options are included at site level for the industries, distinguishing between hydrogen-use, electrification, and CCS. Constant production profiles are assumed for the companies. Based on the II3050 National Direction Scenario an additional hydrogen demand is included predominantly based on synfuels production, reaching up to 960 kt/a by 2050. Figure 26 indicates the evolving development of hydrogen demand. Local production and (regional) import of green electricity and hydrogen are potential sources for these commodities.

In the Reference Scenario a CO2 emission reduction of 55% in 2030 and 100% in 2050 is assumed with respect to base year 1990.No public information on regional CO2 emission data for SWNL in 1990 was retrieved. Therefore, a scaling from national 2019 industrial GHG-emissions is applied: this means a 35% reduction relative to 2019 needs to be achieved to reach 55% reduction compared to the reference year 1990.

The main results for the Reference Case for this region are presented in the dashboard in Figure 27, covering KPI's (Key Performance Indicators), investments and installed capacity, CO2 emissions and key observations. As may be observed from the figure on CO2 emissions, the regional industry is well able to reduce its emissions within the limits of the GHG emission cap, with a reduction of more than 90% already by 2030. The emission reduction is largely driven by CO2 emission costs, as the emission cap kicks in only by the end of the evaluation period in 2049. Most emission reductions are attained in 2025-2035, through large investment in predominantly CCS and ATR for H2 supply (i.e., blue hydrogen), and several smaller investments in electrification (electric cracked-gas and refrigerant compressors, indicated Elec_Compr and Elec_RC respectively). In 2035-2048 green hydrogen deployment increases, driven by the (II3050 input scenario based) hydrogen demand for synfuel production, and the limitations of the CCS system. In the final stages of the evaluation period, full CO2 emission reduction is achieved in 2050 by introduction of electric furnaces that render to be preferred over H2-fired furnaces based on the NPV. In this stage 380KV network investments are required to assure supply of electricity. In these final stages, some additional ATR investments are required to source the increasing hydrogen demand (Figure 26) as well. As electric cracking is introduced in those years as well, CCS capacity becomes available for the additional ATR capacity and no additional investments in CCS capacity are required. Security of supply challenges largely shift from natural gas and electricity to electricity only, as no hydrogen is imported in the Reference Case.

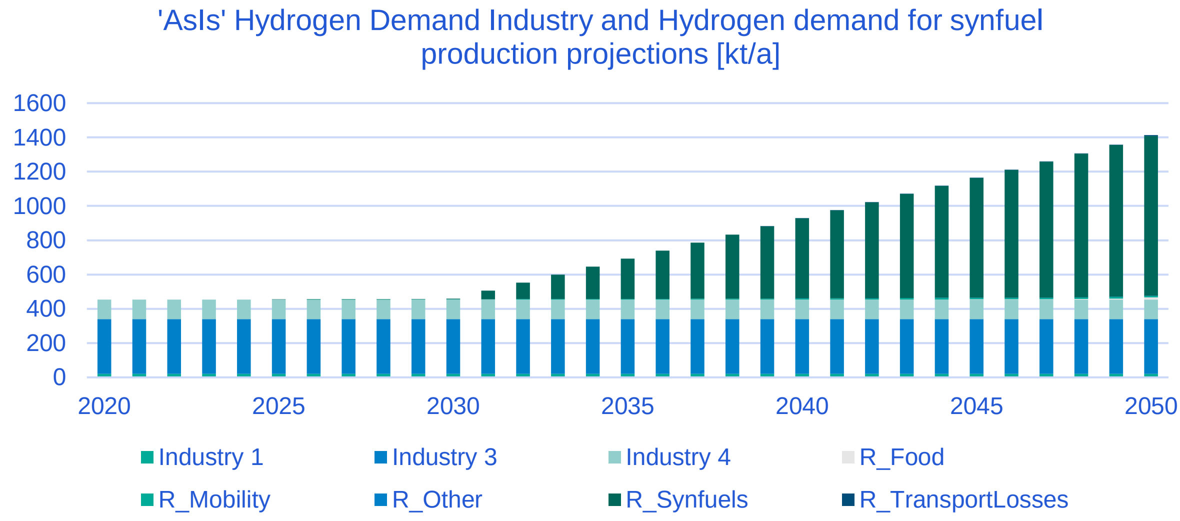
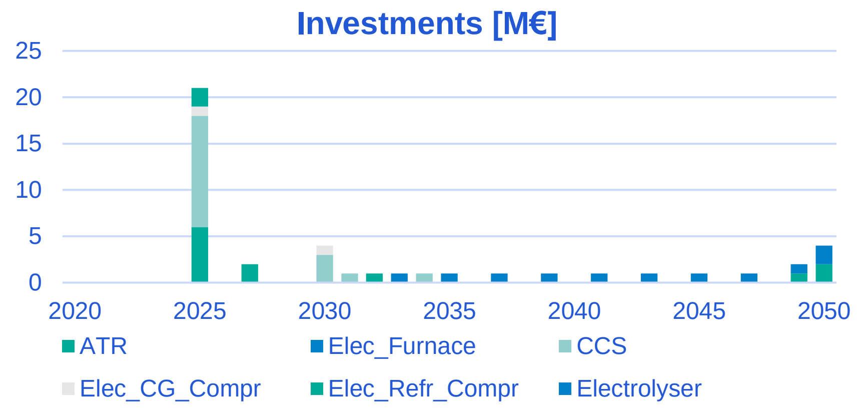


*Figure 26: Hydrogen demand 'As Is' and 'SynFuels' in the Reference Case for the South-West Netherlands region.*

| **KPI's** | | |
|---|---|---|
| NPV of the gross Margin | | 20881 M€ |
| | **2030** | **2050** |
| $H_2$ Production [kt/a] | 466 | 1413 |
| $H_2$ Import [kt/a] | 0 | 0 |
| Electricity Production [GWh/a] | 5524 | 25427 |
| Electricity Import [GWh/a] | 4893 | 33790 |
| CO2 emission [kt/a] | 794 | 0 |



**Key Observations**

**CO2 emission reduction** is largely driven by CO2 emission costs, as the emission cap kicks in only by the end of the evaluation period in 2049.

- Most emission reductions attained in 2025-2035 through large investment in predominantly CCS, ATR for H2 supply, and smaller investments in electrification (electric cracked-gas & refrigerant compressors, indicated in the figure on investments as Elec_CG_Compr and Elec_Refr_Compr respectively).
- Additional emission reductions are attained in 2035-2048 increasing hydrogen deployment from newly installed electrolyser capacity in response to the growing availability of green electricity in the II3050 National Direction Scenario
- Zero CO2 emission in 2050 is achieved by electric furnaces (preferred over H2), along with required 380KV network investments and additional ATR investments.

**Security of supply** challenges largely shift from natural gas and electricity to electricity only. No Hydrogen is imported.

**Installed capacity by 2050**

- 720 kt H2/a ATR capacity installed
- 1700 kt CO2/a CCS capacity installed
- 1120 GWh/a electric Cracked-Gas compressors (Elec_CG_Compr) and refrigerant compressors (Elec_Refr_Compr) capacity installed
- 800 kt/a Electrolyser capacity installed
- 380kV network (in 2049)

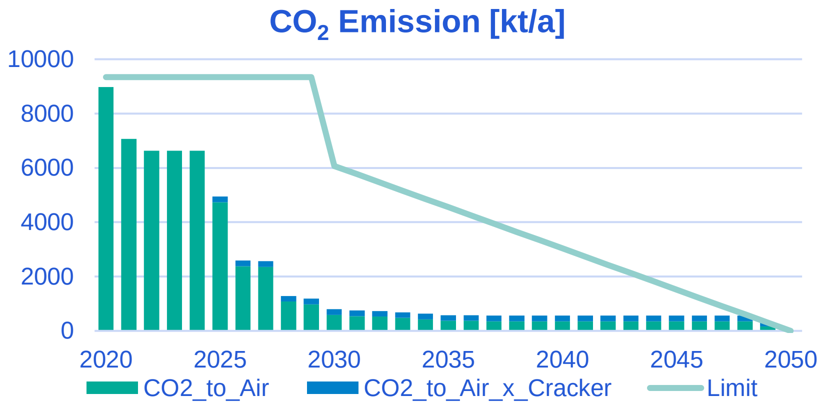


*Figure 27: Overview of the main results for the Reference Case for the South-West Netherlands Region.*

## Reference Case for the Port of Rotterdam region

As described in the previous chapter, Section on Port of Rotterdam Regional Model, 36 companies are included on site level. Company information was based on the E-mix data for 35 companies, while data for Shell Moerdijk is included as additional company with E-mix data based on inhouse expertise and team analysis. For industrial companies, constant production profiles are assumed. In addition, 14 electricity producers in the Port of Rotterdam are included. The electricity producers can switch off their production to reduce CO2 and do have one additional explicit decarbonization option in the model by form of adding hydrogen to the feed. Other decarbonization options for the power sector, such as CCS, are not (yet) included in the Port of Rotterdam model. The data cover approximately 98% of industry CO2 emissions in Rotterdam. A CO2 emission reduction of 55% in 2030 and 100% in 2050 with reference year 1990 is assumed, in line with Fit-for-55.

In this E-mix data, five strategies per company are included, all with their own energy-mix, potential CAPEX and CO2 emission:

- The *As Is* Strategy, which corresponds to the current E-mix of a company
- The *Business as Usual* or BaU Strategy (2030 plan[6]
- The *CCS Strategy* (available from 2031 onwards)
- The *Hydrogen Strategy* (available from 2031 onwards)
- The *Electrification Strategy* (available from 2031 onwards)

Further, current initiatives are incorporated in the model as reported in the CES 2.0 - *Cluster Energy Strategie Industriecluster Rotterdam-Moerdijk*[7] (Port of Rotterdam, 2022):

- Hydrogen network Rotterdam
- Porthos onshore backbone
- Aramis
- H-vision
- Conversionpark (Electrolysis)

Other hydrogen demand in the region is included, based on II3050 National Direction Scenario. Production of synfuels/green base chemicals is not enforced, as costs will drive the production. CO2 sourcing for synfuel production is based on either biogenic CO2 (HEFA/IsoButanol) or CO2 via DAC.

The first model run resulted in infeasibility as the E-mix assumptions as a starting point did not allow a 100% reduction by 2050. The reason for this is that for some companies all strategy options have remaining CO2 emissions in 2050, which implicates that a 100% reduction cannot be achieved, (given the assumption of the same production in the future). Though this is already an interesting finding, the case run was repeated with slight relief of the CO2 emission target for 2050 to 90% to allow further analysis of the Reference Case.

The main results for this Reference Case with 90% emission reduction by 2050 are presented in Figure 28, KPI's, investments, industrial CO2 emissions and key observations.[8] In case of the PoR analysis, and in contrast to the SWNL case analysis, investments are presented as strategies of companies over time in view of confidentiality of underlying data. The strategies of companies over time, indicated in the top right figure, are presented as strategy (2030Plan, CCS, Electrification, Hydrogen) presented as contributing to the percentage emission reduction of total initial GHG. If company x accounts for 20% of the initial emission in Rotterdam and this company chooses CCS as option 2030, 20% will be CCS in the graph from 2030 onwards.

As was the case in SWNL Reference Case, CO2 emission reduction turns out to be largely driven by CO2 emission costs, as CO2 price drives CO2 emission reduction in Rotterdam below the target of 55% in 2030. No production of synfuels/green base chemicals emerges in de Reference Case, as the associated costs do not justify investment.

The emission reduction strategy follows the imposed BaU Strategy until 2031, except for the refineries. In case of the refineries a hydrogen strategy is applied with the H-vision initiative. A large additional CO2 emission reduction is achieved from 2031 onwards though investment in CCS, blue H2 and

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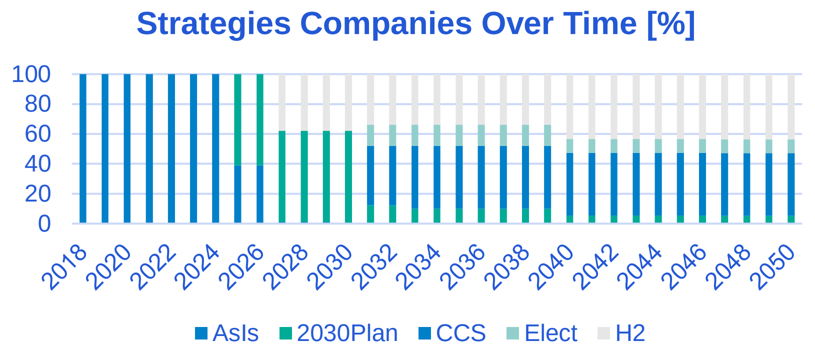
[6] The BaU includes decarbonization options (energy efficiency improvements, CCS) that are considered feasible before 2030. See also (Port of Rotterdam, Stedin, Deltalinqs, 2022): "BAU represents the relatively simple measures companies could take in the next 5-10 years. Examples are energy savings and, in some cases, additionally, for example, capture of existing CO2 flows, the use of e-boilers or heat pumps and/or CCS."

[7] Available at https://www.portofmoerdijk.nl/media/2375/cluster-energie-strategie-rotterdam-moerdijk-2022.pdf

[8] The NPV calculation covers supply costs for all imported products, CAPEX, fixed OPEX, as well as revenues based on sales price for refinery products and base chemicals (as sales for other companies are not covered within the model). Due to this limited incorporation of revenue streams, NPV's of the complete Rotterdam system will be negative.

| KPI's | | |
|---|---|---|
| NPV of the gross Margin | | -4339 M€ |
| | 2030 | 2050 |
| $H_2$ Production [kt/a] | 379 | 374 |
| $H_2$ Import [kt/a] | 0 | 147 |
| Electricity Production [GWh/a] | 30410 | 30410 |
| Electricity Import [GWh/a] | 0 | 3496 |



**Key Observations**

**CO2 emission reduction** is largely driven by CO2 emission costs, as CO2 price drives CO2 emission reduction in Rotterdam below the target of 55% in 2030.

- Until 2031 the strategy follows the BaU Strategy as imposed, with the exception of the refineries (hydrogen strategy in combination with H-vision initiative)
- A large additional CO2 emission reduction step in 2031 is caused by investment in CCS, blue H2 and electrification.
- The Hydrogen Strategy and CCS Strategy are the dominant strategies in the Reference Case after 2030.

**Security of supply** challenges largely shift from natural gas and electricity to hydrogen and electricity.

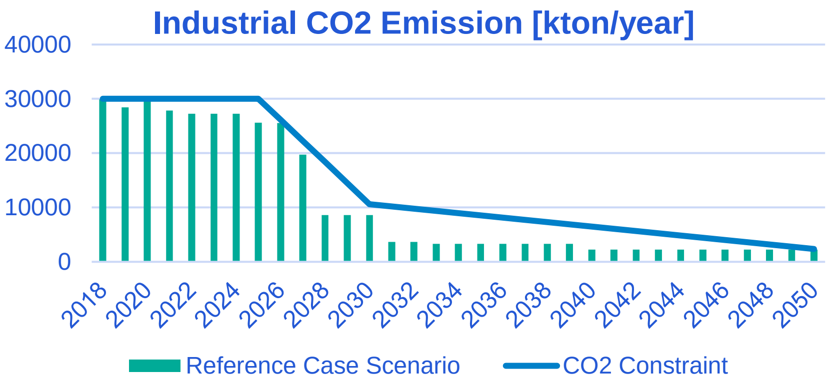


*Figure 28: Overview of the main results for the Reference Case for the Port of Rotterdam Region*

electrification. In this case no regional production of green hydrogen develops, driven by the more attractive business case of blue hydrogen via H-vision. Moderate levels of regional green hydrogen imports occur after 2040 instead. The Hydrogen Strategy and CCS Strategy are the dominant strategies in the Reference Case after 2030. Accordingly, security of supply challenges largely shifts from natural gas and electricity to hydrogen and electricity.

## Case Analysis

In this section the assessed cases covered in this case analysis will be introduced one by one. Each case report is introduced by a brief case description followed by the case results and conclusions.

### Case 1: Accelerated GHG Emission Reduction (both PoR and SWNL)

The regional models have been geared to cover Cluster Energie Strategies 2022 (CES 2.0) to support development of the Strategies as published by SDR and Port of Rotterdam respectively. The Cluster Energie Strategies cover the outlook for industrial decarbonisation pathways at cluster level to establish infrastructural requirements. The strategies account for GHG emission reduction policies and policy goals such as the emission reduction target for 2030 and 2050 for industry. Developments in recent years gave rise to acceleration in system decarbonization, with enhanced EU target of 55% GHG emission reduction, the far-reaching fit-for-55 package and frontloading of climate policy measures in the REpowerEU plan as proposed by the European Commission. During the scoping session, an accelerated GHG emission reduction scenario was proposed, to assess impacts of GHG emission reduction.

