Harbours: the heart of the energy transition

The role of Northern harbours in the provision of clean energy

The Havenschets project was carried out with subsidy from the Ministry of Economic Affairs, National schemes for Economic Affairs subsidies, Topsector Energy implemented by the Netherlands Enterprise Agency (RVO).

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This study has been coordinated by New Energy Coalition and has been created in close collaboration with TNO and University of Groningen. An industry-based review-group was established – consisting of representatives of Port of Amsterdam, Port of Den Helder, Groningen Seaports, Gasunie, and EBN – to validate the findings and to put them in perspective of the existing and future harbour activities.

Executive summary

Harbours will play a significant role in transmission of energy (both electricity and hydrogen) towards 2050. The extension of North Sea offshore wind capacity up to 2050 (38 to72 GW on the Netherlands' continental shelve; and some 200 to 300 GW on the total North sea area will partly be unlocked via harbours (1), (2)**. The aim of this study is to identify what role harbours play as hub(s) in the energy transition towards 2050. In doing so, we specifically zoom in on the Northern Netherlands harbours: Groningen Seaports, Port of Den Helder and Port of Amsterdam. These three northern Netherlands harbours may well develop in the next few decades into an energy hub of national or even North-Western European proportions. Green hydrogen, blue hydrogen and hydrogen imports take a comparable share in hydrogen transmitted via these harbours, the collective electrolyser capacity may grow towards 150 PJ (or some 8 GW[1]) in our base scenario, or even some 300PJ (or some 16 GW[2]) in our optimistic scenario. In addition, blue hydrogen production capacity may rise towards levels ranging from 150-290PJ (or some 4.5 - 9 GW[3]), and hydrogen imports towards 1.2 - 2.4 Mton per year.**

A major part of the projected extension of the offshore wind capacity in the North Sea area will be located north or north-west of the Netherlands coast. The northern Netherlands harbours therefore are a logical transmission point for a serious part of the future energy generated offshore. To the extent that the North Sea energy will be converted into hydrogen or derived products, the same harbours are a logical location for conversion activity and/or transmission of hydrogen, and the various industrial activities that are likely to be linked to such large-scale hydrogen production. In this report we have assumed a base scenario - given the future location of offshore windfarms - in which, by 2050, the three harbours combined will handle about 25% of the total projected hydrogen demand of the Netherlands and the German main industrial clusters ($450PJ_h$ out of $1800PJ_h$ (3), (4), (5)[4]. At least some $120PJ_h$ of this volume is absorbed in the harbour areas themselves (6), (7)).

The same harbours have a good position to act as transmission points of CO_2 for offshore subsurface storage due to their relative proximity to offshore-depleted gas reservoirs and related platforms and compression capacities. This emphasizes their suitability as production points of blue hydrogen.

The port regions – especially the Port of Amsterdam region (including IJmuiden and Schiphol) and the Groningen Seaports region (including the chemical cluster in Delfzijl) – are likely to face a considerable growth in local demand for hydrogen during the upcoming decades.

The harbours can collectively act as a major hydrogen production and transmission hub not only for their own regions but also for the wider hinterland, if linked via a dedicated hydrogen transmission backbone with each other as well as with the major industrial centres in North-Western Europe. The existing strong infrastructural connections of the three harbours (both via the gas grid and via the electricity grid) may well strongly support this emerging hydrogen hub function.

There is clear evidence that a close collaboration between the three harbours is likely to generate serious synergy benefits. Our modelling suggests that, depending on the scenario, these benefits can add up to €100 – €300 million per annum for the three harbours combined.

- By operating as a collective energy hub, the harbours' position will strengthen e.g. in their positioning on the national and European energy agenda towards the energy transition.
- By working together the three harbours will be better able to further specialize in their unique selling points and thereby to generate economies of scale and reducing energy system expenditures (M€/PJ) with some 30%-50% in comparison to a situation in which the harbour regions are completely isolated.
- Synergy advantages are strongly dependent on a hydrogen backbone connecting the three harbours, such that hydrogen flows can easily be exchanged and collectively transmitted further into the hinterland. The current projections of planned backbone investments suggest that only Groningen Seaports and Port of Amsterdam will be connected to such a backbone (8). To unlock the full potential of the three northern Netherlands harbours as an energy hub, a connection to Port of Den

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[1] Based on 5250 operational hours
[2] Based on 5250 operational hours
[3] Based on 8760 operational hours
[4] Note that this projection does not include the demand for hydrogen required for the production of syngas and/or liquid fuels. If that demand would be included, the 2050 demand figure could easily grow to by a third (3), (5).

Helder should be connected as well. Some projections made for this report suggest that in the absence of a backbone, the three harbours combined will transmit only ~120 PJ of energy by 2050, whereas if the backbone does exist, the energy flows can easily grow towards levels in the order of 400 – 875PJ per year by 2050.

- By collaborating via the backbone connection, the harbour hub will be able to act as a flexibility provider to the energy system: because hydrogen can be transported back and forth, a stable and secure energy supply can be guaranteed, which is crucial for some dedicated industrial activities in particular.

Each of the three harbours may well specialize in specific hub functions given local conditions and positioning to existing grids and industrial activities.

Sspecialization generates economies of scale and therefore comparative advantages for scaling up specific additional economic activity. When the benefit of such economies of scale are not valued, avoidance of hydrogen transport expenditures may lead to favoring a decentralized approach. The value of centralized production versus locational cost advantages have to be significant enough to weigh out the energy transport costs of the interconnection. The balance between transport expenditures, economies of scale and location advantages is defining for the distribution of activities in the future energy system between the three harbour regions

Generically speaking, Groningen Seaports is well situated to develop into a major green hydrogen production and transmission location, e.g. because the presence of extensive chemical industry and its proximity to large-scale storage facilities (5). Port of Den Helder is well-positioned for blue and dedicated green hydrogen related activities e.g. due to its location next to feed-in points into major gas trunk lines and its proximity to offshore wind locations. Port of Amsterdam has a promising profile to develop into a major hydrogen import location including related conversion and end-use (steel and aviation fuels), given that Port of Amsterdam is already a leading player in liquid bulk

The fact there is strong diversity in unique selling points of the three harbour regions as well as the fact that they complement each other, leads to a broad range of services related to the various elements of the hydrogen value chain when the harbours act as an energy hub.

How energy transmission will be divided over the three harbours is still hard to predict. The role of the individual harbours in transmission of hydrogen towards 2050 will strongly depend on: the development of the hydrogen market as a whole; if the three harbours succeed in positioning themselves as a successful energy hub; the degree to which blue hydrogen will be part of hydrogen supply by 2050; and the share of imported hydrogen from other regions than the North Sea region in the energy mix.

Each of the harbours’ future development as a regional energy hub depends on specific conditions. For Groningen Seaports it is important that (i) additional connections other than the Cobra and NorNed cable, e.g. nearby German windfarms, can be established, (ii) that new nearby windfarms will be developed that are well-suited for green hydrogen production, and (iii) that the hydrogen value chain will fly in the region. For Port of Den Helder a connection with the hydrogen backbone is rather crucial; in addition it is important for this area whether the existing gas pipeline connections with offshore gas fields/platforms can and will be used for transport of CO_2 and possibly hydrogen from and towards the area. For Port of Amsterdam the growth of import of hydrogen may help the area to benefit from existing infrastructure; additionally further industrial development e.g. towards producing and handling carbon-neutral bunker fuels and steel will play an important role in the further growth perspective.

Several organizational issues will have to be tackled timely and effectively in order for the three harbours to successfully develop into a major energy hub. Organizing good collaboration between the various stakeholders involved is an obvious precondition as well as clear targets and strategies. The wide variety of private and public stakeholders involved leads to an equally wide variety of stakeholder objectives, perceptions and issues. These objectives, perceptions and issues are moreover likely to change over time. Identifying the stakeholders and their role in the development of energy-related activities in the harbour areas is therefore crucial to be able to collaborate effectively.

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[5] significant parts of the North Sea are relatively shallow, which makes it easy to install wind turbines, and helps to produce power at relatively low costs (i.e. in the order of currently some 0.50€/MWh (51)).

Additionally it is crucial that the emerging energy hub importance for the overall national and even European economic development is acknowledged and included in the organization of port-related activities. Inclusion in the European TEN-E network and linking to the TEN-T corridors could strategic devices to achieve this.

In accordance with the ESPO view, it will have to be organized that the harbours will explicitly be linked to the new energy corridors under the TEN-E and TEN-T network. That way harbour clusters can contribute to a swift introduction of alternative fuels by supplying hydrogen to inland industry clusters, bunkering infrastructure for inland navigation, and fuelling stations for road and rail. It is important that the national government recognize the strategic position of the three northern harbours as a (green) energy hub for the national economy.

To develop the three northern Netherlands harbours into an energy hub, large-scale investments (tens of billions of euros) need to be made in activities ranging from harbours facilities and connecting infrastructure to conversion, production and import capacities for the industry, mobility and the build environment. All these activities will need to be coordinated in order to fit together. For this to happen public-private coordination is crucial, but also a clear system of rules and regulations clarifying responsibilities, liabilities, and legal competences. This will require a serious additional legal framework, for example:

- Given that municipalities are currently the main shareholders in most Netherlands' ports (and therefore also responsible for long-term spatial planning), port authorities will increasingly link with private companies through Private-Public Partnership (PPP) transactions e.g. covering investment-intensive construction works. This requires additional legal guarantees. The same applies to the recent wave of privatisation with regard to port activities, which also poses new legal challenges.
- Existing regulatory frameworks do not provide the legal certainty necessary to sufficiently support the conversion of wind energy to hydrogen onshore due to e.g. uncertainties on responsibilities towards introducing direct windfarm-electrolyser connections and on repurposing existing gas pipelines. The same holds for hydrogen storage and various facilities for hydrogen application.

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1. Context

The importance of port regions for the energy transition is stipulated in the European Green Deal: “airports, maritime and inland ports play a major role, both as inter-connection points in the respective transport networks, but also as major multimodal nodes, logistics hubs and commercial sites, linking with other transport modes, hinterland connections and integrated with cities” (9). So harbour areas are considered an interesting location for centralizing the collection of offshore wind energy, as well as integrating energy functions like the production and import of hydrogen with other industrial and logistics port-related activities.