*Case Description*

Compared to the Reference Case accelerated CO2-emission reduction is imposed. The acceleration in this case analysis: advance the 55% GHG emission reduction target from 2030 to 2027 (see Figure 29).

- What is the impact of strong acceleration of CO2 emission reduction?
- What is the role of hydrogen under accelerated GHG emission reduction
- What are the costs involved?

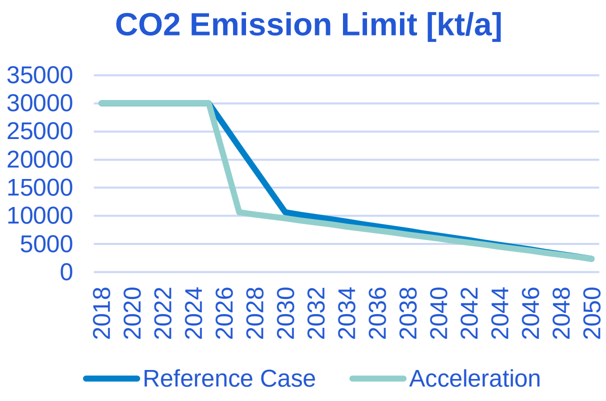


*Figure 29: Implementation of accelerated CO2-emission reduction limit.*

*Case Results for the South-West Netherlands Region*

The adjustment in CO2 target does not influence the investment profile of South-West Netherlands region as the Reference Case already achieves the 2027 accelerated target in 2025 (see Figure 28).

*Case Results for the Port of Rotterdam Region*

In case of the Port of Rotterdam region, the Reference Case assumes that Industry follows the BaU Strategy (2030 plan), so industrial decarbonization remains unaffected by the adjusted CO2 emission limit for the region and strategies of industrial companies do not change. A significant proportion of the CO2 emissions stems from electricity production however, so that accelerated CO2 emission reduction in comparison to the reference case results in this segment. To reach the CO2 emission reduction target in 2027, the current (gas-fired, coal-fired) electricity producers in Rotterdam reduce their production (see Figure 30), and regional electricity imports from the grid or via offshore wind parks increases 3 years earlier than in the Reference Case. Of course, green electricity from grid should be available (approximately 30 TWh by 2027). Accelerated GHG emission reduction further brings forth a cost of 143 M€ discounted.

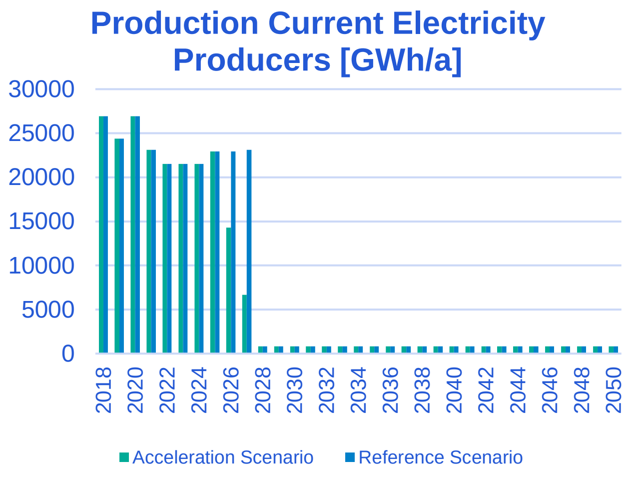


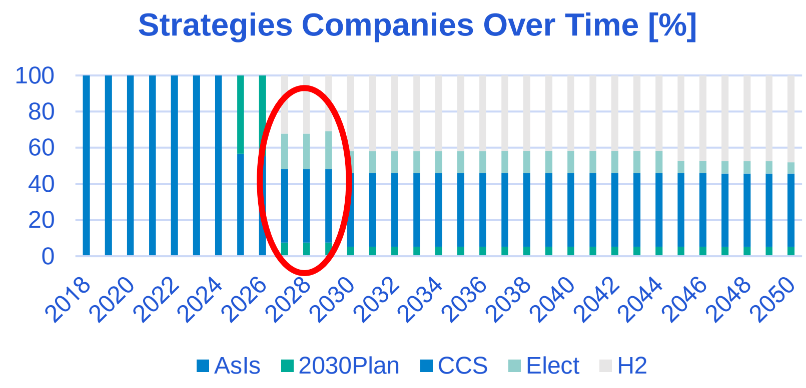
*Figure 30: Decline of electricity production in Case 1 in the Port of Rotterdam region.*

In the Reference Case for the Port of Rotterdam Region, the BaU Strategy (2030 plan) for industrial decarbonization is imposed until 2031. If this restriction is relieved to apply until 2027 only, industrial investments respond to the case assumptions of accelerated CO2 emission reduction as driven by the adjusted regional CO2 emission limit as well.

In that case (see also Figure 31), CO2 emission reduction is accelerated. As in the Reference Case, CO2 price drives CO2 emission reduction well below the 2030 target of 55% several years early and virtually reaches the 2050 target of 90% by 2030. Until 2027 the BaU Strategy is imposed. The main CO2 emission reduction step occurs in the following year, as investments in CCS, H2 and electrification are implemented from 2027 onwards, while the strategy virtually follows the Reference Case strategy from 2030 onwards. Hence, the main divergence from the Reference Case occurs in the years 2027-2030 as indicated by the red circle in the graph on investment strategies in Figure 31.

Under the assumptions applied, accelerating GHG emission reduction generates a positive margin of 221 MEUR compared to the Reference Case: notably some of the strategies (CCS, H2, Electrification) are found to be economically viable for CO2 prices above 100-110 €/tonne while this price level is already reached by 2027 in this case analysis (see also Figure 25). Security of supply challenges largely shift from natural gas and electricity to hydrogen and electricity, as in the Reference Case. Hydrogen imports are required by 2050 according to this case analysis, but only to limited extent.

| **KPI's** | | |
|---|---|---|
| Delta NPV of the Gross Margin (vs Reference Case [%]) | | +5.1% (221 M€) |
| | **2030** | **2050** |
| $H_2$ Production [kt/a] | 392 (379) | 320 (374) |
| $H_2$ Import [kt/a] | 0 (0) | 105 (147) |
| Electricity Production [GWh/a] | 30410 (30410) | 30410 (30410) |
| Electricity Import [GWh/a] | 3460 (0) | 3558 (3496) |



**Key Observations**

**CO2 emission reduction** is accelerated, as the CO2 price drives CO2 emission reduction below the target of 55% in 2030.

- Until 2027 the strategy follows the BaU Strategy as imposed.
- In 2027 main CO2 emission reduction (2031 in Reference Case), as alternatives become available. Blue Hydrogen Strategy and CCS Strategy are the dominant strategies from 2027 onward.
- After 2031 the strategy virtually follows the Reference Case strategy.
- Accelerating GHG emission reduction generates a positive margin of 221 MEUR compared to the Reference

**Security of supply** challenges largely shift from natural gas and electricity to hydrogen and electricity, as in the Reference Case.

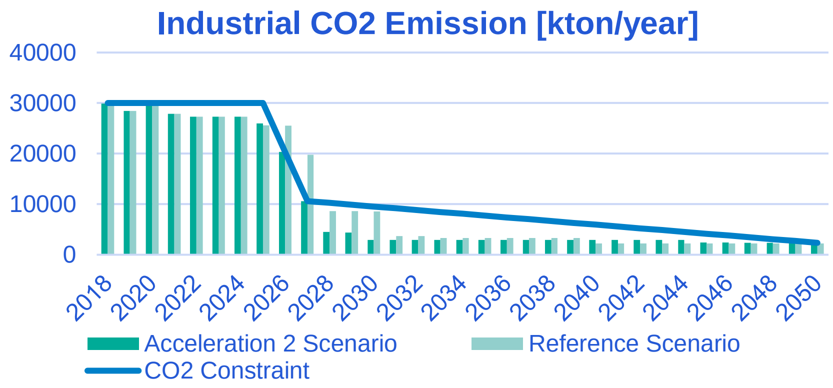


*Figure 31: Overview of the main results for the Accelerated GHG Emission Reduction Case in the Port of Rotterdam Region.*

### *Reflection & Conclusions*

As in the Reference Case, the 55% GHG emission reduction target for 2030 is achieved well before 2030, while the 90% target for 2050 is virtually met from 2030 onward. While the Accelerated GHG Emission Reduction Case leaves the South-West Netherlands region largely unaffected, it accelerates the transgression from the BaU strategy in Port of Rotterdam area to alternative strategies as covered by the model from 2031 to 2027. Hence, the main divergences from the strategies in the Reference case occur between 2027 – 2030, as indicated by the red circle in Figure 31.

## Case 2: Promotion of Green Hydrogen Production (SWNL region only)

Many consider blue hydrogen as route for acceleration of hydrogen system development at scale, while green hydrogen offers a long-term perspective on system decarbonization. Fit-for-55 proposes strong energy policy interventions to promote green hydrogen production, with a proposal for an industrial green hydrogen obligation (42% in 2030 and 60% in 2035) and the REpowerEU plan targets a strong hike in climate policy by frontloading green hydrogen system development while seeking to replace Russian natural gas supplies. Availability of renewable electricity may then become a concern.

### *Case Description*

Variation regarding Reference Case: enforced promotion of electrolysers in Delta region. The enforced electrolyser installation rate scales with maximum availability of renewable electricity and availability of the required regional import infrastructure (capacity of the 380kV network) while investment in infrastructure is enforced by 2032 as well.

- What is the impact of promotion of green hydrogen production on the investment portfolio?
- What does it imply for the balance between blue and green hydrogen?
- What are the costs involved?

### *Case Results for the South-West Netherlands Region*

The dashboard for this case analysis is presented in Figure 32. As before, CO2 emission reduction is largely driven by CO2 emission costs, as the emission cap kicks in only by the end of the evaluation period in 2047. Most emission reductions attained in 2025-2030 as in Reference Case, though significantly lower emission reductions are achieved with emissions in 2030 remaining twice as high. Investment levels in predominantly CCS and ATR for H2 supply are lower as well, as might be expected in anticipation of future investments in enforced electrolyser capacity for the case. Investments in electrification (electric cracked-gas and refrigerant compressors, indicated as Elec_Compr and Elec_RC respectively) are comparable to the Reference Case. Additional emission reductions are attained in 2035-2048, increasing hydrogen deployment from newly installed electrolyser capacity. Green hydrogen deployment increases after 2030 and notably between 2035 – 2040. In the early years SMRs and ATR are still economically more attractive. Electrolysers are selected because reduction of use of SMRs and limiting new ATRs is imposed. Note that subsidies for green $H_2$ are not included. After 2035, electricity imports hike significantly, with 30% more imports in comparison to the reference case in 2050. Zero CO2 emission is achieved in the latest stage before 2050 through investment in electric furnaces that is preferred over H2 as fuel (as in the Reference Case), along with investments in CCS. The ATR investments that occurred at late stage in the Reference Case, are not needed as they were preceded by the enforced electrolyser investments. The NPV declines by 5.9%, as the enforced electrolyser investment renders higher cost levels and pushes the result away from optimal investments as attained in the Reference Case. Security of supply challenges largely shift from natural gas and electricity to electricity only, as no hydrogen is imported in this analysis.

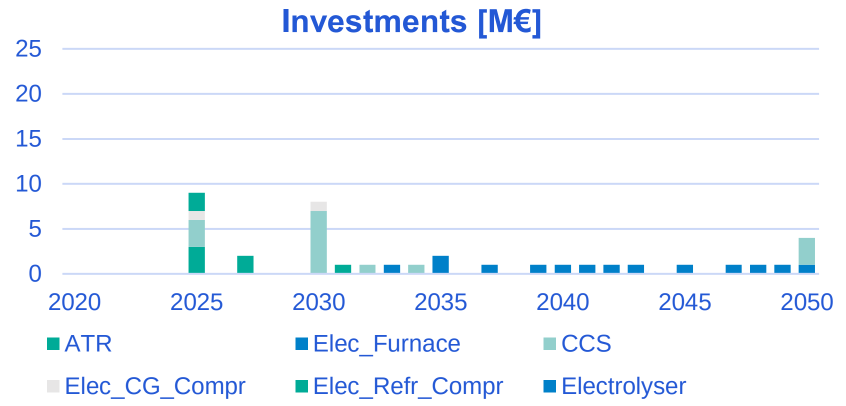
### *Reflection & Conclusions*

The Promotion of Green Hydrogen Production Case in the South-West Netherlands region accelerates the installation of electrolysers in comparison to the Reference Case. Alternative investments for hydrogen supply (ATR) are lowered in comparison to the Reference Case. Less CO2 emission reduction through CCS is resultant. In other words, the main trade-off upon promotion of green hydrogen production involves that blue hydrogen investments are shifted to green hydrogen investments. Nevertheless, scaling electrolyser deployment is lagging the currently debated European target setting for green hydrogen obligations in industry being 42% in 2030 and 60% in 2035, mainly caused by the higher costs of green hydrogen production, not taking into account potential subsidies . Since regional green hydrogen production scales with regional renewable electricity and import infrastructure (capacity of the 380kV network), the results indicate that regional green hydrogen imports are required for the targets considered.

*Table 1: Case 2 development of grey, blue and green hydrogen production versus current outlook on in industrial green hydrogen obligation (42% in 2030 and 60% in 2035).*

| Year | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|
| Grey $H_2$ [kt/a] | 239 | 243 | 173 | 44 | 44 | 44 |
| Blue $H_2$ [kt/a] | 216 | 216 | 284 | 284 | 281 | 281 |
| Green $H_2$ [kt/a] | 0 | 0 | 237 | 600 | 839 | 1087 |
| Total [kt/a] | 455 | 459 | 693 | 928 | 1164 | 1413 |
| % Green $H_2$ of Total | 0% | 0% | 34% | 65% | 72% | 77% |
| European Target |  | 42% | 60% |  |  |  |

| KPI's | | |
|---|---|---|
| Delta NPV of the Gross Margin (vs Reference Case [%]) | | -5.9% (-1229 M€) |
| | 2030 | 2050 |
| $H_2$ Production [kt/a] | 459<br>(466) | 1413<br>(1413) |
| $H_2$ Import [kt/a] | 0<br>(0) | 0<br>(0) |
| Electricity Production[GWh/a] | 5463<br>(5524) | 34182<br>(25427) |
| Electricity Import [GWh/a] | 4827<br>(4893) | 44798<br>(33790) |
| CO2 emission [kt/a] | 1874<br>(794) | 0 (0) |



**Key Observations**

**CO2 emission reduction** is largely driven by CO2 emission costs, as the emission cap kicks in only by the end of the evaluation period in 2047.

- In 2025-2030 main emission reduction as in Reference Case (predominantly CCS, ATR for H2 supply, and smaller investments in electrification), though reduction and investments are lower.
- Additional emission reductions are attained in 2035-2048, increasing hydrogen deployment from newly installed electrolyser capacity.
- Zero CO2 emission in 2050 is achieved by electric furnaces (preferred over H2), along with investments in CCS. The late stage ATR investments occurring in the Reference Case are not needed as they were preceded by the enforced electrolyser investments.
- The NPV declines by 5.9%, as enforced electrolyser investment involves higher cost than the CCS and ATR investments in the Reference Case.

**Security of supply** challenges largely shift from natural gas and electricity to electricity only, much like Reference Case. No Hydrogen is imported.

**Installed capacity by 2050**

- 2.5 times less than 720 kt H2/a ATR capacity installed in Reference Case
- 1.1 times less than 1700 kt CO2/a CCS capacity installed in Reference Case
- 1120 GWh/a Cracked-Gas compressors (Elec_CG_Compr) and refrigerant compressors (Elec_Refr_Compr) capacity installed
- 1.5 times more than 800 kt/a Electrolyser capacity installed in Reference Case
- 380kV network was enforced in 2032, while it resulted in 2049 in the Reference Case

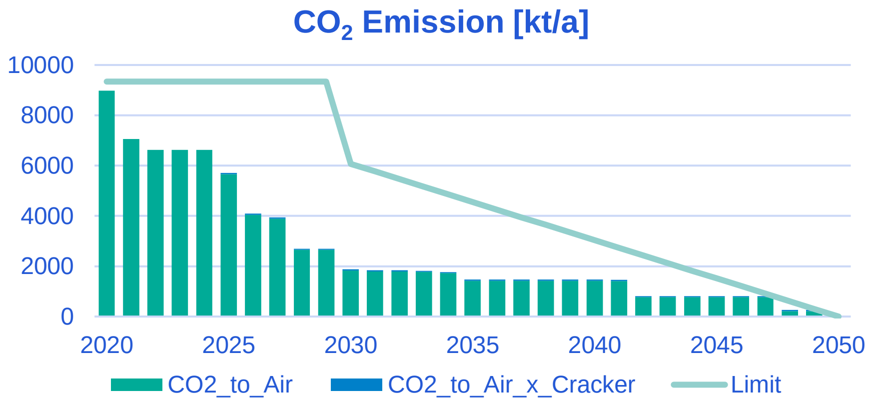


*Figure 32: Overview of the main results for Promotion of Green Hydrogen Production in the South-West Netherlands Region.*

### Case 3: Potential for Hydrogen as Feedstock (PoR only)

Aside from hydrogen deployment for energy, outlooks on regional hydrogen deployment for feedstock show significant potential. Notably in the Rotterdam area future demand developments of green base chemicals and bio/synfuels are thought to play an important role in the development of hydrogen demand in Rotterdam. On the other hand, synfuel routes require significant volumes of biogenic CO2 or DAC that may impose a limiting factor.

### *Case Description*

Variation with regard to the Reference Case: demand for base chemicals synfuels and associated CO2 and hydrogen is accounted for explicitly. Current demand for marine fuel and kerosine are used as markers for the future synfuel demand, while naphtha and ethene are used as markers for future green base chemicals demand (see Figure 33).

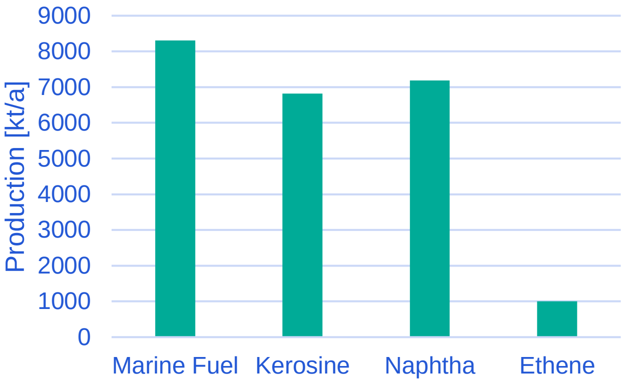


*Figure 33: Current production of assumed markers for fuels and base chemicals demand, based on public CBS and TNO MIDDEN data*

For the fuels we assume no total volume changes over time and constant replacement rate of fossil with both a bio- and synfuel market in 2050. Five scenario variations are considered:

- 0% synfuel, 100% biofuel
- 25% synfuel, 75% biofuel
- 50% synfuel, 50% biofuel
- 75% synfuel, 25% biofuel
- 100% synfuel, 0% biofuel

For base chemicals we assume that the current production is completely replaced by green base chemicals in 2050, as described by Figure 14. In the current model set-up, the required carbon is delivered through Direct Air Capture, industrial CCS or import (see also Port of Rotterdam Regional Model), and in this case analysis it is based on either biogenic CO2 (HEFA/IsoButanol) or CO2 via DAC (as in the Reference Case).

- What hydrogen potential is associated with future development of base chemicals?
- What hydrogen potential is associated with future development of synfuels?
- What CO2 supplies are involved?

### *Case Results for the Port of Rotterdam Region*

As scenario variations for the 2050 balance between synfuel production and biofuel production are considered, we diverge from the dashboard presentation of case results. Results of optimal investments to serve assumed demand may be presented by form of relative proportions of synfuel - and green base chemicals production in 2050 and the associated CO2 and hydrogen demand, as presented in Figure 34.

Major production and/or import of hydrogen is required to fulfil the potential synfuel market in Rotterdam, ranging from 5000 to 45000 kt/a, overtaking the 521 kt/a that was found to be produced and imported in the Reference Case by one or even two orders of magnitude. The demand is predominantly driven by synfuel demand and syn-naphtha demand for base chemicals. Potential demand for green ethene only contributes marginally.

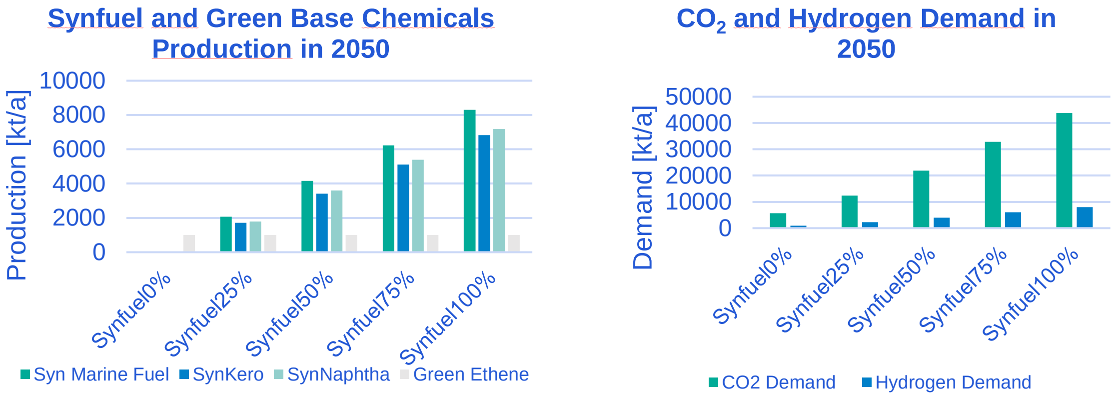


*Figure 34: Production of synfuel and green base chemicals in 2050 (left-hand side), and associated CO2 demand and hydrogen demand (right-hand side). Note that the latter figure illustrates that hydrogen has a (much) lower molar mass that CO2.*

The required CO2 reaches up to 8 Mton/a, well over todays estimated biogenic CO2 emissions in the Rotterdam area of some 1 or 2 Mt/year. The source of these CO2 in the scenarios is Direct Air Capture (DAC). Note that the alternatives of syn-kerosine imports and syn-naphtha imports are not considered in this model set-up.

*Reflection & Conclusions*

Clearly, the impact of notably the potential for synfuel production and syn-naphtha as set out by current demand for fossil products serving these markets is very large in comparison to alternate hydrogen demand in the Rotterdam area. These findings align with findings in related system studies, indicating that notably hydrogen demand for domestic production of synfuel - and green base chemicals at such scale on top of alternate demand for hydrogen in the Dutch energy and feedstock system is very likely to outstrip domestic technical potential for renewable hydrogen production (TNO, 2022; Netbeheer Nederland, 2023). Further analysis through a more in-depth set-up of synfuel and green base chemicals production (including infrastructure, but also import potentials and spatial requirements) are required to assess future market potential in more detail.

### Case 4: CCS Phase-Out (both PoR and SWNL)

While CCS projects currently offer a key route for large-scale GHG-emission reduction in industry, public support for CCS may deteriorate over time or the technology may turn out to face technical challenges upon large-scale application. Such drivers may impose CCS applications to be phased-out in later stages of the energy transition towards 2050.

*Case Description*

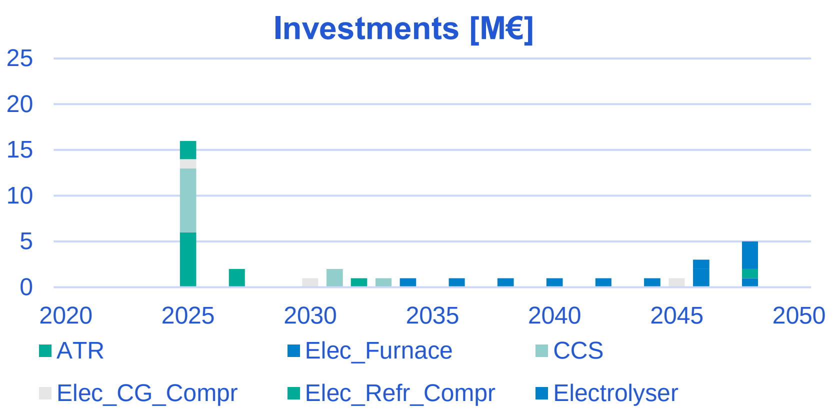
Variation with regard to the Reference Case: no CCS deployment after 2045.

- What is the role of green H2 in this scenario?
- What alternate pathways result, or does early application of CCS remain robust?
- What cost implications are involved?

*Case Results for the South-West Netherlands Region*

As for the Reference Case, CO2 emission reduction is largely driven by CO2 emission costs, as the CO2 emission limit kicks in only by the end of the evaluation period (be it in 2045 rather than in 2049 as resulted in the Reference Case). Most emission reductions are attained in 2025 - 2035 through high investment in

| KPI's | | |
|---|---|---|
| Delta NPV of the Gross Margin (vs Reference Case [%]) | | -3.5% (-729 M€) |
| | 2030 | 2050 |
| $H_2$ Production [kt/a] | 466 (466) | 1558 (1413) |
| $H_2$ Import [kt/a | 0 (0) | 292 (0) |
| Electricity Production [GWh/a] | 5443 (5524) | 25500 (25427) |
| Electricity Import [GWh/a | 4806 (4893) | 48688 (33790) |
| CO2 emission [kt/a] | 1507 (794) | 0 (0) |



**Key Observations**

**CO2 emission reduction** is largely driven by CO2 emission costs, as the CO2 emission limit kicks in by 2045 (a few years earlier than in the Reference Case).

- Most emission reductions attained in 2025-2035 as in Reference Case (predominantly CCS, ATR for H2 supply, and smaller investments in electrification). Reductions are lower however, with 40% lower investment in CCS.
- No additional emission reductions are attained in 2035-2045, and newly installed electrolyser capacity only serves increasing demand for hydrogen.
- Zero CO2 emission in 2050 is achieved by slightly accelerated investment in electric furnaces and the required 380KV network. Additional investments in electrification of cracked gas and refrigerant compressors is undertaken respective of the Reference Case.
- The NPV declines by 3.5%, as the enforced CCS phase-out pushes up costs compared to optimal investment as attained in the Reference Case.

**Security of supply** challenges largely shift from natural gas and electricity to hydrogen and electricity in this case. Some 20% of required hydrogen is imported, where no imports were required in the Reference Case.

**Installed capacity by 2050**

- 1.4 times less than 720 kt H2/a ATR capacity installed in Reference Case
- 1.7 times less than 1700 kt CO2/a CCS capacity installed in Reference Case
- 1.4 times more than 1120 GWh/a Cracked-Gas compressors (Elec_CG_Compr) and refrigerant compressors (Elec_Refr_Compr) capacity installed as in Reference Case
- 1.25 times more than 800 kt/a Electrolyser capacity installed in Reference Case
- 380kV network in 2046, while it resulted in 2049 in the Reference Case

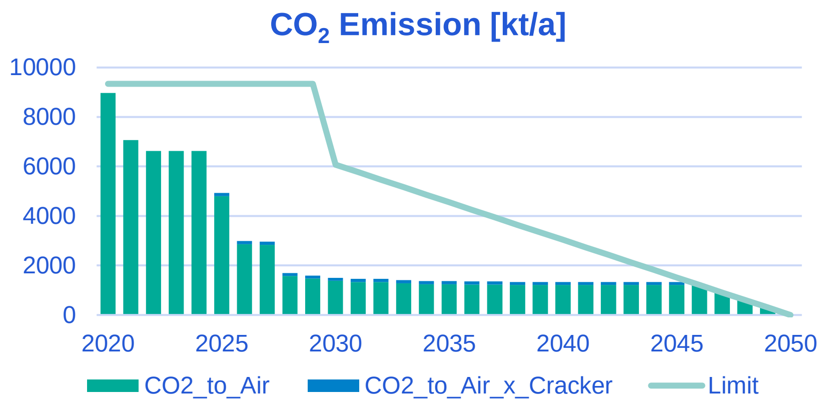


*Figure 35: Overview of the main results for the CCS Phase-Out in the South-West Netherlands Region.*

CCS and ATR, along with moderate investments in electrification. Emission reductions in this period are lower however, as investment in CCS is significantly lowered by some 40%. As a result of lowered investment in CCS, annual CO2 emissions remain roughly twice as high as those in the Reference Case from 2030 onward, until CO2 emission limit is hit after 2045. Hence, prospects for CCS appear cloudier in this case analysis where enforcement of CCS phase-out is assumed after 2045. No additional emission reductions are attained in 2035 – 2045. Hence, the main trade-off in comparison to the Reference Case appears to be lowered CCS investment at cost of higher CO2 emissions in 2035 - 2045. Of course, this trade-off depends on the assumed ETS prices that may in practice turn out to result higher than assumed here. In this sense, CCS also allows to limit exposures to higher future ETS prices. Zero CO2 emission in 2050 is achieved by slightly accelerated investment in electric furnaces (again preferred over H2), along with required 380KV network investments. In this late stage of the evaluation period, additional electrolyser investments and electrification of electric cracked-gas and refrigerant compressors is undertaken. The NPV declines by 3.5%, as the enforced CCS phase-out comes at a cost of higher CO2 emissions from 2035 onward. Security of supply challenges largely shift from natural gas (for blue hydrogen production) and electricity to hydrogen and electricity; in this case some 20% of required hydrogen is imported by 2050, where no imports were required in the Reference Case. In other words, limiting prospects for long-term CCS deployment, induces a shift from blue hydrogen to green hydrogen production and regional hydrogen imports as cost-optimal approach to GHG emission reduction.

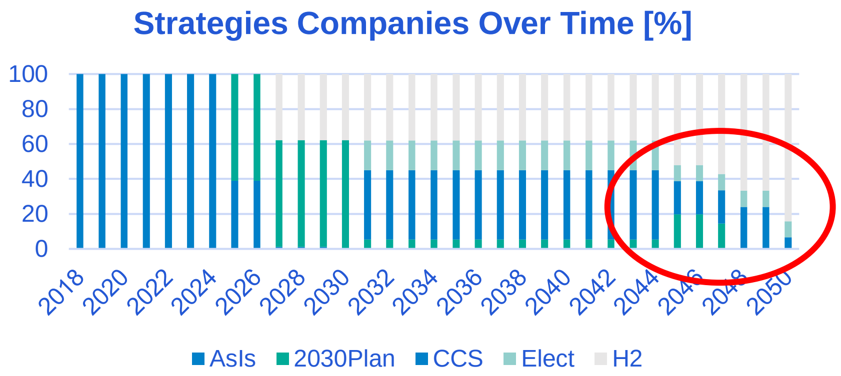
### *Case Results for the Port of Rotterdam Region*

Also for this case CO2 emission reduction remains to be largely driven by CO2 emission costs (like in the Reference Case), driving CO2 emission reduction in Rotterdam well below the target of 55% in 2030. Until 2030 the strategy follows the BaU Strategy as imposed, except for the refineries (Hydrogen Strategy in combination with H-vision). A large CO2 emission reduction step by 2030 is caused by CCS (some 40% of total investment) and blue H2 (also some 40% of total investment). Hence, the CCS Strategy and Hydrogen Strategy remain to be dominant in this case analysis. The remainder of investments relate to electrification. By 2045 the CCS phase-out kicks in, and CO2 emissions initially increase. Furthermore, CCS remains to be deployed until 2049. Decarbonization with CCS limitations as imposed, requires changes in manufacturing processes. Given the assumed (imposed) industry plans in the E-mix data and the assumption of continuing production, CCS deployment can only by reduced to 6 Mt (or 20% of CCS capacity) after 2045 in Rotterdam (indicated by the red circle in the figure at the top righthand side of the dashboard). Especially electrification does have a limited CO2 reduction potential in the current E-mix data due the conservative approach on technology development. Production of hydrogen via Refinery Fuel Gas (RFG) as proposed in the H-vision project is no longer applied in 2050 due to the imposed CCS squeeze. The main trade-off induced by the enforced CCS phase-out, in other words, is that the CCS investments align with the Reference Case but are replaced by investments in hydrogen deployment in the last five years of the evaluation period. Production of blue hydrogen is not applied in the last five years and import of green hydrogen becomes the source. This is 770 kt in 2050, whereas in the Reference case only 147 kt green hydrogen was import. The main trade-off induced by the enforced CCS phase-out, in other words, is that the CCS investments align with the Reference Case, but are replaced by investments in green hydrogen deployment in the last five years of the evaluation period Accordingly, the NPV for this strategy is significantly lower than for the Reference Case with a 14% decline. Security of supply challenges largely shift from natural gas and electricity to hydrogen and electricity, notably after 2045 with H2 imports running up to 770 kt/a.