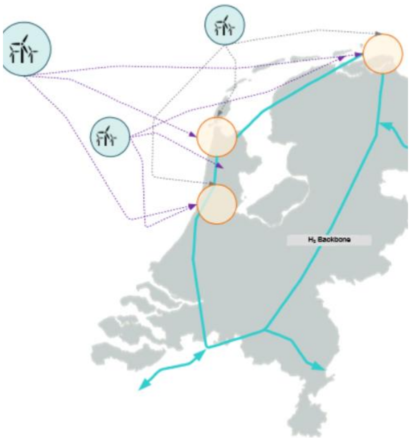

Figure 1: Graphical description of research areas

The term 'port-related activities' is broad, covering several types of activities. Traditionally, port-related activities are typically associated with facilitating: (i) the arrival and departure of ships; (ii) navigational aid and vessel traffic separation facilities; (iii) pilotage, tugging and mooring activities; (iv) the use of berths, sheds, and loading facilities; (v) the discharge, storage and distribution of cargo; and (vi) supply chain logistics and management. By contrast, the development and operation of energy activities (e.g. hydrogen production) within a port area are less perceived as typical port-related activities. The aim of this study is to fill this gap and to instead focus on the potential role of harbour regions in the energy transition towards 2050. In doing so, we will specifically zoom in on the Northern Netherlands harbours: Groningen Seaports, Port of Den Helder and Port of Amsterdam. The potential of energy-related activities in these harbour areas has been studied before for the individual regions of Noord-Holland (7) and Groningen (6) but these studies only focused on how the harbour activities could contribute to the regional energy system. The current study, instead, focusses on a much wider regional scale by analysing with the help of a scenario approach and energy flow modelling, what role these harbour regions can play as an energy hub not only for the harbour regions themselves, but also for a much wider hinterland covering part of the Netherlands and Germany combined (see Figure 1). In doing so, a first-order estimation is provided of the energy/hydrogen hub perspectives of the three harbour regions individually, and collectively. The latter is done to assess how synergies between the harbour regions can be created if they closely work together on positioning themselves as a significant future energy/hydrogen hub.

The scenarios to be developed in this study are designed to gain a better understanding not only of the flexibility towards seasonal balancing harbour areas can provide to the energy system via conversion, storage and imports, but also of the synergies that may be achieved if harbour areas collaborate in their roles as energy hubs. In developing the scenarios, a consistent reality check has been carried out with the port authorities in order to get to an accepted overall picture of the harbours‘ future energy roles. As part of the scenarios energy flow modelling has been carried out in order to assess the optimal profiles of energy flows from a minimum cost perspective (next section for methodological details).

To that end, the following research questions have been addressed:

- **What investment levels with respect to hydrogen related energy activities correspond to the defined scenarios collectively describing the potential energy hub futures of the three harbour regions mentioned?**
  The overall scope of a future hydrogen economy obviously strongly affects the related investment levels in the various harbour regions. We distinguish between four scenarios, each of which is characterized by what we consider as key pillars shaping the future role of the port areas as an energy hub in 2050. The first pillar is the geographic location of production in which we distinguish national and/or international production of hydrogen. The second pillar is the carbon content of hydrogen production - and thus the production technology considered, will have a major effect on the required investments in the harbour region. By combining these two key variables, four scenarios have been defined as the foundation of the analyses.

- **What opportunities for synergies exist between the different harbour areas and how can these be realised?**
  The different harbour regions and energy interconnectors are first considered in isolation i.e. under the assumption of operating almost completely independent from each other. Subsequently, synergies are analysed by introducing a clear physical interconnection between the three northern harbour regions, and/or their hinterland, by way of a hydrogen infrastructure backbone. The latter enables the harbour areas to achieve economies of scale by collaborating, which has also been analysed with the help of an energy flow model.

- **To what extent do the current laws and regulations act as a hindrance for achieving the the potential roles of ports as important energy/hydrogen hubs in the future?**
  From a legal perspective, definitions and scope must first be clear, e.g. what constitutes a port, what are the legal rights and responsibilities of a port and what rules apply to energy-related investments in port areas. Next, it must be clarified to what extent the current rules and regulations for port-energy-activities may increasingly become incompatible with the role that the various authorities see for ports as major future energy hubs. In doing so, specific attention will be paid to the possible function of Public-Private-Partnerships (PPPs) in future port development.

The outline of the report is as follows:
In chapter 2, the three harbour areas are described in detail with respect to their energy function. For each area, the unique infrastructure elements currently present are assessed. The scenario-based approach in this study will extensively be explained in chapter 3, where the four scenarios are subsequently described. The energy flow modelling, both the model set-up as well as the boundaries and data, is the central element of chapter 4. Chapter 5 and chapter 6 reflect on the role of the ‘hard and soft’ system elements that are required to facilitate the transition of the harbour areas into future energy/hydrogen hub(s), with and without synergetic collaboration. The ‘hard’ infrastructure relates to the physical energy infrastructure including the hydrogen grid, conversion and storage equipment, and import and other logistic facilities (chapter 5). The ‘soft’ infrastructure relates to such aspects as: the willingness and spirit to work together with stakeholders in the supply chain, the maturity of the envisioned activities, the legal challenges and coordination of developments that are required to facilitate the investments (chapter 6). Chapter 7 finally provides a synthesis of the outcomes of the study and summarizes the main conclusions, whereas chapter 8 provides a reflection on the outcomes and suggestions for further research.

2. The harbours in the energy transition

This study addresses opportunities for the role of the harbours in the energy transition towards 2050. Focus will be on the high-level prospects of the harbours as pivot points in the distribution of electricity and hydrogen in North-Western Europe. As said, the current study focusses on the ambition to have a larger hinterland for energy distribution. This chapter describes the harbour regions as defined in this report. For each harbour region, we will give an overview of the unique characteristics and some important trends that we observed for this region.

2.1 Port of Amsterdam region

The Port of Amsterdam is the fourth busiest port in Europe by metric tonnes of cargo. The port comprises almost 2000ha of land area distributed over 11 harbour areas (see Figure 2). The port of IJmuiden – located at the entrance of the North Sea Canal – comprises an area of 175 ha of land. Although the authority of ports is generally limited to harbour areas, the definition of the Port of Amsterdam region is based on a wider geographic area consisting of: Amsterdam, Amstelland-Meerlanden, Kennemerland & IJmond, Zaanstreek, and Waterland. The data on future energy consumption and production within the geographical area are directly retrieved from a system study on energy infrastructure in North-Holland (7). The region has a high geographical concentration of energy demand. There is also a relatively high electricity demand in the built environment and mobility sector due to a high population density in this area.

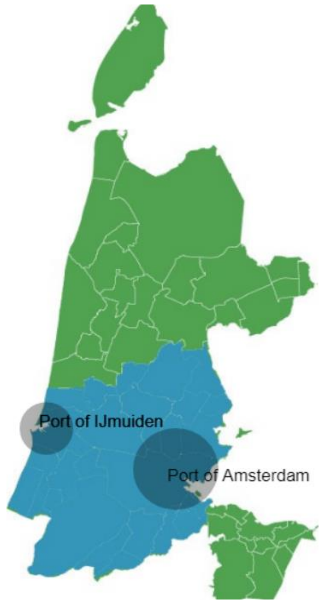

Figure 2: Port of Amsterdam region as defined in this report. The harbours lying in this port area are highlighted.

The main challenge in the region, however, is the decarbonisation of its industrial sector. The electrification of industrial processes is expected to require some 120PJ in 2050, which is threefold the expected demand in 2030. This number will increase further if the hydrogen required by industry is provided via regional conversion of electricity.

A sector that is often left out the decarbonisation plans is aviation. Although the aviation sector is not strongly bound by the Paris Agreement, the expected future decarbonisation of this sector is likely to have a significant impact on the demand for low-carbon fuels, and low-carbon hydrogen in particular.[6] The actionplan 'Luchtvaart Nederland' mentions the ambition to use some 25PJ (1.16 Mton) of synthetic kerosene by 2030 (10) (11). This would require some 2.8PJ (0.342Mton) of hydrogen, given that some 0.885Mton of hydrogen would be required for the production of 2.9Mton of FT-kerosene. Hydrogen demand for synthetic kerosene for aviation could easily grow towards some 14PJ/y in 2050, if one assumes a 2,5% growth in kerosene demand per year, and an annual 1,2% growth of synthetic kerosene admixing target during 2030 to 2050 (11). The demand for bunker fuels in the Port of Amsterdam region is expected to grow from 1 to 1,5Mton. Replacing just half of these bunker fuels, for instance with synthetic methanol, could easily let regional annual hydrogen demand grow with some 20PJ[7]. An overview of the expected future demand for energy in this region is provided in Appendix 1.

2.1.2 Unique characteristics and important trends

High demand for electrification: The decarbonisation of the Port of Amsterdam region – including the aviation sector at Schiphol airport – has a significant impact on the energy infrastructure prerequisites in the area. A large share of electricity produced via offshore wind may find a direct use in the Amsterdam-IJmuiden area for electrification. The energy infrastructure study for North-Holland mentioned before (7) indicates that the expected electricity consumption in the region will grow from 60 PJ/year in 2020 towards 180 PJ/year in 2050.

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[6] Schiphol's kerosene demand amounts to some 155PJ/y (2016 data), which, when combusted, results in emissions in the order of 11 Mton CO_2/y. Given the expected growth of air-traffic (some 2.5 to 3.5% per year, assuming Covid-19 will be under control relatively soon) and the desire to switch towards toward clean fuels, the potential demand for synthetic (low-carbon) kerosene may well grow considerably. To illustrate, even decarbonising only a third of the current kerosene demand would, for instance, already require 15GW of offshore wind capacity in combination with some 2GW of solar capacity.

[7] Considering energy density for diesel fuel of 45,6 MJ/kg and for methanol some 19,7 MJ/kg.

Production of green hydrogen and biofuels: The intermittency of renewable electricity production may require the need for local flexibility provision. Electrolyser systems could be of use to convert (excess) wind electricity into green hydrogen and into green hydrogen based energy carriers. The question is what the most logical location would be for green hydrogen production. One of the options could be the Tata-steel terrain, as they could become one of the major hydrogen users for green steel production. However, we do know that the spatial claim for hydrogen production facilities currently is quite substantial. Whether the spatial requirements could be met at this location strongly depends on the developments in electrolyser technology and sizing towards 2050. Currently, at least some 15 ha. is already available around IJmuiden and with the ambition to abandon coal by 2030, the resulting available harbour space of Port of Amsterdam (some 100 ha.) may create room for shifting to the production and/or import of low-carbon hydrogen (carriers).