### *Reflection & Conclusions*

The enforced phase-out of CCS results in lower investments in CCS that occurred in the early phase of the evaluation period in the Reference Cases. In case of the South-West region CCS investments are lowered significantly with 40%, resulting in higher CO2 emissions from notably 2030 onward. In the latest stage of the evaluation period, Remaining CCS deployment is displaced by additional investments in electrolysers and electrification. In case of the Port of Rotterdam region, initial CCS investments are reduced only marginally. CCS phase-out after 2045 induces a shift to green hydrogen deployment with associated additional investments. While impact on NPV is limited to a 3.5% decline for the South-West Netherlands, a significant cost increase results for the Port of Rotterdam region with a 14% decline of NPV as a result.

| KPI's | | |
|---|---|---|
| Delta NPV of the Gross Margin (vs Reference Case [%]) | | -14% (588 M€) |
| | 2030 | 2050 |
| $H_2$ Production [kt/a] | 379 (379) | 0 (374) |
| $H_2$ Import [kt/a] | 0 (0) | 770 (147) |
| Electricity Production [GWh/a] | 30410 (30410) | 30410 (30410) |
| Electricity Import [GWh/a] | 0 (0) | 3702 (3496) |



**Key Observations**

**CO2 emission reduction** remains to be largely driven by CO2 emission costs (like in the Reference Case), driving emissions below the target of 55% in 2030.

- Until 2031, the strategy follows the BaU Strategy as imposed except for the refineries (Hydrogen Strategy in combination with H-vision initiative)
- CO2 emission reduction step 2025 - 2030 by investment in predominantly CCS and H2, with CCS investments only marginally lower than in the Reference Case.
- Around 2045 emissions increase with declining CCS deployment, limited to 20% annually.
- The NPV declines by 14%, as the enforced CCS phase-out pushes up costs the Reference Case

**Security of supply** challenges largely shift from natural gas and electricity to hydrogen and electricity, notably after 2045 with H2 production doubling to 770 kt/a.

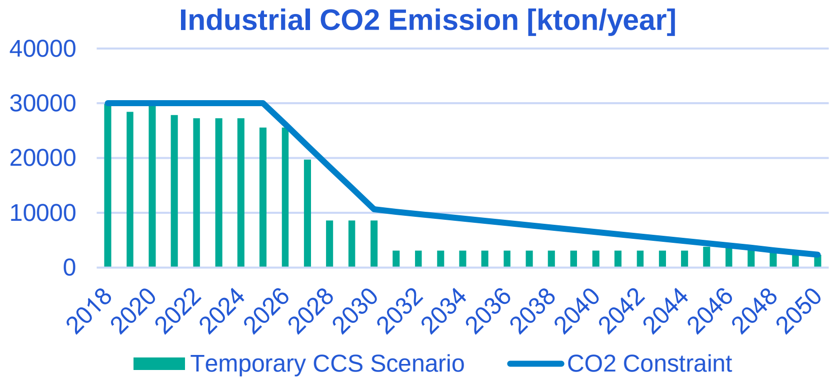


*Figure 36: Overview of the main results for the CCS Phase-Out in the Port of Rotterdam Region.*

## Case 5: Delayed Regional Power Grid Reinforcement (PoR only)

Regional grid development (HV/MV and grid connections) will play a critical role to establish grid access for industry in the industrial clusters. During the workshop it was discussed that such system development may face challenges in timely realization. How does delayed grid development affect industrial emission reduction during the energy transition at cluster level?

*Case Description*

Variation regarding the Reference Case: gradual and limiting grid reinforcements in the Rotterdam area are applied.

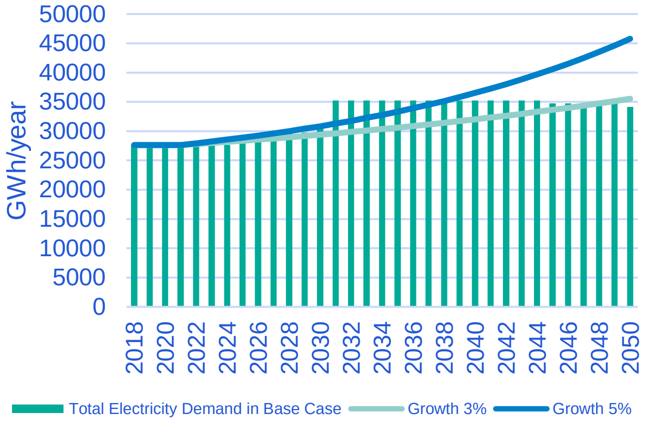


*Figure 37: Reference Case electricity demand and maximum grid reinforcement rate assumption variants for Port of Rotterdam Region.*

In the Reference Case, an electricity demand hike results in the Port of Rotterdam region after 2030. A gradual reinforcement of the regional power grid in Rotterdam, lagging the electricity demand hike, would impose a limit on attainable industrial electrification. Figure 37 illustrates how an annual 3% or 5% grid reinforcement assumption would limit the annual electrification rates that resulted from the Reference Case. In this case analysis a grid reinforcement rate of 3% and 5% per year is deployed respectively. The grid reinforcement rate of 3% and 5% was imposed on the total electricity demand in the region, to have viewpoint from the full region. The focus is not on individual segments or substations in the region. The following is tested in this analysis:

- How does regional grid time delay affect industrial CO2 emission and investment strategies in the cluster?
- What costs are involved?

*Case Results for the Port of Rotterdam Region*

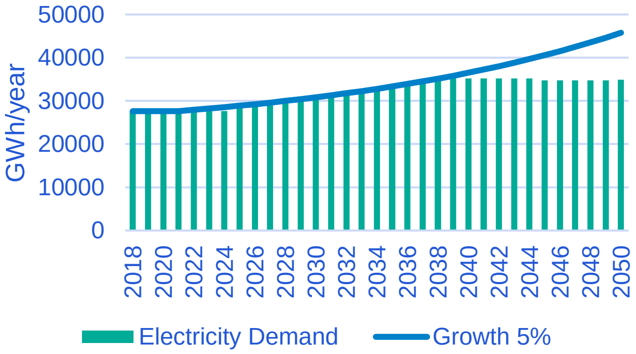
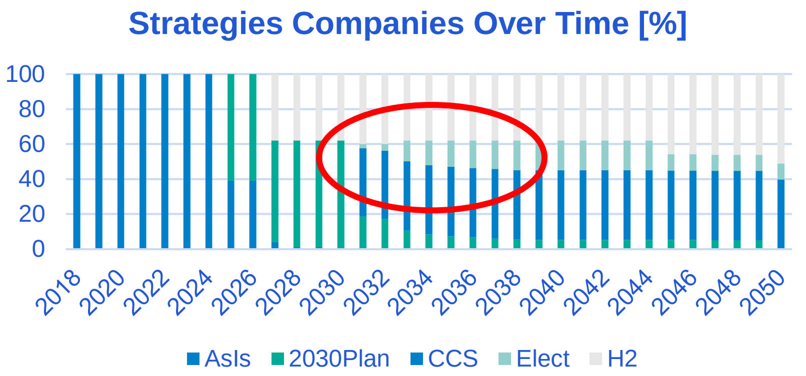


*Figure 38: Electricity demand and the limiting maximum grid reinforcement rate of 5% year-on-year in the Rotterdam area.*

With a reinforcement rate of 3% per year, the BaU Strategy (2030 Plan) of industry in Rotterdam cannot be realized, so that an infeasible simulation resulted. The 3% annual grid reinforcement rate was therefore dismissed. This is different for the 5% annual reinforcement rate. With such reinforcement rate as limiting factor for both direct and indirect electrification, the electricity demand hike observed in the Reference Case is capped by the reinforcement rate. This is shown in **Error! Reference source not found.**, presenting both the electricity demand in the Rotterdam area as well as a 5% growth rate representing the cap imposed by the grid reinforcement rate. The cap remains limiting until 2040.

An overview of results for the 5% annual grid reinforcement rate is presented in Figure 39. As might be expected, CO2 emission reduction remains to be largely driven by CO2 emission costs (like in the Reference Case), as driving CO2 emission reduction in Rotterdam below the target of 55% in 2030. Until 2031 the strategy follows the BaU Strategy, as imposed (except for the refineries which have the option to combine their Hydrogen Strategy with H-vision). Investments in CCS and hydrogen remain to over dominant segments in the portfolio.

| KPI's | | |
|---|---|---|
| Delta NPV of the Gross Margin (vs Reference Case [%]) | | -5.3% (235 M€) |
| | 2030 | 2050 |
| $H_2$ Production [kt/a] | 379 (379) | 384 (374) |
| $H_2$ Import [kt/a] | 0 (0) | 117 (147) |
| Electricity Production [GWh/a] | 30410 (30410) | 30410 (30410) |
| Electricity Import [GWh/a] | 0 (0) | 4218 (3496) |



**Key Observations**

**CO2 emission reduction** remains to be largely driven by CO2 emission costs (like in the Reference Case), driving CO2 emission below the target of 55% in 2030.

- Until 2031 the strategy follows the BaU Strategy as imposed, with the exception of the refineries (Hydrogen Strategy in combination with H-vision initiative)
- In period 2030-2050, CO2 emissions are reduced more gradually with gradually increasing electrification.
- A large CO2 emission reduction step in 2031 is caused by investment in CCS and H2 as in the Reference Case, while electrification materializes only gradually.
- Gradual Reinforcement leads to 235 M€ additional costs, predominantly caused by ETS-exposure in period 2031-2038.

**Security of supply** challenges largely shift from natural gas and electricity to hydrogen and electricity as before, with slight increases of hydrogen imports (as electricity supply was more limited due to limited grid reinforcements).

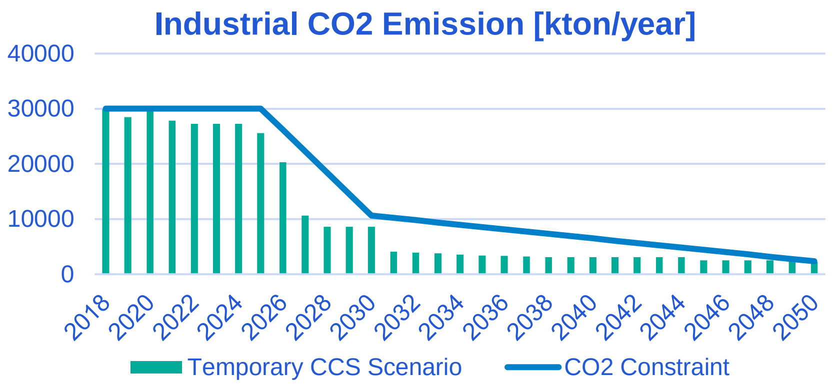


*Figure 39: Overview of the main results for the Delayed Regional Power Grid Reinforcement in the Port of Rotterdam Region.*

Though the relative contribution of investments in the Hydrogen Strategy are somewhat higher in this case (as are hydrogen imports), both CCS investments and hydrogen investments span some 40% of the investment portfolio each and remain comparable to the Reference Case. Hence, the delayed grid reinforcements induce a trade-off, reducing electrification, while increasing (blue) hydrogen deployment and CO2 emission in this timeframe. Additional investments in the Hydrogen Strategy resulting in 2040 in the Reference occur several years later in this Delayed Regional Power Grid Reinforcement Case. Gradual grid reinforcement leads to 235 M€ additional costs, predominantly caused by ETS-exposure resulting in period 2030-2040.

### *Reflection & Conclusions*

Delayed Regional Power Grid Reinforcement caps electrification efforts and predominantly induces increased hydrogen deployment and lowered CO2 emission reductions over in the 2030 – 2040 timeframe. This leads to 235 M€ additional costs, predominantly caused by ETS-exposure resulting this period.

## Conclusions

In this chapter the HyChain Model was deployed for a Case Analysis. The following cases and associated findings resulted:

Case 1 - Accelerated GHG Emission Reduction, bringing the 2030 GHG emission reduction targets forward to 2027 left the South-West region largely unaffected, as emission reduction was predominantly driven by the EU ETS prices. This is essentially also the case for the Rotterdam area, where a BaU strategy (low hanging fruits until 2030) was imposed in the Reference Case. If alternative strategies were allowed before 2030, emission reduction was accelerated as driven by the assumed EU ETS price profile.

Case 2 - Promotion of Green Hydrogen Production, promoting of green hydrogen deployment in industry as proposed in the Fit-for-55 package drive increased green hydrogen investments at cost of blue hydrogen investments. For the South-West Netherlands Region acceleration of Green hydrogen needs to be supported by reducing the economically more attractive SMRs (grey) and ATRs (blue). The percentage Green hydrogen grows from 0% in 2030 to 34% in 2035, 65% in 2040, 72% in 2045 and 77% in 2050, lagging the European target of 42% in 2030 and 60% in 2035. Note that subsidies for Green hydrogen are not included.

Case 3 – Potential for Hydrogen as Feedstock, exploring the potential for hydrogen deployment in synfuel production and syn-naphtha as set out by current production of fossil products in Rotterdam is very high in comparison to alternate hydrogen demand in the Rotterdam area in alignment of findings in literature.

Case 4 - CCS Phase-Out, assuming an end to the CCS era by 2045 would significantly reduce attractiveness of CCS investments in the South-West of the Netherlands, while such is not the case for the Rotterdam area. In the first case higher CO2 emissions result from notably 2030 onward, while in the latter case investments in alternatives by the end of the evaluation period drives up overall costs significantly. In the Rotterdam area, green hydrogen development becomes dominant from 2045 onwards, with import as source.

Case 5 - Delayed Regional Power Grid Reinforcement in the coming decade may limit electrification efforts and predominantly induces increased hydrogen deployment and lowered CO2 emission reductions over in the 2030 – 2040 timeframe, inducing additional costs predominantly caused by the resulting EU ETS exposure.

The analysis was undertaken in a multi-stakeholder setting with project partners representing regional authorities, industry, energy and network operators. Reference Cases were established, and a series of case analyses was undertaken. The cases were designed to explore the impact of uncertainties in predominantly energy policy (Cases 1, 2 and 4), but also relating to technical potential for new markets (case 3) and delays in grid reinforcement (Case 5). The workshops allowed for joint fact-finding and development of a common understanding of trade-offs (for example, regarding blue hydrogen, green hydrogen, and regional hydrogen imports) involved with these uncertainties and implications for the investment strategies for hydrogen supply chain development and industrial GHG emission reduction. This experience suggests significant benefits may be attained, both for individual stakeholders as well as joint stakeholder efforts in the Dutch hydrogen supply chain development. This experience confirms the necessity of making the HyChain Model available, as intended with the development of a service model. The following chapter presents such a service model.

# Service Model

## Introduction

In the coming decades we aim to transform society from fossil-based to renewables-based. From an industry perspective there are two main challenges. Firstly, the emissions associated with fossil energy use have to be removed, either by sourcing renewable emission-free energy sources or by capturing the emissions and storing CO2. Secondly, as we aim to move away from fossil sources entirely, the industry will also have to develop routes to source renewable feedstocks. Replacing carbon from fossil origin to alternatives and through circular use of carbon have to show the way. In both routes the role of hydrogen is key. On the one hand hydrogen is seen as a future energy commodity that can bridge long-term seasonal energy production and use cycles and can be transported in various forms on long distances. On the other hand, it is a basic chemical compound necessary to upgrade renewable carbon streams from many types of sources (e.g. CO2 or CO) into base chemicals.

The HyChain project has studied the development of hydrogen supply chains to feed into these two uses, to decarbonize the industry. For this purpose, initially investigations were done into expected future use of hydrogen and in import routes, and a technology assessment was done to develop an inventory of technologies available to build the supply chains.

In HyChain 4 we have built on these initial investigations and developed detailed transition models. The core question was to figure out what role hydrogen, in various forms, has to play in a future renewable based industrial system, and under which conditions hydrogen is preferred over its alternatives – e.g. CCS or direct electrification.

For this purpose, detailed industrial transition models have been built over the course of 2020-2022. The models capture the transition options of different industries, and look at these coherently, together with interconnecting (available and future) infrastructure for gas, CO2, power and of course hydrogen. With these models the dependencies of the development pathways on price scenarios, public support actions and regulations, and the own believes of the industry can be studied in detail and provide transition pathways. These models were built for the industrial cluster in Zeeland (in the area covered by the Smart Delta Resource partnership, covering Dow, Yara and Zeeland Refineries) and for the Port of Rotterdam Harbour Industrial Cluster (HIC), covering over 30 industries from refinery, (petro) chemicals, and many others, and including the relevant infrastructure and options under study development as the Hydrogen Conversion Park (for electrolysis) and the H-Vision program.

The models built are powerful tools, valuable for further strategy development. During the project the models already have attracted attention and have supported discussions on the Cluster Energie Strategie – a policy request from the Ministry of Economic Affairs for planning infrastructure and in relation to e.g. the II3050 project of the infrastructure operators for infrastructure explorations towards the year 2050. Therefore it is clear the models are capable of providing valuable strategic insights and can be very functional in facilitating the discussions and collaborations necessary to explore and quantify transition pathways at the interface between stakeholders – industry, grid operators, local authorities and bodies such as the Port Authority, coordinators like Deltalinqs and Smart Delta Resources, local provincial governing bodies and national organizations like the ministry of economic affairs and climate, and national grid operators.

In this document we pave the way for a future life after the project. The valuable investment of time and energy by the many consortium stakeholders has delivered a unique tool that provides a basis for further use. We therefore describe our vision on how we can organize a sustainable service model that secures the long-term availability and use of these tools to secure that the potential value they bring is harvested to its' full potential.

## Service Model Approach

### Scope of the HyChain Model Implementation – Technical Domain, Regional and National Level and Stakeholders

For a sustained use of the models developed in the HyChain project we need to assess for which stakeholders the tools bring value. We then can determine how this value is best captured in a way that basic costs associated with the use and maintenance of these tools are recovered. The scope of a typical cluster is presented in Figure 40, showing that the models in a region engage at company level, but also exceed that to regional matters such as need and use of infrastructure for various commodities.

In the project these stakeholders have engaged and participated in various forms:

- Industry – we explored transition options for industry at technology level in SDR, but also at company level, in Rotterdam. Both approaches proved to provide valuable insights and can be applied. Examples are given in Figure 41 and Figure 42.
- Infrastructure – infrastructure maps have been made for both SDR region and Rotterdam region and existing and anticipated infrastructure trajectories have been built into the models, as part of the selection process.  Example given in Figure 43.
- Regional cluster coordinators – in the HyChain project we have worked with the Zeeland Cluster, governed by Smart Delta Resources (SDR), who is in charge of the Cluster Energy Strategy, and with the Port of Rotterdam and Deltalinqs, both working together on infrastructure planning and harbour transition, also responsible for the CES development.
- Local authorities – example is the Province of Zuid Holland – who has an objective to stimulate regional development of hydrogen related activities and has its transition goals.

With the relevance of the work for so many different stakeholders it is important to realize that the value generated by the system-modelling approach is not just harvested by a single party, but by the set of different types of parties. This is further demonstrated by the examples in the following Figure 41 to Figure 44.

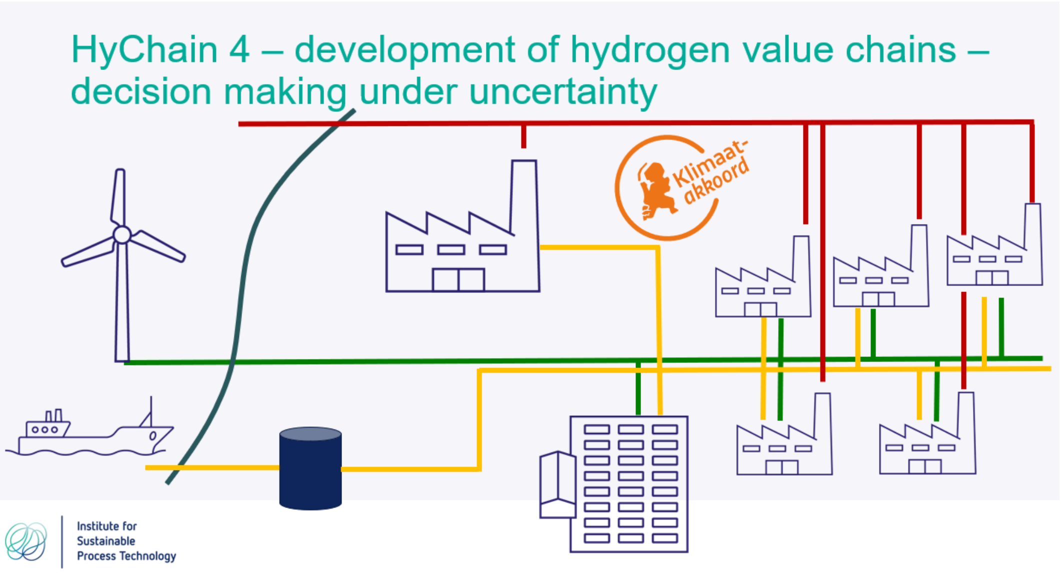
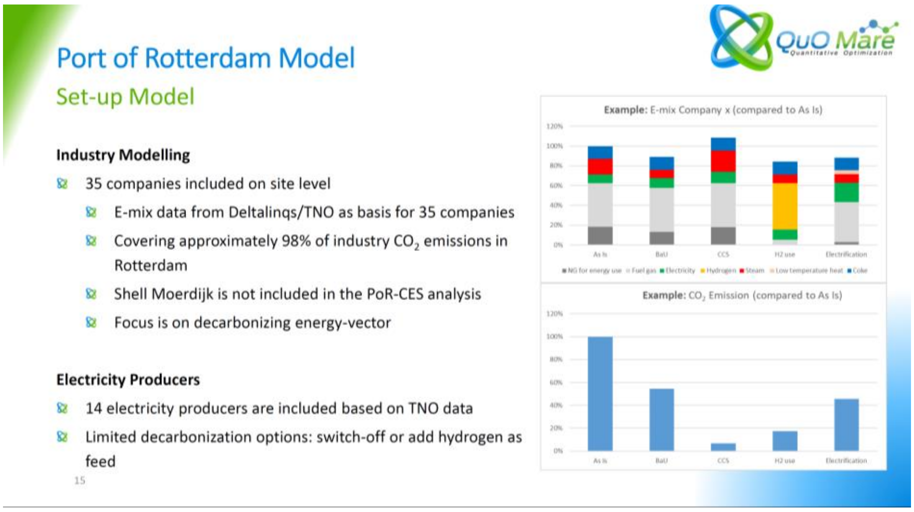

HyChain 4 – development of hydrogen value chains – decision making under uncertainty

*Figure 40: Typical scope of HyChain Cluster modelling – describing transition at the interplay between industry, infrastructure, supply of power (green) and imported feedstock/energy carriers (hydrogen, yellow) as a connection between supply of energy and feedstock and potential CCS storage capacity red), and the demand for clean products.*


Port of Rotterdam Model

Set-up Model

**Industry Modelling**

- 35 companies included on site level
  - E-mix data from Deltalinqs/TNO as basis for 35 companies
  - Covering approximately 98% of industry $CO_2$ emissions in Rotterdam
  - Shell Moerdijk is not included in the PoR-CES analysis
  - Focus is on decarbonizing energy-vector

**Electricity Producers**

- 14 electricity producers are included based on TNO data
- Limited decarbonization options: switch-off or add hydrogen as feed

*Figure 41: Extent of modelling at Rotterdam industry and power sector – covering the four scenarios defined in the Energy-mix study of 35 companies in the region (e-mix data), focused on an 'as-is' reference scenario, a Business-as-Usual scenario, and transition pathways on CCS, Hydrogen use and Electrification.*

In Figure 41 and Figure 42 we see two different ways in which industry has been modelled. In the Port of Rotterdam area, the e-mix dataset has been used as a basis for the model development, representing CO2 emission reduction strategies compared to an as-is situation:

- BAU – basic improvements and adherence to climate targets are implemented.[9]
- CCS – emission reduction focused on end-of-pipe CCS.
- H2 – adoption of hydrogen (blue and green) in industry.
- Electrification – implementation electricity as mitigation option.

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[9] The BaU includes decarbonization options (energy efficiency improvements, CCS) that are considered feasible before 2030. See also (Port of Rotterdam, Stedin, Deltalinqs, 2022).

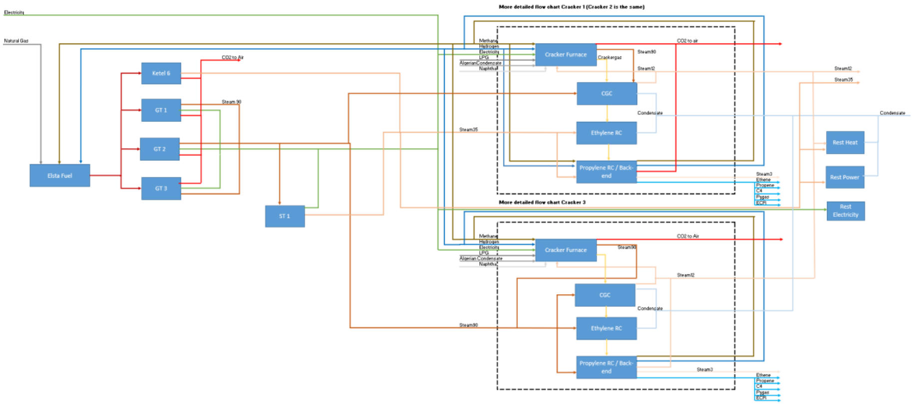
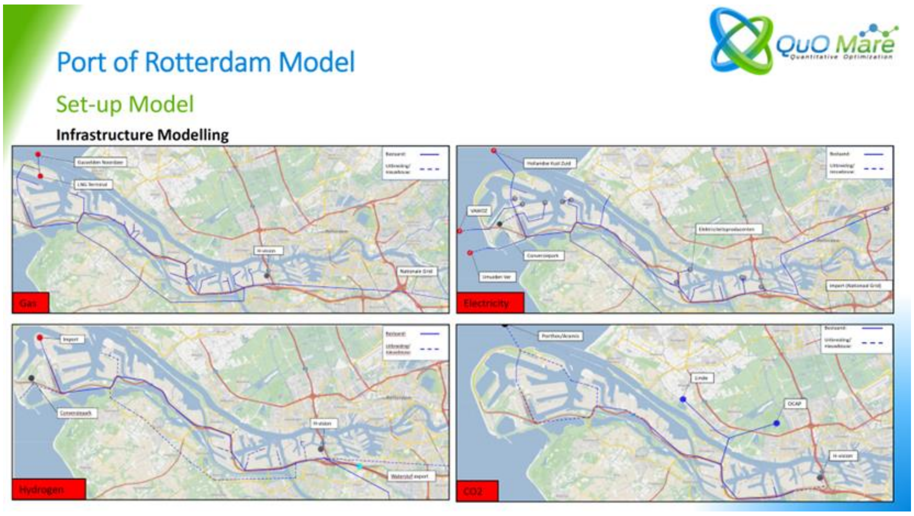


*Figure 42: Example industry model at factory level (see also figure 8), showing individual assets and commodity/utility/product streams, and including alternative options for transition at asset level.*


Port of Rotterdam Model

Set-up Model

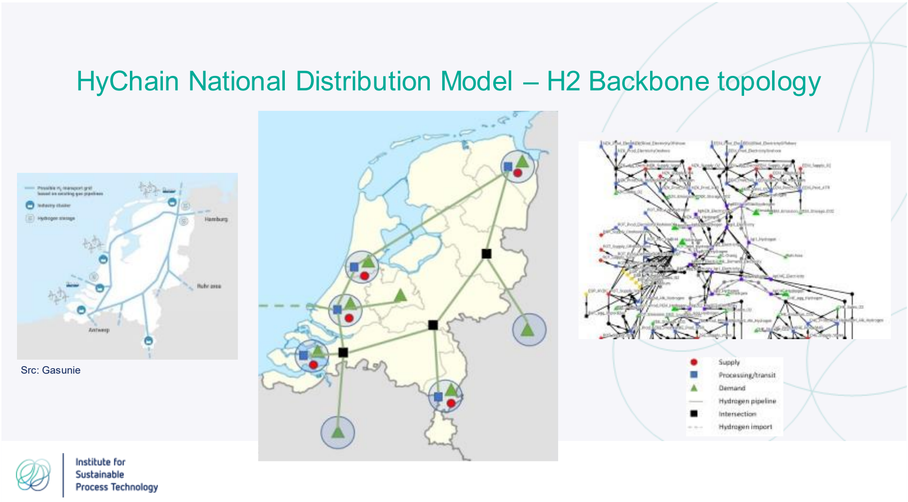
**Infrastructure Modelling**

*Figure 43: Example scope of HyChain Cluster infrastructure modelling, showing the extent of infrastructure covered in the Port of Rotterdam model.*

For each of these scenarios an analysis has been made for each company and the model selects from this set of decarbonization strategies.

In SDR area a more detailed approach has been used where behind-the-fence options are implemented, so a deeper understanding of the investment options and underlying process changes is considered. This allows for a more refined analysis and enables capturing also the product value in the analysis, allowing for capturing a full NPV approach for the cluster.

Besides industry also the underlying grid infrastructure has been modelled and optionality has been considered. This is shown in Figure 43 for the Port of Rotterdam area. Thus, investments both in industry and in infrastructure are addressed in the analysis.



HyChain National Distribution Model – H2 Backbone topology

Src: Gasunie

- ● Supply
- ■ Processing/transit
- ▲ Demand
- — Hydrogen pipeline
- ■ Intersection
- - - Hydrogen import

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Process Technology

*Figure 44: Hydrogen National Distribution Model – the national model captures exchanges between developing hydrogen demand and supply centres across the Dutch industry clusters over time. The figure shows the projection of Gasunie's Backbone, the HyChain representation including import overseas and cross-border exchange, and the underlying topology of the model.*

Finally, the HyChain model also allows aggregation of the analysis to the National level. Figure 44 gives an impression of the National model, which captures the exchange of demand and supply between industry clusters.

## Sustained Use of the HyChain Model Framework

For the sustained use of the model framework, it is important to secure two elements:

1. Secure involvement of a user community that is supported in its use and where continuous development of the models is secured.
2. For the models to play its' best role in decision-making processes we need to secure its role in the right stakeholder-arena, between industry, grid operators and government.

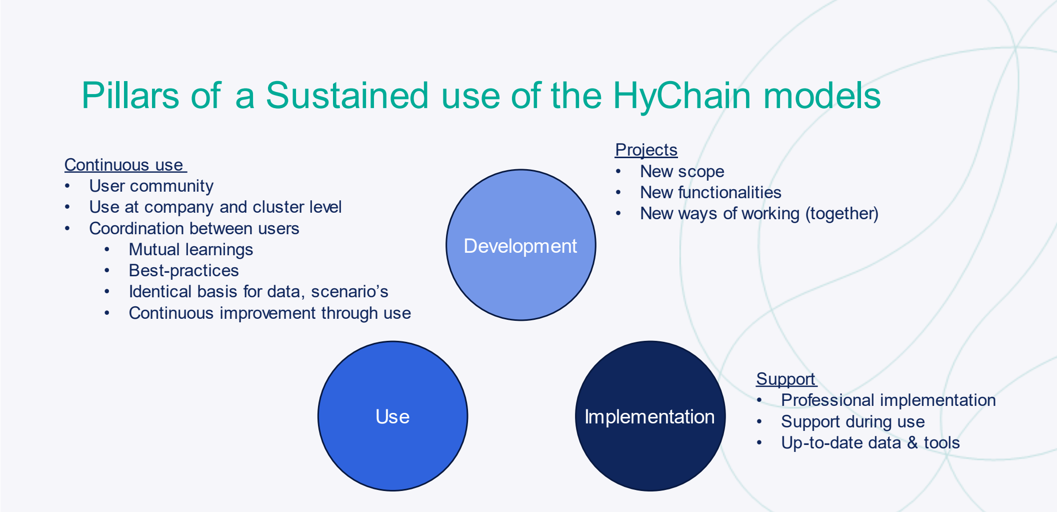
We elaborate on these two points and illustrate how these can be addressed.