Import of hydrogen and local buffering: The import of hydrogen requires two important assets: (i) opportunity for large ships to efficiently dock and unload hydrogen, and (ii) opportunities for sufficient local liquefied hydrogen storage. Both assets a currently present, given that Port of Amsterdam is a leading player in liquid bulk[8]. Amsterdam is the largest gasoline port in the world and specializes in blending products. The authorities in the port work together with their customers to develop and attract traditional liquid bulk, as well as green cargo such as biofuels and hydrogen. This requires a large import terminal to be developed in the current harbour, most likely behind the locks. A similar reasoning holds for local buffering of liquefied hydrogen or other derived products. Part of the existing bunker facilities may be re-used with either no or minor adaptions (12). Although, one does not expect that large-scale (seasonal) buffering of hydrogen will take place in the area, the existing infrastructure may be used for the buffering of hydrogen carriers like biomethanol and synthetic kerosene. Most likely large parts of the import will be either directly used in the region, fed into the hydrogen backbone or transported in other ways.

CO_2 storage and availability of a network: the technical potential for CO_2 storage in the Port of Amsterdam region will be studied in the Athos project. This project has been initiated for the construction of a basic capture and transport infrastructure in the North Sea Canal area, to enable the use or storage of CO_2 (13).The network is expected to be operational in 2027. Having a CO_2 network in place may also provide opportunities to integrate hydrogen production form ATR with carbon capture.

2.2 Port of Den Helder region

The Den Helder port region – as defined in this report – consists of the 'Kop van Noord Holland' and of the municipalities Texel, Den Helder, Schagen en Hollands Kroon (see also Figure 3). The data on future energy consumption and production within the geographical areas are directly retrieved from the system study on energy infrastructure in North-Holland (7). Port of Den Helder is currently the pit stop port for logistics services for offshore maintenance and supply activities at (the southern part of) the North Sea. Port of Den Helder has been the most important offshore operations and maintenance hub for over 40 years. The port region is also the historical homeport of the Royal Netherlands Navy.

The region selected has a number of nature reserves, of which the dunes and the Wadden Sea area fall under Nature 2000 area and the latter under UNESCO protection. The Tønder's statement (5 February 2014) requires Wadden supply ports to apply more sustainable management to the North Sea. The provision of infrastructure for green shipping - for instance by hydrogen or bio-methanol - may be part of such management strategy. Significant savings on CO_2 emissions within the port-area could be realised by replacing shipping fuels with e-fuels, for instance hydrogen.

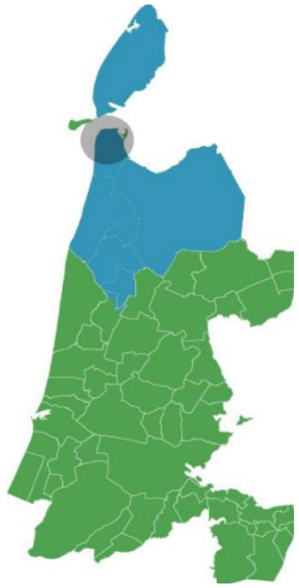

Figure 3: Den Helder port region as defined in this report.

Under the assumption that the number of vessels remains constant towards 2030 and 2050, the demand for hydrogen from shipping could easily grow to some to 3.6PJ/y by 2050 (Appendix 1). The Green Maritime Methanol project concluded

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[8] In 2019 some 100Mton (a sixth of the Dutch total) of the bulk was imported via Port of Amsterdam (40)

that methanol has the potential to be the future fuel of choice for the Royal Netherlands Navy's support vessels, which could even trigger a bigger growth for hydrogen in the Port of Den Helder.

The availability of space should not be an issue on this location in the short term. Within the control region of the port authorities, there is currently some 30 ha. directly available (Kooypunt ca 10 ha. Kooyhaven ca 15 ha.; Oostoever ca 5 ha.). The spatial capacity in Kooyhaven can easily be developed further to support the evolvement of energy-related activities in the region.

2.2.2 Unique characteristics and important trends

No extensive transmission of electricity: an important element in the energy position of the Den Helder port region is the status of the electric infrastructure. At first, no landing of offshore wind is expected in Den Helder. The region indicated that they foresee to be in a good position to transport molecules, but are less well positioned to land electrons, especially up to 2030. In the current position, all electricity is expected to be converted to hydrogen – either offshore or onshore before entering the grid - and transported via the existing pipeline infrastructure to the hinterland. Currently, opportunities for offshore hydrogen production at e.g. energy islands are intensively studied in various forums like the North Sea Wind Power Hub (14), the IJVER-island consortium (15), and the North Sea Energy program (16). Whether it is realistic to produce such amounts of hydrogen on offshore structures in 2050 is yet still unclear. Similarly, the fact that the capacity on the current electricity in the port region is limited has strong implications for the expected growth in datacentres in the Agriport region. The electricity demand for datacentres is expected to grow towards 6,6 TWh in Noord-Holland-Noord by 2050.

Blue hydrogen can still play a role in 2050, even though it is considered as a transition phase to a fully sustainable energy system. The H2Gateway consortium investigates the feasibility of a blue hydrogen production facility on Oostoever by 2027. This facility is seen as a strategic building block in the upscaling of the large-scale use of hydrogen in the process industry and energy generation. A noteworthy potential (smaller) demand centre for CO_2 (from blue hydrogen production) could be the Agriport region.

Offshore pipeline connections: transport of offshore produced green hydrogen might be done through reuse of the existing pipeline network. The three main pipelines that land near the harbour that may be relevant for this are WGT, NOGAT and LOCAL. In general, timing is vital for the usage of these pipelines for hydrogen transport. Independent of whether modifications can be made, the usage of these lines for transport of other gases may cause competition in time. Currently, these three lines are still used for natural gas transport. However, LOCAL is considered in the Aramis project for CO_2 transport to the offshore locations for CCS purposes. There is a large storage potential in K14/K15 and K7/K8 fields (171,2 & 104MT (17) (18)) accessible with current infrastructure. If a significant amount of blue hydrogen production is still in place by 2050, LOCAL may not yet be available for offshore hydrogen transport. In that case, WGT and NOGAT together should still have sufficient capacity to transport the hydrogen produced offshore to shore.

Hydrogen import: neither opportunities for large ships to efficiently dock and unload hydrogen, nor opportunities for sufficient local liquefied hydrogen storage are present in the region. An extension of the current harbour to be able to dock large ships is currently being considered by the port region authorities. For temporary storage, liquefied hydrogen storage tanks could be developed. To illustrate, for the storage of hydrogen throughput of 2-3 days, 26 Kennedy Space Center tanks equivalents are needed.

2.3 Groningen Seaports region

The authority of Groningen Seaports covers two harbours: the Eemshaven, Delfzijl, and adjacent industrial areas. The port authority has an area of almost 2800ha. under management of which some 25% is still to be allocated (19). Again, a broader definition of the harbour area was used in our techno-economic model than what is conventionally done. The broad Groningen Seaport region consists of the municipalities: Het Hogeland, Delfzijl, Loppersum, and Appingedam (see Figure 4). The future energy demand estimates for: mobility, the built environment, utilities, datacentres, and agriculture are retrieved from the Regional Energy System Outlook of Groningen and Drenthe (6). Energy data was unfortunately not available at the municipality level for the province of Groningen, so that the distribution for energy resource has been based on population data. The energy demand from industry and datacentres is fully allocated to the harbour region, given the high density of such activity in this region. An overview of future potential demand for energy is provided in Appendix 1.

Figure 4: Groningen Seaports region as defined in this report. The highlighted area indicates the region of control of the port authority.

2.3.2 Unique characteristics and important trends

Landfall of offshore wind: the Groningen Seaports region offers serious potential for the landfall of offshore wind. Until 2030, the landfall of electricity from the Gemini Wind Park is already operational and some new wind capacity from 'Ten Noorden van de Wadden' is already planned in or near the Groningen province, either via Eemshaven, or via Vierverlaten, or via Bergum in Friesland (20). The region has the potential to host multiple GW offshore wind capacity, but this will require a strong build-up of electric infrastructure in the region. The capacity of the current power stations is expected to be close to their maximum around 2030. An additional 8-10 380 kV fields with a capacity of 1500 MW each would be needed to ensure safe landing of the expected power from the generating wind capacity. Additionally, HVDC and AC/DC transformation are expected to be required as the produced wind power is most likely to come from larger distances to shore. At this stage, one does not foresee major spatial issues to make this work for the port area.

Blue hydrogen production or import: it is uncertain if the production of blue hydrogen in the region would still be accepted as part of the energy mix by 2050. Under the assumption that this would be the case, the availability of large pipelines to transport the CO_2 to storage locations offshore could create serious challenges.[9] This is especially true if the CO_2 is derived from natural gas, such that the transport of natural gas and CO_2 may compete with each other in the region. In such a case, an option would be to extend the currently planned Northern Lights project (21), where CO_2 produced from the planned blue hydrogen production site at the Magnum energy plant at Eemshaven will be shipped to Norwegian depleted gas fields to be stored. Next to this there is potential for hydrogen import in the region, although this probably would require suitable docking harbours and possibly local storage options for e.g. liquefied hydrogen. Based on the available knowledge no major challenges for that are foreseen, as there is sufficient space for expansion of the harbour facilities in both Eemshaven and Delfzijl.

Green hydrogen: The Northern Netherlands holds a strong aspiration to remain a leading European hydrogen ecosystem beyond 2030 (22). The northern investment plan stipulates a number of key areas to fulfil this ambition: i) hydrogen production, infrastructure and demand; (ii) offshore wind capacity; (iii) the wider triple-helix hydrogen ecosystem; and (iv) overall hydrogen program management. These ambitions can mark the development of the region into a major European green hydrogen energy hub, with capacities of 100 PJ per annum by as early as 2030 (22).

Hydrogen buffering: the region (in its broad definition) is currently very well located for large-scale storage of hydrogen, which may contribute to making the harbour area an interesting place to produce large amounts of hydrogen (either green or blue). The area is close to a number of onshore salt caverns that are currently used for natural gas storage. The HyStock project is for example exploring opportunities for large-scale subsurface hydrogen storage in the area (23). This asset, combined with the fact that a substantial part of the produced hydrogen could be used locally, positions the area as a good location for regional hydrogen production, transmission, storage, distribution, and implementation.

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[9] The only large pipeline in the area is NGT, which has a natural gas transport capacity of ~100 TWh/year (16).