### *The Three Pillars for Sustained Use of Models and Practices*

In Figure 45 we depict the three interacting pillars for keeping the models developed in the HyChain project alive:

1. **Implementation**: If you want to use the models it is very important to know that the models are available, and that when you run into questions you can get the support necessary to get quickly going forward. To secure this availability professional implementation is key. Professional implementation consists of the following elements:
    - The model is programmed and implemented in a high-quality software environment that is provided professionally and is kept up to date with current IT developments to secure that fact computation of problems is warranted and availability for the long-term is supported.
    - The model is maintained actively and there is a support organization that can help troubleshooting when problems are reported, albeit from bugs, from input errors, or with result interpretation.

- The support organization can also provide training, helpdesk services and other support such as model development support when needed, to secure that iterations with the model can be made in short cycles at the time that you want or need to work with it.



Pillars of a Sustained use of the HyChain models

Continuous use
- User community
- Use at company and cluster level
- Coordination between users
  - Mutual learnings
  - Best-practices
  - Identical basis for data, scenario's
  - Continuous improvement through use

Projects
- New scope
- New functionalities
- New ways of working (together)

Support
- Professional implementation
- Support during use
- Up-to-date data & tools

*Figure 45: Three pillars for sustained use of the HyChain models: Implementation, Use and Development.*

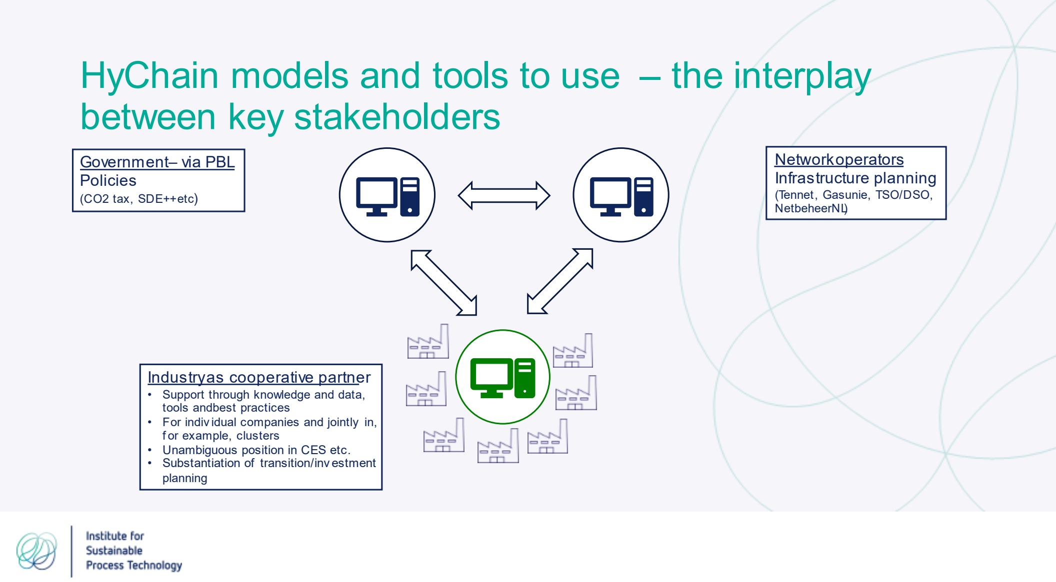
2. **Use**: For a high-quality model to be alive it is essential that it is used often. Through its' use it proves its value and continuous improvement of the tools is warranted. Key points to secure with using the models are the following:
   - By applying the model, you gain the insights needed. It is very important to support an active user community, stimulate their use of the models, and arrange engagement between users to encourage learning. By learning from others how they apply the models you get inspired. Sharing of best practices in use leads to overall improvement of modelling practices in the user community. Providing feedback to the developers through use leads to quality improvement of the models by reduction of bugs and improvement of consistency.
   - By working with models in different environments, e.g., within single companies or within an industry cluster with a group, the models get tested in diverse environments. On the one hand you learn this way how better to use the models, on the other hand you share issues and insights with the tool developers, leading to reduction of bugs and errors and by developing new features and capabilities, by which the tools improve continuously.
   - From use you also learn what the models cannot do yet. This leads to ideas for new projects that enhance the scope or functionality of the models – see also point 3.
3. **Development:** It is also important to continuously develop new capabilities to the tools, to secure their value to address relevant problems. We expect the following needs to occur:
   - More resolution – the aggregated options of the e-mix data have limitations and may need to be updated with new ideas and transition plans of the industry, as well as from grid operators.
   - New scope – currently we have addressed a national model with clusters SDR and Port of Rotterdam as predominant clusters. New scope can be addressed for example geographically, by expanding to other clusters, to North Sea areas, or across the border in Belgium or Germany.

- New functionality – the way you interact with the models can be modified. For example, user interfaces, reporting approaches, or interaction with different datasets is a possibility that gives new functionality to the tools. Using the models in different ways, e.g., through decision simulations in a game-like setting can be developed to explore scenarios in teams. The functionality to communicate between specific stakeholders and aggregated settings in clusters needs to be developed, and for example the analysis in a year-long timeseries is important to implement to allow both capacity analysis and flexibility exploration in given moment-in-time configurations will be very important for analysis of use of renewable power in industrial applications.
- New ways of working also relate how different model can interact, e.g. how the HyChain and CTM/ETM models interact, how cluster models are aggregated, how in group settings the models are best used, and whatever other ways come across or needs arise when working with the tools.

### *Three Key Classes of Stakeholders*

For system integration in transition planning there are three key stakeholder classes that all have their own responsibility and all three interact. The common success to achieve reaching climate goals against the committed timelines is reached when there is a common understanding, a common basis for decision-making. The models developed in the HyChain project support the decision making and enable communication of insights between these three groups:

1. **Government**: the government sets rules and regulations for subsidies and penalties (carrot and stick) and for what is and what is not allowed in industrial practice. Furthermore, national policies determine the room to manoeuvre for industry within their locations. To test their ideas and insights the government also has its capacity to develop models and carry out analysis, for example through the PBL, the Netherlands Environmental Assessment Agency, the independent policy advisor of the government.



HyChain models and tools to use – the interplay between key stakeholders

Government– via PBL
Policies
(CO2 tax, SDE++etc)

Networkoperators
Infrastructure planning
(Tennet, Gasunie, TSO/DSO, NetbeheerNL)

Industryas cooperative partner
- Support through knowledge and data, tools andbest practices
- For individual companies and jointly in, for example, clusters
- Unambiguous position in CES etc.
- Substantiation of transition/investment planning

*Figure 46: Three stakeholder classes (Industry, grid operators and government) that are supported in their decision making and interactions through the HyChain models framework and practices.*

2. **Grid Operators**: Grid operators like Gasunie and Tennet, but also local DSO's like Stedin, Enexis etc, determine their investment plans in a cycle that iterates bi-annually. On top of that a process has been

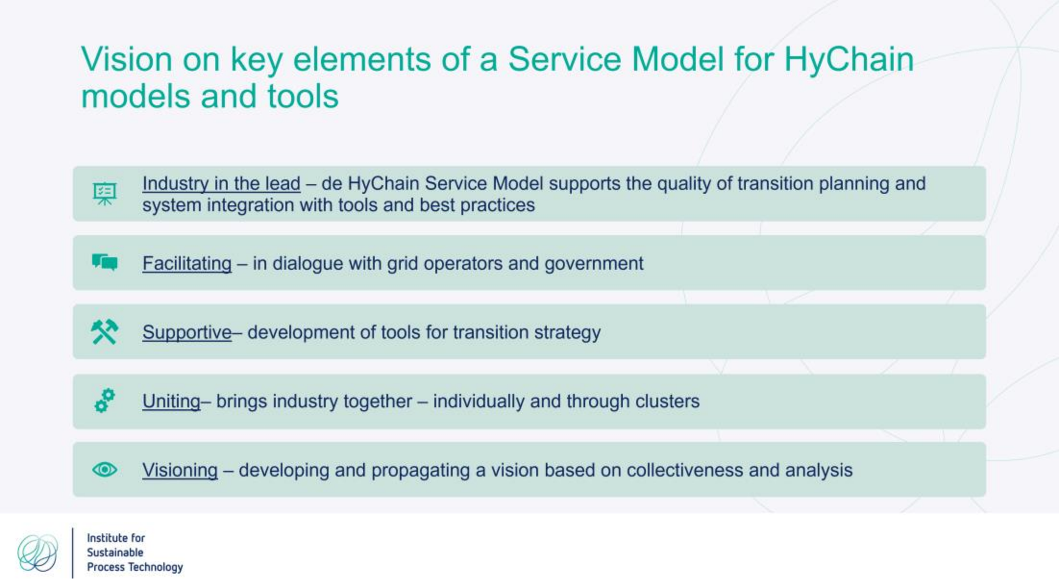
installed to align with industry plans through the PIDI – Program for Infrastructure for Sustainable Industry. And finally the grid operators also make their own long-term outlooks – the II3050 – forecasts to 2030 and 2050 to determine the bandwidth of expected grid expansions. For these processes the grid operators do extensive modelling and strategic analysis to anticipate the large-scale investment development needed to reach climate targets. In various processes the grid operators interact with industry and local industry coordinators to obtain their views on industry plans and priorities.

3. **Industry**: Industry makes its own plans for transition to stay in line with reaching climate goals. Electrification, Hydrogen and CCS are all ingredients of this. At the same time, for large corporates investment plans are evaluated both in a local context, and at a corporate level, where local presence is part of global operations. Therefore, companies to a certain extent are capable of making their transition analysis, and to another extent have to deal with local uncertainties. The HyChain models can support companies in making their local decisions against a sharper backdrop of the regional embedding.

As the views of these three stakeholders are developed in parallel, and are engrained in a larger programmatic process, the support of this interaction between these three classes of stakeholders can benefit the decision making in each of these groups and supports the communication between these.

### Value Proposition of a Long-Term Service Model of the HyChain Models and Tools

It is important to unify the industry around a common practice to develop joint strategies for their transition planning. The grid operators and government already have their toolbox and analysis methods in place, but industry is fragmented across 5 clusters, and on top the remaining companies located across the Netherlands in the 6th cluster. Enabling the industry to explore their own future options in a coherent toolset will provide them with their own insights and enables them to communicate and share their insights to the government and grid operators.



Vision on key elements of a Service Model for HyChain models and tools

- Industry in the lead – de HyChain Service Model supports the quality of transition planning and system integration with tools and best practices
- Facilitating – in dialogue with grid operators and government
- Supportive– development of tools for transition strategy
- Uniting– brings industry together – individually and through clusters
- Visioning – developing and propagating a vision based on collectiveness and analysis

*Figure 47: Elements of the vision to secure a long-term supported availability and use of the HyChain models.*

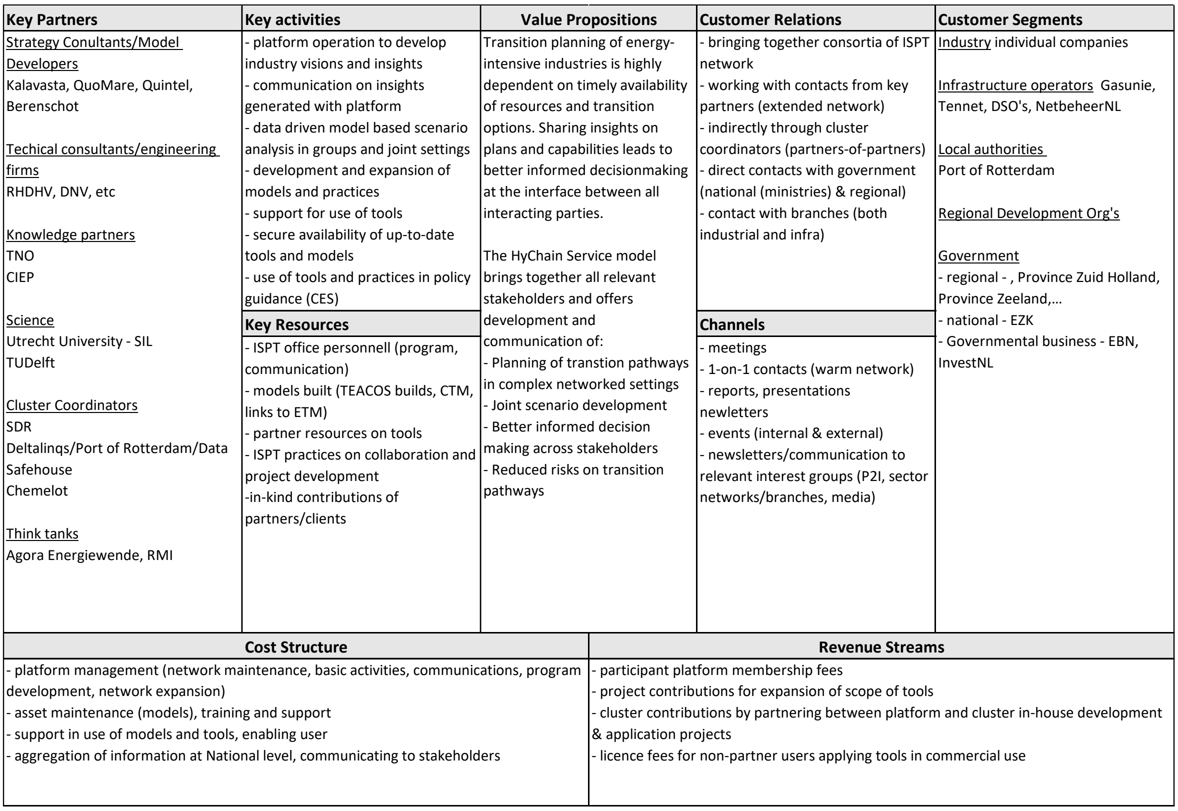
Figure 47 summarizes the key boundary conditions that need to be fulfilled through this service model. To secure that the tools are used it is important that they are trusted. This means industry has the be involved in their development and engaged in its use. Therefore, the model has to be service oriented with the needs of industry in mind, in particular in the interaction with government and grid operators.

Implementation of this vision via a long-term sustainable service model allows the HyChain tools to be used to unlock the following value proposition, also presented in the core of the business model canvas in Figure 48:

> *Transition planning of energy-intensive industries is highly dependent on timely availability of resources and transition options. Sharing insights on plans and capabilities leads to better informed decision-making at the interface between all interacting parties.*
>
> *The HyChain Service model brings together all relevant stakeholders and offers development and communication of:*
>
> - *Planning of transition pathways in complex networked settings.*
> - *Joint scenario development.*
> - *Better informed decision making across stakeholders.*
> - *Reduced risks on transition pathways.*

Implementation requires providing services to the key customers. For these services the key partners, key activities and resources are summarized in the left-hand side of the business model canvas. Customer relations, channels and customer segments are summarized on the right.