3. Scenarios

We use the scenario-based approach to systematically reflect on the possible future role of previous described harbour regions. In doing so, we distinguish between four scenario's, each of which is characterized by what we consider as key pillars shaping the future role of the port areas as an energy hub in 2050. The key pillars are i) the role of national production versus imports of hydrogen; and ii) the allowed volume of carbon storage related to the hydrogen produced. The four scenarios have been established on the notion that synergies can be realized by introducing a physical interconnection between the harbour regions and the hinterland by a dedicated hydrogen backbone. This interconnection catalyses the growth of the harbour regions and their role in the energy system of North-Western Europe. These four scenarios will collectively mark the likely boundaries of the future energy system and should be considered as extreme scenarios.

National vs imports

The first pillar is the geographic location of production in which we distinguish national and/or international production. For international production we considered low carbon hydrogen production from Russia and no carbon hydrogen production from the Sahara. Important to note is that the energy flow model applied in the research upon hand only considers capital and operational expenses in the harbour areas. Other required investments - outside of the harbour region are not considered - for example investments in the national backbone. In addition, benefits such a labour effects are not quantified. For instance, the investment plan for hydrogen in northern Netherlands expect that the local hydrogen ecosystem can secure up to 66.000 existing FTE's and attract up to 41.000 new FTE's (by 2050), in addition to the 104.000 FTE's of one-off jobs between 2020 and 2050 (24). In addition, though hard to quantify, the development of a well-established, secure and clean local energy infrastructure may attract new industry and business.

Low carbon versus no carbon

Hydrogen is classified in different 'colours' (grey, blue or green), with the classification dependent on the method of production and the amount of carbon released during its production. Grey hydrogen is produced using fossil fuels (e.g. natural gas reforming) and the CO_2 stream is emitted into the air. Grey hydrogen production is not considered in this study, as we believe that this technology does not contribute to the decarbonisation path as ratified in the Paris Agreement. If the CO_2 – which is a by-product of producing hydrogen from fossil fuels – is captured and permanently stored, the hydrogen produced is classified as blue hydrogen. However, we refer to blue hydrogen as low-carbon hydrogen production as there will always be a small volume of CO_2 emitted into air. No-carbon hydrogen – also called green hydrogen - is produced from 100% renewable energy without any direct emission of CO_2.

The carbon content of hydrogen production - and thus the production technology considered, will have a major effect on the required expenditures in the harbour region. The study will not address the question whether low-carbon production should still be part (in 2050) of the Dutch decarbonisation strategy, though, will focus on what the implications it may have for the harbour regions. EBN & Gasunie have shown that existing storage capacity in the Dutch Continental Shelf is sufficient to store 1678 Mton (17). The harbour regions are well connected to most of these reservoirs via existing pipelines and therefore may have play a role in the facilitation of low-carbon hydrogen production.

Based on these pillars the following four scenarios (see Figure 5) have been distinguished each of which describes an scenario of hydrogen economy developments in and around the considered harbour areas by 2050.

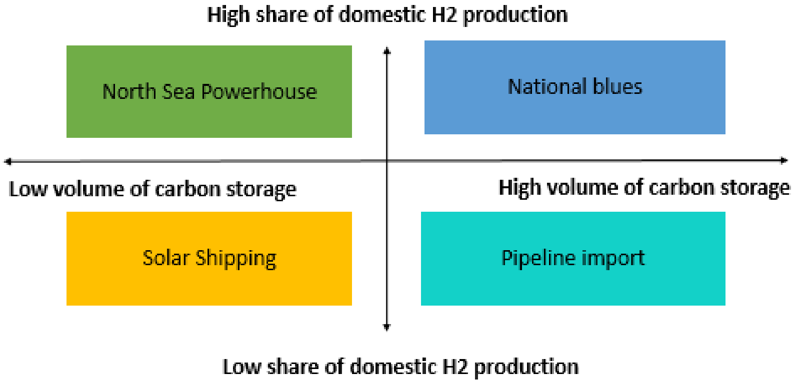

Figure 5: Scenario matrix based on the two pillars: the role of national production versus imports of hydrogen; and the allowed volume of carbon storage related to the hydrogen produced

3.1 Pipeline Import

The first scenario that is called Pipeline Import describes a future in which a considerable part of the hydrogen uptake is imported via existing pipeline systems connecting major gas production sites (e.g. Russia) with the demand centres. The existing natural gas roundabout will be replaced by a similar roundabout, but now for low-carbon hydrogen. In this scenario the role of the selected harbours in transmitting hydrogen flows will remain relatively modest, simply because most of the hydrogen will not be supplied by shipping, nor via local electrolyzers with offshore connections. The domestic production of hydrogen will remain subdued because on whole the imported hydrogen will be more competitive. It is assumed that this hydrogen is produced with low carbon content; i.e. that the hydrogen is produced by plasma-pyrolysis or with the help of ATR in combination with CCUS is irrelevant as long as it can be proven that the imported hydrogen has a low-carbon content. Because hydrogen will massively enter the country via the existing natural gas roundabout, the Groningen area, which is at the heart of the current natural gas roundabout, will develop into a key hydrogen valley/hub coordinating further distribution, balancing, storage and possibly implementation of hydrogen.

3.3 Solar Shipping

The second scenario that is called Solar Shipping is quite the opposite of the former one for a number of reasons. First, just like in the former scenario, domestic production of hydrogen will remain rather limited and will only relate to a part of the offshore wind capacity from the North Sea. Secondly, technology advancement in solar power production, electrolyser, liquefaction (incl. LOHC) and related shipping technology has reached various parts of the world, which has led to a rapid build-up of solar-based hydrogen production against very competitive terms in some areas surrounding the EU, such as northern Africa and the Middle East (25). Third, as a result a significant part of the hydrogen in North-western Europe will be imported via the harbours based on a transport system in which hydrogen bunker shipping dominates. Only those harbours having the right conditions (fairway, quay-area, bunkering facilities, regulatory and safety acceptance, etc.) will develop into key landing places of hydrogen, and thus play an important role in the development of a hydrogen economy. The hydrogen backbone will take care of the further distribution to the main demand centres in the hinterland. A final difference with the former scenario is that shipping facilities can play a role in the supply of flexibility, which means that, apart from bunkering facilities, considerably less large-scale underground storage capacities will be needed.

3.3 National Blues

The third scenario, **National Blues**, assumes a major share of hydrogen production to be concentrated domestically, primarily based on the national production of low-carbon hydrogen. The production of low-carbon hydrogen will be based on natural gas transported via the traditional gas infrastructure and produced with the help of onshore-located ATR facilities combined with CC(U)S facilities storing the CO_2 predominantly offshore. Part of the natural gas might be imported as (offshore) Dutch natural gas production is in decline. Due to import and transport of natural gas, the pipeline capacity for hydrogen might be limited to the L-gas system. The existing offshore gas grid is used to transport the serious volumes of CO_2 to depleted gas fields located on the North Sea; in addition, some CO_2 shipping activity may develop for some CO_2 niche market. The role of the harbours in this scenario is crucial in several respects: the harbours may develop into major blue hydrogen production locations; they may turn into important collection/bunkering points of CO_2 for offshore storage, but – which is not studied in this research - possibly also for chemical conversion of CO_2 (and possibly H_2) into methanol, synthetic kerosene and other CO_2-based fuels; and there may be a development of compression and shipping locations of CO_2. Those harbour areas that are well connected via existing pipelines to potential high-volume offshore CO_2 storage sites have a clear economic advantage in developing such ATR and CO_2-related activities and facilities. To the extent that blue hydrogen cannot be absorbed in the local harbour areas themselves, the backbone will be used to transport the hydrogen volumes to the main consumer centres elsewhere.

3.4 North Sea Powerhouse

The final scenario, **North Sea Powerhouse**, assumes a dominant role for locally produced green hydrogen from offshore wind. There will be some imports of hydrogen including some blue hydrogen, but those volumes remain relatively modest in this scenario. North Sea based green hydrogen production turns out to be quite cost competitive because of amongst others economies of scale, technology evolvement or rising gas prices. Another reason could be that policies and measures try to restrict blue hydrogen production or energy import dependence for environmental reasons or reasons of security of supply or to support the own economy. As a result, domestically produced green hydrogen will dominate in the hydrogen uptake. It is not unlikely that massive GW-scale electrolyser capacities will be installed in the harbour areas if the available space allows so, converting offshore green power into large volumes of green hydrogen. Part of this hydrogen will be used in the harbour areas for further chemical conversion or other applications; the hydrogen backbone will take care of the transmission of the remainder flows to other destinations incl. other harbour areas. Due to the intermittency of wind energy production, back-up services, storages and other flexibility measures are needed and may be facilitated by the harbour regions connected via the backbone.

3.5 Supply constraints in scenarios

Supply constraints are applied in the model to help define the four scenarios. These constraints are required to be able to arrive at acceptable scenario conditions. Table 1 depicts the supply constraints considered per scenario reflecting, for instance, policies and measures discouraging hydrogen production from fossil fuels or diminishing import dependence. In scenarios where a specific hydrogen source is considered to remain subdued in the energy system, the maximum supply capacity in the harbour area is limited to 20% of the total hydrogen supply in the system. Import of low carbon hydrogen via the existing gas pipeline infrastructure (e.g. from Russia) is only explicitly considered in the **Pipeline Import** scenario, as this route of supply does not affect the energy activities in harbour regions. In practice, a combination of supply resources will be favourable given that certain technologies either deliver flexibility to the national electric grid, or provide backup during low peak green hydrogen production periods. The optimization process, executed for each scenario, determines whether investments in these supply resources are actually economically preferred, and if so, what the optimal location may be given the location-specific circumstances.

Table 1: Supply constraints applied in the analysis

	Supply constraint			
Scenario	National low carbon hydrogen production	Import of low carbon hydrogen	National carbon neutral hydrogen production	Import of carbon neutral hydrogen
National Blues	Max 100%	0	Max 20%	Max 20%
Pipeline Import	Max 20%	Max 100%	Max 20%	Max 20%
North Sea Powerhouse	Max 20%	0	Max 100%	Max 20%
Solar Shipping	Max 20%	0	Max 20%	Max 100%

4. Methodology

First, the approach, i.e. the modelling-framework and the energy system boundaries developed and implemented in this study, are described in this section. Next, the optimization algorithm will be described, and in particular, the parameters allowing the modelling exercise to find an optimum for the year 2050 in the given scenarios, including the main cost-factors and the applied locational factors.

4.1 The non-linear model

The optimal (i.e. from an overall energy system expenditures optimization perspective) configuration of the energy flows via the harbour regions and the type and levels of investment associated with these flows will vary between the four scenarios described before. Such an optimal configuration is calculated with the help of a non-linear optimization modelling approach developed for this study. The model uses a broad range of energy related variables and physical and logistical constraints as an input to find the minimum of total cost objective function.

The objective of the model is to retrieve the minimum annual energy system expenditures for the year 2050 for the three harbour regions combined, by optimizing the yearly distribution of energy flows via the harbour regions to the hinterland. This will generate an optimised energy system for each scenario, which can be considered as limiting boundaries of the future energy system. The annual energy system expenditures consist of the cost per energy flow (M€/PJ) multiplied by the volume of the energy flows (PJ) (both electricity and hydrogen). Equation 1 represents the objective function of the model, which is the minimisation of the total expenditures of the three harbours combined consisting of both annualized capital and operational expenditures for the year 2050.

Equation 1: Cost function model

$$\mathrm{min} \sum \mathrm{cost} = \mathrm{TotalCapex} + \mathrm{TotalOpex}$$

All energy flows have a cost factor (CF) in M€/PJ. The cost factors are calculated as Equivalent Annual Costs (EAC), i.e. the annual cost of owning, operating, and maintaining an asset over its entire life. The EAC is used for capital budgeting decisions, as it allows a company to compare the cost-effectiveness of various assets with unequal lifespans. The EAC concept only reflects the cost of owning an assets at a particular point in time, however, it does reflect when the asset is constructed.

The operational expenditures are calculated with a monthly frequency to, among others, reflect the effect of seasonality in offshore wind production (see Equation 2). This seasonality (higher wind speeds in winter periods) has implications for the availability of energy at shore and therefore affects the potential for conversion and the need for storage facilities. Wind data was selected for Borselle, Fino and Meteomast IJmuiden (26). To keep calculation manageable, the curtailment option of wind capacity has not been included.

Equation 2: OPEX Cost function

$$\mathrm{TotalOpex} = \sum_{\mathrm{i=1,j=1}}^{\mathrm{m=1}} \mathrm{CF}_{\mathrm{ij}}^{\mathrm{e,m}} \mathrm{WF}_{\mathrm{ij}}^{\mathrm{m}} + \mathrm{CF}_{\mathrm{j}}^{\mathrm{h,m}} \mathrm{H2}_{\mathrm{PEM}}^{\mathrm{m}} + \mathrm{CF}_{\mathrm{j}}^{\mathrm{h,m}} \mathrm{H2}_{\mathrm{ATR}}^{\mathrm{m}} + \mathrm{CF}_{\mathrm{j}}^{\mathrm{h,m}} \mathrm{H2}_{\mathrm{LOHC}}^{\mathrm{m}} + \mathrm{CF}_{\mathrm{j}}^{\mathrm{h,m}} \mathrm{H2}_{\mathrm{russia}}^{\mathrm{m}} + \mathrm{CF}_{\mathrm{j}}^{\mathrm{h,m}} \mathrm{H2}_{\mathrm{BB}}^{\mathrm{m}} + \mathrm{CF}_{\mathrm{j}}^{\mathrm{h,m}} \mathrm{H2}_{\mathrm{storage}}^{\mathrm{m}}$$

Where, $\mathrm{CF}\ [\mathrm{M€/PJ}] = \frac{\mathrm{OPEX}\ [\mathrm{M€}]}{\mathrm{Energy}\ [\mathrm{PJ}\}}$

The capital expenditures strongly depend on the energy flowing via the harbour regions, required to fulfil total final demand. In contrast to the OPEX-function, considerable economics of scale are assumed to apply to the CAPEX-function. Due to the non-linearity of the model, it recognizes the cost efficiency potential and optimises the outcomes accordingly (see Equation 3). Scaling characteristics support the tendency to concentrate production facilities on one location, and supply energy to the other locations via the backbone. The trade-off between the benefits of centralized production and the consequential transport costs is key for the optimization of the energy system expenditures. Some industrial equipment costs are more subject to economies of scale than others, which implies that their cost of capital increase with a lower rate than the size of the capacity. Economics of scale have been applied to the ATR and the electrolyser technology. For blue hydrogen production technology (SMR and ATR) it has been assumed that scaling effects of ATR technology are similar to those of SMR technology units, since the equipment is comparable, despite the addition of air separation units for ATR.

For green hydrogen production electrolyser capacities are commonly produced based on combining standard modular capacities, and only have economies of scale in the upscaling of their balance of plant. In contrast to ATR-technologies, the potential economics of scale is therefore minor due to such modular stacking. An economics of scale factor of 0.95 is applied to the electrolyser system (27), and a factor of 0.8 to the ATR-system (28) (29).

Equation 3: CAPEX Cost function

$$\mathrm{TotalCapex} = \mathrm{CF}_{\mathrm{ij}}^{\mathrm{e}}\mathrm{WF}_{\mathrm{ij}} + \mathrm{CF}_{\mathrm{j}}^{\mathrm{h}}\mathrm{H2}_{\mathrm{LOHC}} + \mathrm{CF}_{\mathrm{j}}^{\mathrm{h}}\mathrm{H2}_{\mathrm{russia}} + \mathrm{CF}_{\mathrm{j}}^{\mathrm{h}}\mathrm{H2}_{\mathrm{BB}} + \mathrm{CF}_{\mathrm{j}}^{\mathrm{h}}\mathrm{H2}_{\mathrm{storage}} + \mathrm{CF}_{\mathrm{j}}^{\mathrm{h}}(\mathrm{H2}_{\mathrm{PEM}})^{\mathrm{sf}} + \mathrm{CF}_{\mathrm{j}}^{\mathrm{h}}(\mathrm{H2}_{\mathrm{ATR}})^{\mathrm{sf}}$$

Where, $CF\left[\frac{M€}{PJ}\right] = \frac{CAPEX\,[M€]*(AF*I_t[Y])}{Energy\,[PJ\}}$.

The annuity factor (AF) reflects the financial costs of the investment for a t-amount of years. The annuity factor is calculated as: $AF = \frac{WACC}{[1-(1+WACC)]^{It}}$ The Weighted Average Cost of Capital (WACC) is set at 7%.[10] The applied WACC is fixed for all regions and for all technologies. An overview of all abbreviations used is provided in Table 2. The final output of the model consists of the distribution of energy flows to suffice all the demand for energy within the system while achieving minimal expenditures, and meeting the scenario-constraints. The model therefore optimizes the energy flows between the hubs from the system perspective. These flows can be used to get a scenario-dependent perspective on the various individual expenditures needed per area and/or stakeholder. The output is an optimised energy system for each scenario, which can be considered as limiting boundaries of the future energy system.

Table 2: overview of abbreviations

M	Month
i	Wind area
j	Harbour region
e	Electricity
h	Hydrogen
SF	Scaling factor
EAC	Equivalent Annual Costs
CF	Cost Factor
AF	Annuity Factor
It	Investment time
WACC	Weighted Average Costs of Capital

4.2 The system boundaries

The system is defined as the combination of the three harbours' energy handling capacities and the energy flows via these harbour regions (or hubs) satisfying a predetermined volume of local and hinterland-based energy demand. Demand of energy consists of demand for electricity and for hydrogen. Fulfilment of the demand for electricity by the harbour activities is assumed to be limited to the harbour area itself, whereas the fulfilment of hydrogen demand is assumed to come from both the harbour area and the hinterland. Demand profiles are subject to seasonality effects (both electricity and hydrogen).

The following additional assumptions have been used in the modelling:

- It is assumed in the model that green hydrogen production in the harbours does not require an extension of the electricity infrastructure as the electrolysers will be placed right next to the sea. It means that no potential reinforcement in electric infrastructure in the harbours is required for landfall of wind energy to these harbours. This is a very important assumption and could lead to different results than other studies on this topic. This also implies that electrolyzers cannot take additional electricity from the grid to increase the operational time of the conversion process.
- In the optimization process the demand for heat, as well as the infrastructure requirements for heat networks, is not included because it is expected to be delivered otherwise. To illustrate, the potential annual demand for heat in the various regions is: some 14PJ (typically utility and built environment) for the Port of Amsterdam Region, and some 3PJ for the Groningen Seaports region (typically industry).
- The study assumes that hydrogen storage is the dominant technology to balance out seasonality; other storage-technologies and/or storage of electricity for daily or hourly variations in demand are therefore not considered in the model.
- Potential revenue streams of CO_2 storage are not considered.

The system elements considered in the modelling exercise are subdivided in: Production, Conversion, Storage and Demand (see the energy supply chain in scope visualised in Figure 6). Transport, offshore

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[10] The debt/equity share of investment is set at 50%/50%, the net interest rate at 4% and the minimum return on equity at 10%.

via cables and/or onshore via the backbone, is represented by the blue line. So far, the different harbour regions and energy interconnectors are considered individually and operate almost independently.

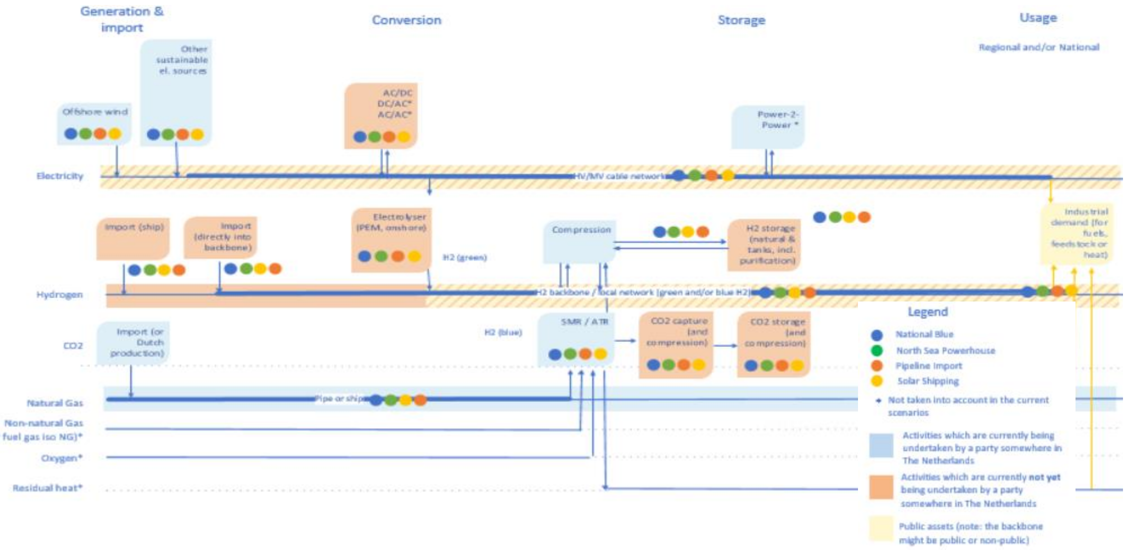

Figure 6: Energy System Elements under study

However, synergies can be realised by not only combining the energy flows within the energy hub region but also between various energy hubs. The energy hubs are connected to each other and other consumer centres (regional, national or international) via the hydrogen backbone. This requires the development of a national and international hydrogen interconnection. Gasunie & TenneT have for example indicated various options for the development of such a hydrogen transport backbone (3). The backbone is currently expected to have a capacity of 10-15 GW of hydrogen (30). Even though it is not the task of the harbours to develop such a hydrogen backbone, the success of the ambition of all three harbours is strongly dependent on the implementation of a backbone and the establishment of an interconnection to the harbour areas. The costs of establishing a hydrogen backbone has been estimated by Gasunie. Transporting a kg of hydrogen is estimated to cost between €0.09-€0.17 per 1,000 km, depending mainly on what the compressor costs will turn out to be (31). We assumed an average cost price of 0.13€/kg of hydrogen transported. These expenditures are included in the analysis.