To secure long-term viability the cost structure has to be balanced with the revenue stream. It is anticipated that all three customer segments contribute to the implementation of the service model. Services are then provided by the central operator, in this case it is foreseen to be carried out by ISPT or a central, trusted national non-profit operator, and is facilitated through its key partners.



| **Key Partners** | **Key activities** | **Value Propositions** | **Customer Relations** | **Customer Segments** |
|---|---|---|---|---|
| Strategy Conultants/Model Developers<br>Kalavasta, QuoMare, Quintel, Berenschot<br><br>Techical consultants/engineering firms<br>RHDHV, DNV, etc<br><br>Knowledge partners<br>TNO<br>CIEP<br><br>Science<br>Utrecht University - SIL<br>TUDelft<br><br>Cluster Coordinators<br>SDR<br>Deltalinqs/Port of Rotterdam/Data Safehouse<br>Chemelot<br><br>Think tanks<br>Agora Energiewende, RMI | - platform operation to develop industry visions and insights<br>- communication on insights generated with platform<br>- data driven model based scenario analysis in groups and joint settings<br>- development and expansion of models and practices<br>- support for use of tools<br>- secure availability of up-to-date tools and models<br>- use of tools and practices in policy guidance (CES) | Transition planning of energy-intensive industries is highly dependent on timely availability of resources and transition options. Sharing insights on plans and capabilities leads to better informed decisionmaking at the interface between all interacting parties.<br><br>The HyChain Service model brings together all relevant stakeholders and offers development and communication of:<br>- Planning of transtion pathways in complex networked settings<br>- Joint scenario development<br>- Better informed decision making across stakeholders<br>- Reduced risks on transition pathways | - bringing together consortia of ISPT network<br>- working with contacts from key partners (extended network)<br>- indirectly through cluster coordinators (partners-of-partners)<br>- direct contacts with government (national (ministries) & regional)<br>- contact with branches (both industrial and infra) | Industry individual companies<br><br>Infrastructure operators Gasunie, Tennet, DSO's, NetbeheerNL<br><br>Local authorities<br>Port of Rotterdam<br><br>Regional Development Org's<br><br>Government<br>- regional - , Province Zuid Holland, Province Zeeland,...<br>- national - EZK<br>- Governmental business - EBN, InvestNL |
| | **Key Resources** | | **Channels** | |
| | - ISPT office personnell (program, communication)<br>- models built (TEACOS builds, CTM, links to ETM)<br>- partner resources on tools<br>- ISPT practices on collaboration and project development<br>-in-kind contributions of partners/clients | | - meetings<br>- 1-on-1 contacts (warm network)<br>- reports, presentations newletters<br>- events (internal & external)<br>- newsletters/communication to relevant interest groups (P2I, sector networks/branches, media) | |

| **Cost Structure** | **Revenue Streams** |
|---|---|
| - platform management (network maintenance, basic activities, communications, program development, network expansion)<br>- asset maintenance (models), training and support<br>- support in use of models and tools, enabling user<br>- aggregation of information at National level, communicating to stakeholders | - participant platform membership fees<br>- project contributions for expansion of scope of tools<br>- cluster contributions by partnering between platform and cluster in-house development & application projects<br>- licence fees for non-partner users applying tools in commercial use |

*Figure 48: Business model Canvas, summarizing the service model that can support long-term implementation and availability of the HyChain models.*

### Centralized or De-Centralized?

To support decision-making on planning of infrastructure for energy transition it is important to address the correct aggregation level. As Figure 46 showed, the decisions of industry, grid operators and national government all are connected, but have a different perspective. For industry it is important to explore your options in your direct environment. Integration with local infrastructure will enable you to make your transition projects work. However, a government or a TSO holds a centralized viewpoint. The government needs to assure a level playing field from a national perspective and takes decisions for top-down measures. Grid operators at national level – TSO's – have similarly a role at national level with gas and power infrastructure connecting transport across large distances. At regional level the role of the DSO – the Distribution System Operator – comes together with that of regional authorities (Port Authorities, municipalities and provincial government) and coordinators such as Deltalinqs or Smart Delta Resources and interacts directly with the industry. Figure 49 shows therefore the aggregation levels chosen to address in the HyChain project accordingly to those three perspectives, that of the individual company, that of the region and that of the national viewpoint.

This perspective has consequences for the service model. The direct value for individual companies is in the first place to assess their transition options in the regional constellation. So between individual companies and a cluster there is a joint interest to build a aggregate picture in the cluster model and continuously build on that. A regional coordinator who governs the model, the underlying dataset and develops the regional scenarios is very important.

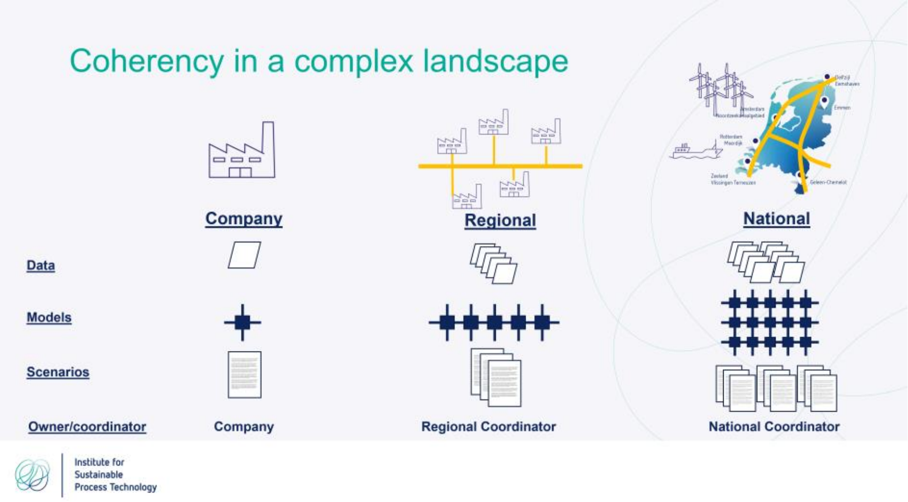
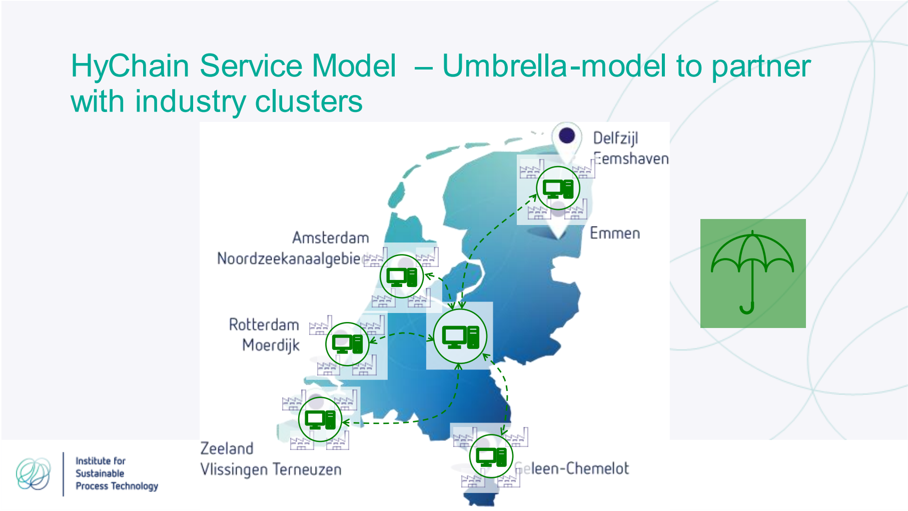

Coherency in a complex landscape

*Figure 49: Development of HyChain models related to their different aggregation level. We recognize the importance of addressing individual, regional and national levels, where the perspective of decisions shifts from single company to cluster/regional interest to national interest.*

However, for communication to TSOs and national government the aggregation from regions to national picture is also important. ISPT acts as national coordinator and can aggregate regional models into a national picture. It can also function to harmonize datasets, models, basic assumptions and starting points for scenarios and thus support the development of a coherent national approach.

Figure 50 shows how the business model then can be implemented in a umbrella model. Each cluster is regionally coordinated and managed by a trusted advisor who understands best the local situation. A national coordinator supports regional model development and use to secure high-quality use of the tools and consistency in approaches between clusters. Aggerating the results coming from the models in a



HyChain Service Model – Umbrella-model to partner with industry clusters

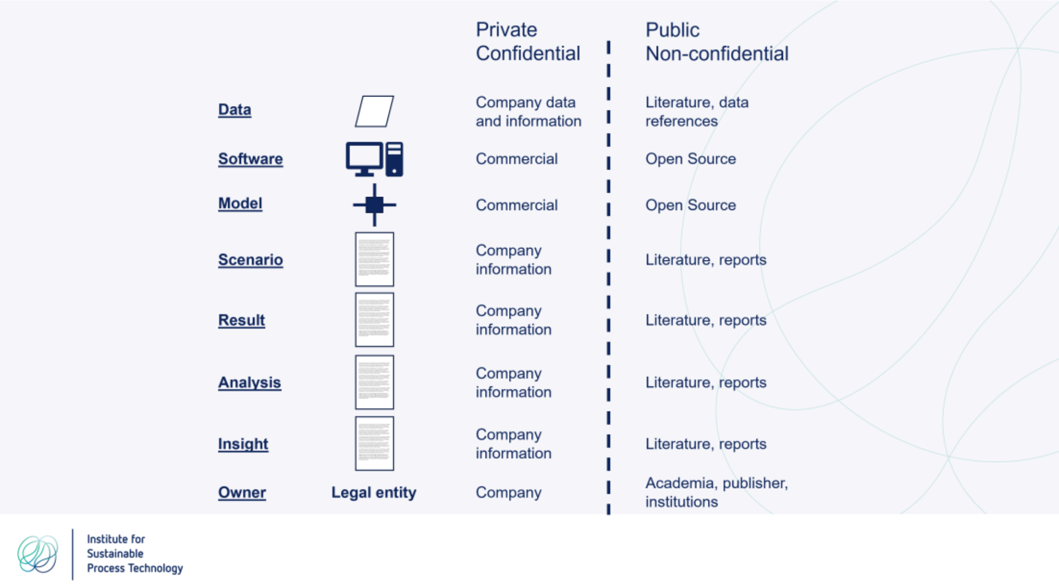
*Figure 50: The HyChain model approach can be implemented across The Netherlands in a consistent way in an umbrella approach. Each region develops its own set of data-model-scenarios in the same framework. Centrally the development is supported and coordinated to secure consistency in data-model-scenarios and secure that adding regionals models leads to consistency at national level.*

coherent approach then allows to create a national picture that can be communicated with national stakeholders, and allows to check if ambitions, plans and goals match with the capacity and limitations at national level. In this way bottom-up insights and plans can be communicated to grid operators and policy makers, thus increasing the consistency and quality of informed decision making.

## Confidentiality and Governance

The analysis of industrial transformation needs to build on accurate data. Analysis is done in close partnership with the actual decision makers – across companies but also with grid operators and other regional stakeholders. To secure partnership and alignment with the industries a bottom-up approach has been chosen. Going forward the confidentiality needs to be carefully secured, and hand-over mechanisms between parties and between private and public domain needs to be in place. A governance framework will also have to be in place to secure control over this transfer.

Firstly, we need to address the difference between private and public information and data. The difference is quite straightforward, private data is confidential, privately owned and generated or acquired, and often suits private needs or business interests. Public data is shared for the advancement of knowledge, and for sharing insights and public debate. Often public data is created in academic research and published, or created in private settings and published e.g., through patent literature. Figure 51 characterizes how the private and public domains compare to the information generated in transition modelling and analysis. In the context of the HyChain models it is important to realize that the scope extends across the categories of information mentioned. In short, data is all relevant information needed to characterize the investment (type of factory or equipment and all its properties and connectivity) as well as all data of utilities, products, chemical compounds. etc. Software is the tool used to capture the equipment in its context, used to build the models. Commercial tools often used are excel, or in more specialized situations for example the Aspen flowsheet modelling tool. The model is the specific implementation of the factory as represented in the software. The scenarios describe and quantify the future beliefs – expectations of changes to be carried out, for example of price developments and configuration changes. By applying scenarios to the model, results are generated that give the consequences of the future conditions and allow for an analysis and eventually support decision making. For each category there are private as well as public representations. It is important to capture mechanisms that enable analysis in a private setting to be enriched by information



| | | Private Confidential | Public Non-confidential |
|---|---|---|---|
| **Data** | | Company data and information | Literature, data references |
| **Software** | | Commercial | Open Source |
| **Model** | | Commercial | Open Source |
| **Scenario** | | Company information | Literature, reports |
| **Result** | | Company information | Literature, reports |
| **Analysis** | | Company information | Literature, reports |
| **Insight** | | Company information | Literature, reports |
| **Owner** | **Legal entity** | Company | Academia, publisher, institutions |

*Figure 51: Typical categories of public and private information related to the HyChain project setup. A chain from data to analysis needs to be covered to come from bottom-up data to insight in support of strategy development.*

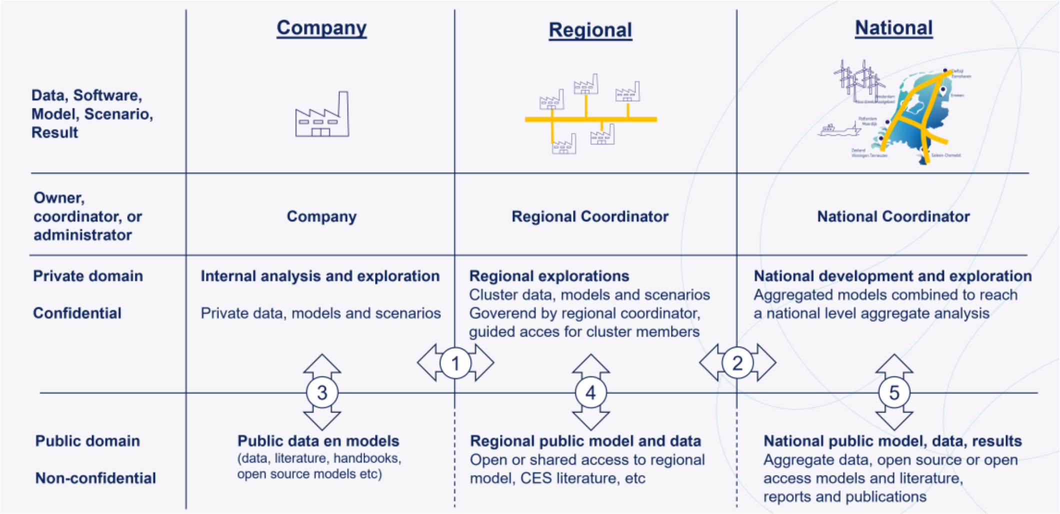
from the broader, public, non-confidential context. Therefore, interaction and handover mechanisms between the public and private domain need to be in place to facilitate communication between the two.

For model building and analysis both public and private data is used. Furthermore, data can be shared, both while keeping the data private, or through making the data public. In the nested approach of the HyChain service model, aggregating the data from bottom-up industry to high-level national viewpoint shown in Figure 49 and Figure 50, requires that you need controlled data handover.

Figure 52 shows the three aggregation levels in column – company, regional and national. By aggregating to higher levels decisions need to be made what is included and how communication across levels is done. At each level we can do the following:

1. Company level (sub-)models of the processes, factories and of entire sites can be built based on in-house available data, plans and strategies. Model representation can be entirely privately owned. The company is the owner and controlling party in charge of (optional) transfer of data and models to another domain. Companies considered are primarily industry, but can also be for example local grid operators, power producers or others who are in control of specific assets that are part of the system.
2. At regional level the cluster model aggregates the data and models that allow for an integral description of the cluster, showing a coherent picture of the supply-demand network in the region. The regional coordinator is responsible for operating and maintaining the models and is in control of collective system data and models on behalf of the cluster. Both a private and a public version of the regional model are foreseen. Further, agreements on confidentiality are in place that secure that the use of the model complies with ACM regulations – industries do not see each other's details and only see and discuss trends in aggregate results of the region.

3. At the national level a aggregate model collects the key information for a national analysis. The national coordinator is the controlling party on behalf of all connected stakeholders and clusters.



| | **Company** | **Regional** | **National** |
|---|---|---|---|
| **Data, Software, Model, Scenario, Result** | | | |
| **Owner, coordinator, or administrator** | **Company** | **Regional Coordinator** | **National Coordinator** |
| **Private domain**<br>**Confidential** | **Internal analysis and exploration**<br>Private data, models and scenarios | **Regional explorations**<br>Cluster data, models and scenarios<br>Goverend by regional coordinator, guided acces for cluster members | **National development and exploration**<br>Aggregated models combined to reach a national level aggregate analysis |
| **Public domain**<br>**Non-confidential** | **Public data en models**<br>(data, literature, handbooks, open source models etc) | **Regional public model and data**<br>Open or shared access to regional model, CES literature, etc | **National public model, data, results**<br>Aggregate data, open source or open access models and literature, reports and publications |

*Figure 52: Hand-over mechanism for data management and controlled access to and transfer of models, scenarios, and data. Distinction between private (confidential) data and models – not in the public domain; and public (non-confidential) data and models present in the public domain at the lowest level of the diagram.*

Governance – the determination who oversees which transfer of data – needs to secure exchange of information. The lower half of Figure 52 shows how information (data, (sub-)models, scenarios, etc) can be exchanged horizontally – across aggregation levels, indicated by arrows (1) and (2); and between the public and the private domain, indicated by arrows (3), (4) and (5).

Every time there is a transaction between the private and the public domain there needs to be a conscious decision of who shares what with whom. Arrows in Figure 52 indicate the transfer and point both ways as data exchange typically goes both ways. The five interactions require a certain degree of control and coordination. Exchange between aggregation levels is the following:

1. Exchange between company and region: The first interaction is between individual companies and the regional model under control of the regional coordinator. It is possible to build proprietary in-house models for private explorations. These can be enriched with outside information. In the ideal situation there is a active link with the regional model to provide context to the in-house analysis. Individual companies can get access to the regional model to test and explore their ideas. Therefore, access to the regional in-house cluster model needs to be secured. At the same time, when companies feel confident or see a need to discuss their ideas with other cluster members a mediated interaction under coordination of the cluster coordinator can take place – securing confidentiality and complianc with ACM rules.
2. Exchange between Cluster and national aggregate level: National aggregation and feedback is necessary to check and balance how national resources are used and distributed across clusters. At national level model analysis is done to understand long-range interactions and dependencies – e.g., for supply and demand of material flows between clusters, timing impact (e.g., availability of green power) on own or regional development, or to aggregate bottom-up the impact of policy measures at national level to engage with national authorities and stakeholders. Therefore, an iterative check between cluster plan and

national allocations needs to be made. A national model capturing transmission infrastructure and allowing exchange between clusters is used to secure a national coherent view.