4.2.1 The model constraints

This section describes the (in)-equality constraints that were set to the model to limit the degrees of freedom in which the optimisation of energy flows takes place. The most important constraints are: the volume of hydrogen that flows via the northern harbour regions to the hinterland, the supply sources as laid out in in scenarios, the cost factors of the hydrogen supply resources, and the unique harbour characteristics captured by location factors applied to the harbour regions.

4.2.1.1 The demand for hydrogen in the northern harbour regions

Carbon-neutral gasses and derived products (such as low-carbon or carbon-neutral hydrogen, synthetic methane, biogas, methanol and ammonia) are expected to play a strongly increasing role in the future, greener European energy and feedstock systems, possibly representing some 40-50% (Netherlands) or 35-40% (Germany) of final energy/feedstock uptake by 2050 (32). Some sources suggest the overall uptake of carbon-neutral hydrogen as a primary energy resource in the area covering the Netherlands and Germany to grow to levels ranging from 900 to 1800 PJ/y by 2050 (3), (4), (5)[11]. Such development will have major implications for the imports, transmission, transport, storage and implementation of carbon-neutral hydrogen, with a likely growing role for industrial harbour activities.

The port regions – especially the Port of Amsterdam region (including IJmuiden and Schiphol) and the Groningen Seaports region (including the chemical cluster in Delfzijl) – are likely to face a considerable growth in demand for hydrogen in their own regions during the upcoming decades (see Figure 7). For

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[11] Note that this projection does not include the demand for hydrogen required for the production of syngas and/or liquid fuels. If that demand would be included, the 2050 demand figure could easily grow to by a third (3), (5).

instance, the expected future decarbonisation of this sector will have a significant impact on the demand for low-carbon fuels, and low-carbon hydrogen in particular. In addition, hydrogen demand by the industry (mainly Tata Steel) increases the total demand in the region. Industry and other stakeholders in the Groningen Seaports region, where already some 8000 MW electric power capacity has been installed, have announced an ambitious plan to invest almost 9 billion euros in hydrogen and hydrogen-related activities during 2020-2030 (22). Hydrogen demand, either energetically or as feedstock, could easily grow to some 50 PJ/y in 2050 in the chemical sector located in Groningen (mostly Delfzijl) northern chemical cluster (6). The industrial demand for hydrogen and electricity is relatively minor in the Den Helder region, though some increasing demand for renewable energy is expected due to regional growth in datacentres, marine vessels and horticulture.

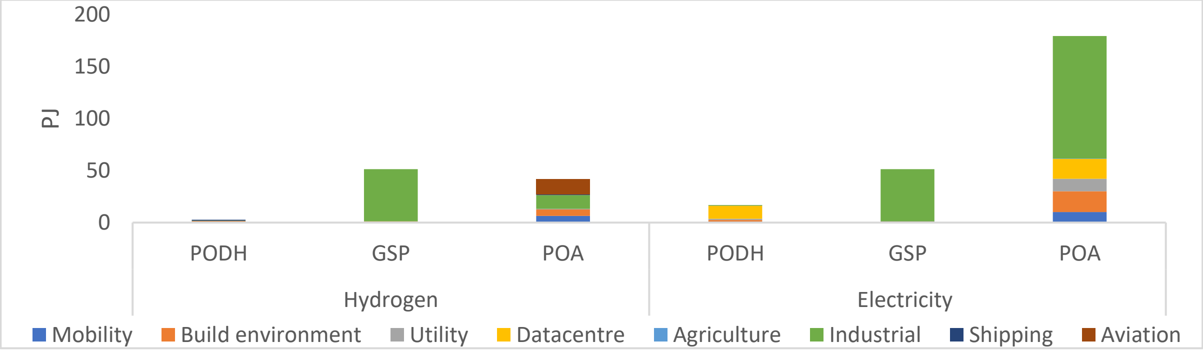

Figure 7: Development in electricity and hydrogen demand for the provinces of Noord-Holland and Groningen. The graph is based on *(6) (7) (33)* **and** *(34)***.**

The used estimated demand for hydrogen and electricity is fixed and therefore in the study the ratio between electrons or molecules is not optimized or modelled. The future demand estimations for mobility; built environment; utility; datacentre; agriculture and fishery are retrieved for the regions of Den Helder and Amsterdam (7) and for Groningen (6) and are discussed in detail in appendix 1[12]. The yearly demand data is converted to monthly values by applying seasonality patterns. The assumption is that the seasonality for hydrogen demand by households shows a similar pattern as the current monthly profile for natural gas consumption as indicated by CBS (35). The seasonality is only applicable to sectors in which strong variation in hydrogen demand can be expected, which is typically the build environment.

The yearly projected uptake of hydrogen – set at 1800PJ_h - does not include the demand for hydrogen required for the production of syngas and/or liquid fuels (32). The northern harbour regions are attractive settling location for the production of synthetic fuels, synthetic chemicals and hydrogen base fuels like biomethanol. To illustrate this, some 40-80MW of green hydrogen production capacity is already planned in Delfzijl for the production of biomethanol (BioMCN) and synthetic kerosene (SkyNRG). The expectation is that the inclusion of hydrogen demand from Netherlands and Germany for syngas and/or liquid fuels, the 2050 demand figure could easily grow to some 2500PJ/y.

4.2.1.2 The volume of hydrogen that flows via the northern harbour regions

The expected volumes of hydrogen, consisting of both the local demand and the demand for hydrogen from the hinterland, to run through the Northern harbours by 2050 may vary very significantly. We assumed that the three harbours could eventually deliver 7.5%-50% of the total hydrogen demand of the Netherlands and Germany by 2050 (set at 1800 PJ_h/y, We assumed a setting in which 25% - or a volume of 450PJ_h/y – goes via the northern harbours, but under the recognition that in reality it can be much more or much less. How do the above figures relate to the projected hydrogen uptake in the harbour areas themselves? To answer the question one can refer to the recent regional energy strategies of the provinces of Noord-Holland (7) and Groningen (6), indicating among others how much hydrogen uptake is expected by 2050 in the three harbour areas (see Appendix 1). Confronting these projections with the above projections of hydrogen flows through the northern harbours, one has to conclude that about 30% - some 120PJ_h - of all hydrogen entering the harbour areas will be absorbed

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[12] The demand for hydrogen for decarbonized bunker fuels for shipping (biomethanol, synthetic kerosene and/or ammonia are not included in the analysis.

in the areas themselves, whereas about 70% of the influx of hydrogen will leave the harbour areas again to be transported to the hinterland via the backbone. This is under the assumption that hydrogen intensive activity in the harbour areas (constant of 120PJ$_h$) will not be affected by the volumes of hydrogen available (7,5%-50% of 1800 PJ$_h$/y). If, however, large volumes of hydrogen in specific harbour areas may induce additional hydrogen related activity, the proportions may vary.

4.2.1.3 Cost factors of the hydrogen supply resources

A database is established in which an annual cost of owning, operating, and maintaining an asset over its entire life is assumed based on recent references. This database comprises of the landing costs for offshore wind, the capital and operational expenses for various sources of hydrogen production and storage, and investment advantages related to the unique harbour characteristics.

Landfall of offshore wind:
The total capacity of offshore wind landing in the harbour region depends on the shortest distance of the windfarm to the harbour region and the demand for electricity in the region itself. The maximum potential for offshore wind in 2050 on the Dutch continental shelf is estimated at 60GW (36). Whether this capacity will be installed strongly depends on the degree of electrification of energy consumption, and the usage of electricity in the production of low carbon molecules (for regional use and for export). Until 2030, the role-out of offshore wind and likely locations of interconnection points onshore is reasonably well known. Just little of this energy will be connected through the Northern Harbours (some 700MW to province of Groningen, and some 1400MW to province Noord-Holland). However, for the subsequent period the locations, which are likely to be used for future, wind farms, one has to typically rely on assumptions, which have been based on indicative scenarios present in the PBL reports mentioned. In this line of reasoning, the distance between these locations and the northern harbours as well as the demand of electricity in the specific region would make them the most economic interconnection points. Based on the geographical size of each of the areas the maximum capacity of offshore wind per area (area C until G) is restricted as follows: C 11GW; D 5GW; E 5GW, F 16GW and G 7,5GW. The wind turbines located in area A and B are out of the scope of this study as they are expected to be connected to the Province of Zuid-Holland or Zeeland. The expenditures of electricity transmission, including the AC/DC and DC/AC conversion, from the offshore wind parks to the harbour areas are based on a 2GW- 525kv HVDC system. The electric infrastructure expenditures are calculated based on a technical design relevant for a typical power transmission system for the Netherlands using a dedicated offshore energy transport model developed by TNO[13] The system expenditures for this offshore grid are calculated based on the shortest distance from the point of measurement offshore and the point of measurement onshore. Table 3 provides an overview of: the wind areas, the measurement points, the calculated distances, and the cost factor in M€/PJ$_e$. It is important to note that the expenditures for rerouting and crossings are not considered, but can alter the cost factor.

Table 3: offshore wind per region, distances to harbours and expenditures

Area	Point offshore	Landfall location	Distance (km)	Expenditure (M€/PJ$_e$)	Visual description
C – 11GW	IJmuiden-ver top	Eemshaven	205	11,18	
		Den Helder	65	9,65	
		Beverwijk	90	9,93	
D – 5GW	K5	Eemshaven	230	11,45	
		Den Helder	120	10,25	
		Beverwijk	160	10,69	
E – 5GW	D15	Eemshaven	270	11,88	
		Den Helder	195	11,07	
		Beverwijk	235	11,50	
F – 16GW	F03	Eemshaven	220	11,34	
		Den Helder	220	11,34	
		Beverwijk	275	11,94	
G – 7,5GW	Gemini	Eemshaven	90	9,93	
		Den Helder	150	10,58	
		Beverwijk	200	11,12	

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[13] The following sub-components are considered: offshore substation consisting of a transformer and converter unit to step-up and convert it to from 66kv (AC) to 525kV (DC), the HVDC cables (procurement), the cable laying costs incl. losses, and finally an onshore substation consisting of a transformer and converter unit to step-down and convert it to 380kV (AC).

Production, conversion and storage technologies:
The cost factors applied to the analysis are depicted in Table 4 and discussed extensively in Appendix 2. Some points should be mentioned:

- The applied WACC is similar for all regions both our own region and regions from which hydrogen can be imported. In practice, however, the Netherlands may have a more stable investment climate than for instance the Sahara region and/or Russia. Therefore, there may be a bias in disfavour of the Netherlands' hydrogen production.
- The same holds for the fact that the grid connection costs and transport expenditures from the solar photovoltaic production field to the hydrogen production facility in the foreign hydrogen producing regions are not considered in the model.
- In practice, the running hours of the hydrogen systems may increase by connecting electrolyser systems to other renewable energy resources. This is not considered but may reduce hydrogen production costs. The same applies if various electrolyser technologies (e.g. Alkaline and PEM) are combined.
- The ATR-technology is considered for blue hydrogen production. In practice, the cost factor of ATR-technology may be higher than the one used in the model, for instance if CO_2 penalties would increase or if financing costs of ATR investment would rise because this technology would be considered transitory and therefore relatively short lived.

Table 4: Applied general cost factors for CAPEX and OPEX investments in M€/PJ_{h2}

	North Sea Region	Sahara region	Russia	Unit
CAPEX Factor Electrolyser	5.1	7.9		M€/PJ_h
OPEX Factor Electrolyser	15.2	6.5		M€/PJ_h
CAPEX Factor ATR	4		4.2	M€/PJ_h
OPEX Factor ATR	5.3		5.3	M€/PJ_h
OPEX Factor CCS	0.6-0.9			M€/PJ_{h2}
CAPEX Factor H2 Storage	4.05			M€/PJ_h
OPEX Factor H2 Storage	0.49			M€/PJ_h
CAPEX Factor H2 Import		1.25		M€/PJ_h
OPEX Factor H2 Import		0.62		M€/PJ_h
CAPEX Factor pipeline import			3.06	M€/PJ_h
OPEX Factor pipeline import			0.93	M€/PJ_h
OPEX Backbone			0.5	M€/PJ_h

4.2.1.4 Unique harbour characteristics captured by location factors

Although the general cost factors as projected in Table 4 encompass the generic annual capital and operational expenditures of installations, they do, however, not differentiate depending on local cost conditions (e.g. with respect to cost of land- and infrastructure use). The unique harbour region characteristics (discussed in previous section) can be appealing cost factors for investors when comparing alternative production locations. In the model, such differentiation has therefore explicitly been taken into account. In fact, various locational aspects can differ and have been recognized in the model:

First, the model includes the expenditure of land-use required per technology, which is based on the average price per m^{2} (Velsen, Delfzijl and Den Helder (37) are used as the reference location) multiplied by the spatial footprint of the specific technology. For instance, the spatial footprint of a GW electrolyser plant, including BOP and additional infrastructure for the system, is based on the reference of 8ha/GW (38). Because of this footprint, providing such space can be costly and vary from one harbour area to the other. This also holds for the spatial footprint of an ATR-plant. Because data on the actual space required for a large ATR plant is not or hardly available, simply because they do not exist yet, an estimation of the space needed is made based on much smaller-scale typologies and has been estimated to be about 17.5 Ha/GW_h (29).

Second, reuse of existing infrastructure could offer significant advantages and the scope of this factor obviously will differ from one harbour area to the other. To illustrate this effect, one could look at the potential to transport CO_2 captured during the production of low-carbon hydrogen to be stored in nearby offshore gas fields. Such offshore storage potential is especially located around the K, Q and L-blocks of the North Sea. Because the distance from the harbour area to the offshore storage facility differs between the harbour areas this harbour specific factor can have serious effects.

With respect to CO_2 underground storage, onshore storage is not considered for reasons of public acceptability. In addition, the presence of other local CO_2 sources and/or local reuse of CO_2 have not specifically been considered. While the Port of Amsterdam and Groningen Seaports regions may have the advantage of other local CO_2 sources (e.g. Tatasteel 6.21 Mt/y, RWE Power plant 8.32 Mt/y) that potentially could contribute to economics of scale in CO_2-transport and -storage (17), it is unclear a priori if these CO_2 sources will keep existing with the increasing influx of clean energy flows, or whether part of these sources will disappear.

In 2017, EBN and Gasunie (17 p. 62) performed an analysis related to the Unit Technical Costs (UTC) of CO_2 -transport and -storage for minimum-sized start-up cases for regions with a high-concentration of CO_2-emissions. The analysis did not consider a minimum start-up case for Den Helder, since this harbour region has a low concentration of CO_2 emissions, but did specifically address the Port of Amsterdam and Groningen Seaports cases. Based on this study the following UTC-values for the harbour regions have been used in the analysis: Port of Den Helder, 9€/ton; Port of Amsterdam, 13.5€/ton; and Groningen Seaports, 11.5€/ton. Appendix 2 gives a broader description of the CO_2 storage potential of the harbour sites.

Also different reuse conditions between the harbour areas hold for local buffering of liquefied hydrogen or derived products. It is considered that the storage facility for the (non-flammable) LOHC consist of conventional large-scale chemical storage units (50.000 m3) at the cost of 12,5 M€ per tank (39). Locally existing facilities and conventional infrastructure can save on expenditures for the import terminal, but are challenging to specify on the system level. Based on data from CBS (40) on the amount of 'wet' cargo import in the harbours, it can be assumed that Port of Amsterdam already has a locational advantage on the handling and storing of this mode of transport and extra capex of storage are considered to be minor due to this location specific advantage. This also applies for Groningen Seaports to minor extent. This locational advantage is reflected in lower investment for buffering facilities in the harbour region (see also Appendix 2).

However, cost for land-use and the potential to reuse existing infrastructure are not the only decisive variables for industries/investors to settle in a specific region. Less easy to quantify, 'soft', factors such as the availability of the right space, distance to clients, and the availability of human capital, will have an impact on settlement decisions. The inclusion of such other unique harbour features could enhance the sensitivity of the model outcomes toward the locational costs even further but have been disregarded in the modelling because they are too difficult to quantify.

5. Results

The first section describes the outcomes of the scenario modelling to provide insight in the role of harbours in the energy system by 2050. The results strongly depend on assumptions made with regard to the model constraints as pointed out in chapter 2. Technology may evolve quicker, investors may differentiate risk-profiles between regions, and the demand for hydrogen from the harbour regions may vary very significantly, and the benefit of the chosen locational factor may be less deterministic and so on. A sensitivity analysis is therefore performed on the previously discussed constraints. The second subsection focusses on the impact of having a connection between the three harbour regions, as well as a connection between the harbour regions and the hinterland.

5.1 Scenario outcomes

For each scenario the model optimizes the distribution of energy flows, both electricity and hydrogen, over the regions in that way that the 2050 annual energy system expenditures (i.e. expenditures for both the electric and molecule transmission systems) are minimized. Figure 8 shows the results of optimization cost efficiency of the energy system activities for the four scenarios. By 2050, the total amount of annual energy system expenditures for the three harbour regions combined per scenario are represented by the overall size of the pie charts. The slices of the pie in the same figure reflect the shares of annual energy system expenditures in the respective harbour areas by 2050. Assuming that the location of various harbour-related energy activities will be based on economic reasons, the simulations performed in this study for this, suggest that, depending on the scenario, each harbour is likely to develop some kind of specialisation of activities that will take place in their region. However, it is more likely that a combination of these scenarios will be realized as these scenarios can be seen as limiting boundaries of a future system.

The figure points out that the overall expected annual system expenditures vary strongly per scenario: for instance the total expenditures amount in the **North Sea Powerhouse** scenario boils down to some €14 billion against some €7 billion in the **National Blues** scenario, etc. Not only do the investment amounts differ between scenarios, but also the type of infrastructure and other investment required, as well as the shares that the various harbour areas are expected to carry in the total system expenditures. To put these values is perspective, TenneT expects to scale up to an annual invest volume of EUR 4 to 5 billion within the period up to 2028 (41).

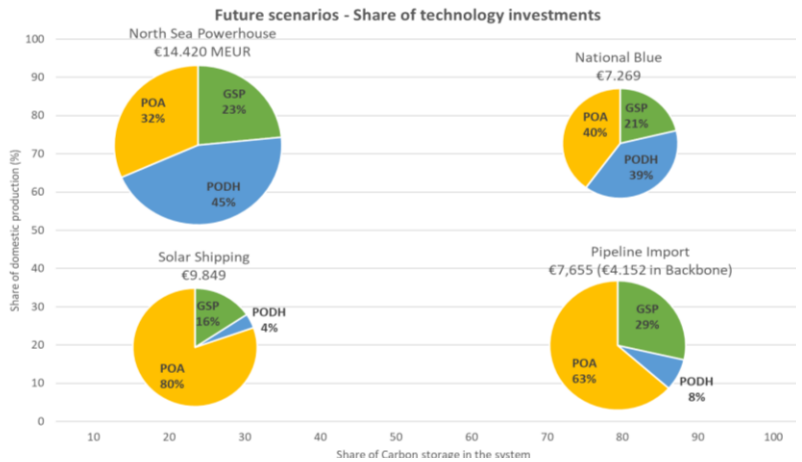

Figure 8: Annual energy system expenditures for the scenarios for the year 2050.The boundary conditions for these scenarios are disguised in chapter 2.