At each aggregation level an exchange between public and private domain is possible. Sometimes it is useful to discuss with a model made publicly available so the representation is non-confidential and can be openly discussed. It remains to be seen and decided which parts are made fully publicly available – datasets, models or complete analysis. Typically, analysis results and insights are often created to communicate the insights. For exchange of views with external parties like the government it can be very useful to have a public open-access description and model available. This can be done at each level:

1. Exchange between company and public domain: A mix of public and private data is often used to build transition scenarios for each company, with underlying data from for example the MIDDEN data, or data from textbooks and general knowledge. Transition plans are sometimes also communicated publicly from single companies, e.g., in support of agreement with the national government.
2. Exchange between regional private and public domain: A certain degree of public representation of the cluster model can be made available in the public domain. A regional model can be updated on a fixed cycle and then this fixed model can be transferred from private to public domain based on common agreement with the cluster partners.
3. Exchange national/other levels and national public domain: At the national level a public model aggregates the regional results to identify material flows, impact of policy measures and global trends.

### Service Implementation

In the HyChain project we worked with two different clusters and several local parties to develop the models and carry out joint analysis. This has proven a good testing ground for the service implementation.

Model development has primarily been done by QuoMare who owns the TEACOS modelling framework, that was used as modelling basis. So, in building up the knowledge the expertise has been delivered by them.

Local ownership and governance at cluster level is foreseen to be carried out by the local network coordinator. In each cluster a local coordinator, or group of parties coordinating locally has been involved. In Zeeland this role was carried out by SDR, Smart Delta Resources. In Rotterdam this was done by Port of Rotterdam together with Deltalinqs. Along the way also the Province of Zuid Holland joined the consortium and strengthened the model development.

Central coordination was done by ISPT as national coordinator.

Going forward the services provided can be mapped on the three pillars presented in Figure 46:

1. Implementation – this is carried out primarily by QuoMare, who provides the model environment and supports with training, maintenance and updates. Together with ISPT trainings and support and coordination work can be organized.
2. Use – the model use can be provided in several manners:
    a. Individual company – a company who wants to explore its own options and strategies can work with the model:
        i. Directly – after proper training and setup of accounts a company personnel can get direct access and work with developing models and running scenarios and analysis. Development of models requires more skills, experience and training than carrying out analysis but is still fairly involved.
        ii. Delegated – models can be developed further, and analysis can be done with various forms of support:

        1. Through QuoMare
        2. With support of trained consultants
        3. With support of trained staff from a trained research organization such as TNO.
    b. Cluster – cluster analysis can follow the same principle. In the HyChain project staff of the clusters has worked closely with QuoMare to develop the models and run the analysis. In the long-term situation it may prove useful to carry out model development and analysis with specifically trained staff in place.
    c. National level – aggregate analysis and a national model have been specifically built in the HyChain project. It has to be developed how this can be done in a future implementation.

### Costs and Revenues

We foresee the following structure with basic costs and revenues:

- Centrally a coordinator needs to be in place who secures alignment across cluster, with national operators and national policy. This is carried out by ISPT who secures that a national platform is in place, running a operational roadmap and carries out national program that is running a fixed cycle. Basic model maintenance, interoperability and availability is secured.
- Costs for the platform function are covered by a platform membership of individual industries and grid operators with whom analysis of ongoing questions and issues is addressed to interact with the national government. It is anticipated that national funding is provided in support of the open platform.
- At the Cluster level, cluster membership is secured by running local development and use projects. The local cluster develops and expands it local model and for that runs its local roadmap. The local project secures data handling and exchange, and operations align with government-imposed processes that are built on the regional transition roadmaps generated through the model analysis. The local/regional projects are funded through local participation of industries in their cluster network.
- Open-source access to (parts of) the model platform can be used for external communication or services. Different revenue models can be developed on top – to be explored still.

## Service Model Development & Implementation

During the HyChain project several steps have been taken to develop the service model. On top of the HyChain project another ISPT project has run, the Carbon Transition Model project which has many similarities. Therefore, going forward the model legacy of these projects has led to the initiation of the Tekenkamer van de Industrie – Industry's Drawing Room. We describe for each of the elements what is the status.

### Case SDR

In the Zeeland region close collaboration with the SDR organization and its members has developed solidly throughout the project. The SDR organization has come onboard during the project and has supported the project actively over time. Towards the end of the project a basic model that covers Dow, Yara and Zeeland refineries has been delivered, and all underlying infrastructure has been captured. Over the course of 2022 the model has been consulted in support of the development of the Cluster Energy Strategy – a regional roadmap for the development of the SDR industry cluster and SDR infrastructure projects.

At the same time, SDR has gained support from its industry members to further develop the model in a 2-year project, together with QuoMare and ISPT. Primary requirement is that the model is expanded across the Belgian border, to build on other modeling work done in parallel project Steel to Chemicals with Arcelor Mittal in Ghent. The regional commitment with this partnership is the first physical activity running outside of the HyChain project, as a steppingstone and example of the long-term service arrangement. Through ISPT participation in this regional project the participation in the Industry's Drawing Room is secured for the cluster.

### Case Port of Rotterdam

During the HyChain project the Port of Rotterdam, Deltalinqs, the Province of Zuid-Holland have teamed up and guided the regional model development. Deltalinqs has provided the basic data from the Energy-mix Study and the Province has supported expansions with implementing the role of CCU and with adding infrastructure. This support was provided to enable the use of the models in preparation of the Cluster Energy Strategy, similar as was done by SDR.

Currently the Port of Rotterdam region is developing its approach to build the model use in its ongoing process to develop the Cluster Energy strategy in a regular management cycle in its cluster. The region has developed the Datasafehouse – a data repository where together with the industry a data exchange mechanism is in place that coordinates the data acquisition for the Cluster Energy Strategy in support of infrastructure development. By incorporation of the HyChain model framework on top of data acquisition the Datasafehouse can transform into the platform that not only acquires the data, but also generates to roadmap and forecasts for infrastructure investment and transition planning. The strategy how to develop this regional platform is currently being developed between Port of Rotterdam, the regional infrastructure planning partners and ISPT, and will be closely aligned with the Industry's Drawing Room.

### Engagement with other Industry Clusters in The Netherlands

Besides the initiatives in the HyChain project it is worth mentioning two other important developments:

- For the Chemelot cluster TNO has developed a transition model in TEACOS framework. The modeling basis is the same as for SDR and PoR. Thus, an alignment with the Chemelot Cluster in principle is possible. It is currently under discussion how to shape this engagement and build the consortium of the Drawing room with inclusion of the Chemelot Cluster and TNO.
- For Tata Steel a transition model based on the Steel-to-Chemicals project has been built in the TEACOS framework. It is currently under discussion how to support Tata to expand this modeling exercise and build a full transition model including their DRP plans as a cornerstone for the cluster transition plans of the North Sea Channel area.

### Case Tekenkamer van de Industrie – Industry's Drawing Room

Over the course of the last years the appreciation has grown of the role of system integration. While originally all transition plans have been developed in stand-alone pillars, between sectors, between clusters and across regions, currently it is clear that more insights are necessary to come to a sound national transition plan. We see that currently at the Ministry of Economic Affairs therefore a National Plan Energy System and a National Plain Sustainable Industry is developing. These plans need adequate alignment with industry plans and need a forward-looking vision of how offshore wind power and large-scale solar power developments are integrated with the daily life in society. Industry is a big part of this and a solid mechanism to align planning and development across the regions and scales, bottom to top, is key to the timely development of the energy transition.

Over the last year ISPT has initiated its initiative titled Tekenkamer van de Industry – Industry's Drawing Room. This Drawing Room will form a platform that facilitates development of a vision of a sustainable industry in The Netherlands, where large-scale developments of power production, infrastructure development and large-scale use in industry are explore, designed and evaluated coherently, together with the field to which it relates. Thus, a high-quality consistent vision of a future Netherlands is developed, matching with the capabilities and roles fitting to the needs and capabilities of The Netherlands.

The HyChain models have an important role to play in this setting. On the one hand they enable to design transition pathways for the clusters, quantifying what is possible and where limitations are encountered. The explorations will have to be based on local scenarios that take into account typical regional geographical aspects. At the same time, the regional scenarios will have to be harmonized with a national viewpoint, where. The HyChain models have a role to play in bringing these levels together. The Carbon Transition Model also has a role to play in bringing the coherency at national level together and communicating the insights to the national grid operators for their forecasting, explorations and investment planning.

Early 2023 the Tekenkamer has held its first initiating meeting and currently the commitments are being gathered, alignment with the Ministry, Grid Operators and Clusters is ongoing and over the next months the first activities will start up.

## Conclusions and Outlook

Throughout the HyChain project we have spent continuous attention to secure long-term availability of the HyChain models in a supporting partnership. We have experienced that there is substantial interest in the availability of digital twins for transition planning for the industry that has a role to play in the process for development of the Cluster Energy strategies. Furthermore, there is a role to play for developing of a forward-looking vision of a future industry that matches with the needs of the Dutch society, both in terms of the material output of the industry, as well as in the economic contribution of industry to the Dutch society. The adoption of the tools and models of the HyChain project in the SDR and PoR clusters is a strong indicator that this role can be fulfilled and the strong support for the Tekenkamer van de Industrie is another indicator that there is a role to play for the models developed in the HyChain project.

In the coming years the following activities will develop that further secure the model basis:

1. HyChain 5 – an academic project has been initiated that is now running, which build on the tools and models developed and will expand scope and strengthen models and model capabilities.
2. SINERGY – a model expansion will be made to expand the scope of the HyChain and CTM models. In this project a connection between major offshore developments in the coming decades and the onshore energy system transformation is made. Results will be adopted in the Tekenkamer.
3. Roll-out to other clusters – engagement with Chemelot, Noordzeekanaal area and Eemshaven is ongoing, activities to support 6th cluster companies are ongoing.
4. Future industry scenarios will be developed in various activities. An initial input has been given to the expert team of the Program Energy System, an EZK initiative, and in the development of the National Programs Energy System and Sustainable Industry alignment and cooperation will be shaped.

# Conclusions

With the HyChain Model an integrated investment optimization model for the hydrogen supply chain for the Dutch industry was developed, in context of alternative decarbonization pathways via direct electrification and CCS as well as associated infrastructure. The model was developed for the Netherlands and two large Dutch industrial clusters, with full coverage of hydrogen and electricity supply chains at national-, regional- and site-level. The model allows for long-term optimal investment modelling of system decarbonisation over the course of the energy transition, presenting optimal multi-stakeholder investments across energy supply, infrastructure and industrial demand on a year-by-year basis.

The HyChain Model was applied in a series of case assessments in a multi-stakeholder setting with project partners representing regional authorities, industry, energy and network operators. The cases were designed to explore the impact of uncertainties in predominantly energy policy (Cases 1, 2 and 4), technical potential for new markets (Case 3) and infrastructural dependencies (Case 5). Accelerated GHG emission reduction (Case 1), bringing the 2030 GHG emission reduction targets forward to 2027, left the SWNL and PoR region results largely unaffected, as emission reduction was predominantly driven by the EU ETS prices. Promotion of green hydrogen production (Case 2), promoting green hydrogen deployment in industry as proposed in the Fit-for-55 package, resulted to drive increased green hydrogen investments at cost of blue hydrogen investments. Potential for hydrogen as feedstock (Case 3), exploring the potential for hydrogen deployment in synfuel and syn-naphtha production rendered to be high in comparison to alternate hydrogen demand in the Rotterdam area. An imposed CCS phase-out (Case 4), assuming an end to the CCS era by 2045 resulted to reduce attractiveness of CCS investments in the SWNL significantly, while such is not the case for the PoR area. In the first case higher CO2 emissions result from notably 2030 onward, while in the latter case investments in alternatives by the end of the evaluation period predominantly drives up overall costs. Delayed regional power grid reinforcement in the coming decade (Case 5) may limit electrification efforts and predominantly induces increased hydrogen deployment, lowered CO2 emission reductions and increased EU ETS exposures in the 2030 – 2040 timeframe.

The workshops allowed for joint fact-finding and development of a common understanding of trade-offs (for example, regarding blue hydrogen, green hydrogen and regional hydrogen imports) involved with these uncertainties and implications for the investment strategies for hydrogen supply chain development and industrial GHG emission reduction. This experience suggests significant benefits may be attained, both for individual stakeholders as well as joint stakeholder efforts in the Dutch Hydrogen supply chain development. We have experienced that there is substantial interest in the availability of the HyChain Model for transition planning in industry and the Cluster Energy strategies, as well as the future role of industry in the Dutch society in terms of the material output and the economic contribution. The service model developed in this project builds on early arrangements to support the Cluster Energie Stategie 2.0 for SDR and Rotterdam-Moerdijk.

The adoption of the tools and models of the HyChain project in the SDR and PoR clusters and the strong support for the initiative to establish the Tekenkamer van de Industrie offer clear indications of the role that the HyChain Model can play. In the coming years the following activities will be developed to further secure the model basis:

1. HyChain 5 – this academic project started in 2022 and builds on the tools and models developed and will expand scope and strengthen model capabilities.
2. SINERGY – a project initiative to expand the scope of the HyChain Model to capture major offshore developments and the onshore energy system transformation.
3. Roll-out to other clusters – engagement with Chemelot, Noordzeekanaal area and Eemshaven is ongoing, as well as activities to support 6th cluster companies.
4. Future industry scenarios will be developed in various activities. An initial input has been given to the expert team of the Program Energy System, an EZK initiative, and in the development of the National Programs Energy System and Sustainable Industry alignment and cooperation will be shaped.

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# Colophon

**Title**
HyChain 4 - Integral hydrogen-based supply chain development

**Subtitle**
A service model for public-private transition planning

**Publication date**
January 18, 2024

**Authors**
Jaron Davelaar (QuoMare)
Sebastiaan Hers (TNO)
Andreas ten Cate (ISPT)

**Published by**
Institute of Sustainable Process Technology (ISPT)

**Address**
Groen van Prinstererlaan 37, 3818 JN Amersfoort, The Netherlands

**Telephone number**
+31 (0)33 700 97 97

**E-mail**
info@ispt.eu

**Website**
www.ispt.eu

**About this report**
This report is part of the series of HyChain projects. Earlier project parts were:

- HyChain 1: Assessment of future trends in industrial hydrogen demand and infrastructure
- HyChain 2: Cost implications of importing renewable electricity, hydrogen and hydrogen carriers into the Netherlands.
- HyChain 3: Hydrogen Supply Chain – Technology Assessment

### The HyChain Project

The HyChain project is initiated by the Institute for Sustainable Process Technology (ISPT) and is part of the Hydrohub Innovation Program. Its mission is 'Largescale electrolysis-based production of sustainable, low cost, hydrogen as a driver for circular industrial chains'. The project is part of the ISPT cluster System Integration. The HyChain central research focuses on the question: 'How can we make an optimization for all the full value chain to deliver the lowest cost, carbon-neutral hydrogen to Dutch industry (domestic and global production) and what barriers and bottlenecks stand in the way?'.

### Public funding

This project is co-funded by TKI Energy & Industry, part of the Topsector Energie, with the supplementary grant 'TKI-Toeslag' for Topconsortia for Knowledge and Innovation (TKI's) of the Ministry of Economic Affairs and Climate Policy.

### Consortium partners

We kindly thank the consortium partners for their support and active participation in the course of this exciting project. It has been a pleasure working with all of you and experiencing your unwavering support, despite rough times starting up this ambitious project in the middle of the Corona crisis period.

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Process Technology

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ISPT.EU

**Andreas ten Cate**
Program Director System Integration
ISPT
andreas.tencate@ispt.eu
t. +31 6 1587 4702

**Sebastiaan Hers**
Senior Consultant
TNO
sebastiaan.hers@tno.nl
t. +31 6 1562 3680

**Jaron Davelaar**
Team Lead Energy Transition
QuoMare
jarondavelaar@quomare.com
t. +31 6 4185 2859