The expenditures have been annualized and are therefore a component of the total annual energy system expenditures. The system expenditures have not been linked with economic value that these innovative energy activities may bring to the region. Part of this value cannot be easily monetized, for instance, the contribution of investments to employment in the region. The investment plan for hydrogen in northern Netherlands expect that the local hydrogen ecosystem can secure up to 66.000 existing FTE’s and attract up to 41.000 new FTE’s (by 2050), in addition to the 104.000 FTE’s of one-off jobs between 2020 and 2050 (27). Therefore, one should consider this caveat when comparing the different modelling results. Note that the system expenditures are linked to economic activities, which are primarily directly linked to the harbour regions, but also may partly relate to i activities to be launched elsewhere. For example, expenditures for hydrogen imports per ship in a certain harbour area comprise not only the expenditures of the import terminal and other facilities in the harbour area itself, but also the expenditure of shipping and conversion of hydrogen to a hydrogen carrier, which may physically take place elsewhere or abroad.

All scenarios assume that those investments will be made that are needed to satisfy the defined demand for electricity by connecting the offshore wind farms with the harbour area. For the Port of Amsterdam region, this implies a 1.7 billion euro annualized level of expenditure representing the offshore cable costs (from wind area C). For Groningen Seaports this amount is some 0.6 billion euro (area G) and for Port of Den Helder the amount is negligible. Note that the amount mentioned only represents offshore cabling costs that can directly be attributed to the delivery of electricity for the sake of satisfying electricity demand, not for energy transport for hydrogen production.

In the scenario with the largest share of green hydrogen in the system (**North Sea Powerhouse**), the total annual energy system expenditure levels are the highest (some €14 billion euros). A relatively large share of these expenditures consists of offshore cabling and green hydrogen production investments (e.g. electrolyser) in all three regions. The Port of Den Helder region has the shortest distance to the wind farms (area D and E). The fact that the capacity on the current electricity grid in this port region is limited, has strong implications for the landfall of electricity in the region and the location of the conversion system. A direct connection via cable between the offshore wind farm (generation asset) and the onshore electrolyser (end-user), which is placed right next to the sea, is assumed, minimizing the impact that landfall of electricity will have on the electricity grid. In the **Solar Shipping** scenario, a relatively large share (80%) of the total annual expenditure levels (some €10 billion euros) is related to the Port of Amsterdam region due to their large import terminal capacity for LOHC. In the scenario with low domestic production and high carbon capture and storage in the future energy system (**Pipeline Import**) energy flows through the harbour regions are minimal. Less than 50% of the total annual energy system expenditures take place in the harbour regions themselves. The hydrogen flows directly into the backbone, and the geographical advantages of the northern harbours that played a key-role in the other scenarios have no significant impact any longer. In this scenario, most expenditures that have to be made are related to the landing of offshore wind electricity for serving local electricity demand. The **National Blues** scenario represents the lowest total annual energy system expenditures (some 7.2 billion euros). The expenditures are relatively evenly distributed over the regions and comprise mainly of expenditures on offshore cabling and blue hydrogen production. More than 50% of the expenditures foreseen in the Port of Amsterdam region (40% of total system investment) are required for the offshore cabling to suffice local electricity demand. These expenditures (some €1.7 billion euros) are required in all scenarios.

This next sub-section discusses the sensitivity of the above analysis with respect to energy demand and the locational factors.

5.1.1 Fulfilment of hydrogen demand in the hinterland

In the above calculations, the assumption was that the three harbours could eventually deliver 25% - or a volume of $450PJ_h$/y – of the total hydrogen demand in the hinterland. Sensitivities are performed under the recognition that in reality this can be a lot more or less, while the demand for hydrogen in the harbour regions themselves has been kept constant at some $120PJ_h$. These effects are summarised for the **National Blues** and **North Sea Powerhouse** scenarios in Table 5.

In case that the northern harbour regions have only a minor role in supplying hydrogen – let us say only 7.5% which is a volume of $135PJ_h$, the total annual investment level in the combined regions will be much lower. The investment levels for the Port of Amsterdam region comprise of: offshore electric cables, electrolyzers and hydrogen import facilities. There is a high demand for electricity in the Port of Amsterdam region, though, due to the summer-winter spreads in electricity supply from offshore wind there may be an oversupply of electricity in the winter periods. This electricity is converted into hydrogen and covers a large share of the local hydrogen demand. As a result, the Port of Amsterdam region will have a relatively large role compared to the other three harbours in the lower hydrogen demand scenarios.

Table 5: sensitivity of expenditures with respect to volume of hydrogen flowing via the three northern harbour regions.

		Port of Amsterdam region	Port of Den Helder region	Groningen Seaports region	Annual system expenditures
North Sea Powerhouse	Low – $135PJ_h$	56%	14%	30%	6.0 B€
	Mid – $450PJ_h$	32%	45%	23%	14.4 B€
	High - $875PJ_h$	27%	26%	47%	25.1 B€
National Blues	Low – $135PJ_h$	57%	11%	32%	5.0 B€
	Mid – $450PJ_h$	39%	39%	22%	7.3 B€
	High - $875PJ_h$	28%	54%	18%	10.2 B€

Wind developments within wind-area C, with a connection both to the Port of Den Helder region and to the Port of Amsterdam region, as well as wind deployment within wind area G, with an connection to Groningen Seaport region are foreseen. If the northern harbours are jointly able to facilitate a higher share of hydrogen supplied to the hinterland, from $135PJ_h$ to $450PJ_h$, the realization of additional wind capacities in the wind areas D and E is required in the **North Sea Powerhouse** scenario (see also Table 3). A connection with these wind regions is mostly provided via the Port of Den Helder region, since this region is – based on distance – well located for a direct connection between the wind regions and the foreseen electrolyser assets. Though, if under the **North Sea Powerhouse** scenario - the northern harbours provide some 50% ($875PJ_h$) of the total hydrogen demand the boundaries of offshore wind production on the North Sea become visible: there is insufficient offshore wind capacity envisioned on the Netherlands continental shelf (60GW (36). The maximum planned yearly capacity from the combined areas C until G is assumed to be $825PJ_e$ per year. Considering the losses of hydrogen conversion (25%) and subtracting the required supply to local electricity demand in the three harbour areas (some 185 PJ_e) the maximum supply of domestically green hydrogen from offshore energy comes down to $480PJ_h$. A solution can be found by relieving the max. hydrogen import supply constraint (in the study set at 20% to 25%). The Groningen Seaports region is relatively well positioned as a landing point for wind farms located around the area F (Doggerbank region) which, in combination with the local storage potential, could explain the relative larger role of this harbour under high demand circumstances[14].

A similar conclusion regarding the investment level of the Port of Amsterdam region in the low demand **National Blues** scenario can be drawn: cabling contributes to a large share of the local system investments. In case that the northern harbours have a large role in the supply of hydrogen ($875PJ_h$) the relative volume of investments shift to the Port of Den Helder region because of their favourable locational factor for large scale carbon storage investments (lower UTC assumed). This effect is amplified due to the effects of economies of the scale that come with centralized production. The impact of the inclusion of economics of scale are analysed by comparing the outcomes of a non-linear model with the outcomes of a linear model. The non-linear model applies an economics of scale factor of 0.95 for the electrolyser system (27) and a factor of 0.8 to the ATR-system (28) (29). The realisation of economics of scale reduces the annual level of system expenditures, though does not alter the relative contribution of the individual harbours. The investments levels of the non-linear model are some 20% lower than the system expenditure of the linear model.

5.1.2 Locational factors

The expenditure for land-use for the installations and the expenditure for CO_2 injection were applied to the initial analysis, which are the only variables different for the three harbours. These steer the optimisation in a specific direction, sensitivity analyses are thus performed to understand how the modelling results are affected by these locational parameters. Table 6 shows the modelling results for the **National Blues** scenario, one in which no expenditures for the land are included and one in which the Unit Technical Costs (UTC) of CO_2 transport and storage are equalized.

The analysis show that the outcomes are very sensitive for the application of these factors and that one should be aware of this effect when interpreting the results

Specific attention is required for the UTC. EBN and Gasunie (17 p. 62) performed an analysis related to the UTC of CO_2 transport and storage for minimum sized start-up cases for regions with a high-concentration of CO_2-emissions. Their analysis does not consider a minimum-start-up case for Den Helder, since this region has currently a very low concentration of CO_2 emissions. Although Den Helder was not in the initial analysis, the potential UTC for CO_2 transport and storage from Den Helder was assumed in this report to be 9€/ton, reflecting their beneficial geographic position[15]. The results of the sensitivity analysis show that the outcomes are very sensitive for this assumption. When these expenditures are equalised between the harbour regions (set at 9€/ton), the relative role of Groningen Seaports region emerges at the expense of the Port of Den Helder region. The assumed UTC for Den Helder region requires therefore further research. The results become even more skewed toward the Groningen Seaports region when the land expenditures is left out the equation. The Port of Amsterdam

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[14] The inclusion of offshore hydrogen production is not included though may alter this conclusion.

[15] The UTC for Groningen Seaport region and Port of Amsterdam region were initially set at 11€/ton and 13.5€/ton.

region is not significantly affected by the locational factors; the main reason might be that the regional demand for hydrogen is already covered by the other sources of hydrogen.

In contrary to the **National Blues** scenario, the role of reuse of existing infrastructure, for instance import terminals, is very important in the **Solar Shipping** scenario. Different reuse conditions between the harbour areas hold for local buffering of liquefied hydrogen or derived products. It is considered that the storage facility for the (non-flammable) LOHC consist of conventional large-scale chemical storage units (50.000 m3) at the cost of 12,5 M€ per tank (39). Based on the amount of ‘wet’ cargo import in the harbour regions (40), it can be assumed that Port of Amsterdam region already has a locational advantage on the handling and storing of hydrogen import given the potential to reuse existing terminal facilities.

The analysis show that the outcomes are very sensitive with regard to this reuse assumption and that one should be aware of this effect when interpreting the results.

When these expenditures for installing storage terminals are equalised between the harbour regions (set at 12.5M€ per tank, and no option for reuse), the relative role of Groningen Seaports region emerges at the expense of the Port of Amsterdam region. Therefore, more insight is required into the potential to reuse the existing terminals in the Port of Amsterdam region (see also Table 6).

Table 6: Effect of not including land expenditures and/or an equal UTC on the role of the ports.

		Port of Amsterdam region	Port of Den Helder region	Groningen Seaports region
National Blues	Equal UTC & no land costs	44%	2%	54%
	No land expenditures	41%	38%	21%
	Equal UTC factor	30%	19%	51%
	Base model	39%	39%	22%
Solar Shipping	No Reuse advantage	49%	19%	32%
	Base model	80%	4%	16%

5.1.3 An inverse relation between import and storage.

Increasing domestic and green hydrogen production from offshore wind comes with a seasonal pattern of energy supply due to variability in wind electricity production. Consequently, the maximum storage levels necessary over the year will grow, along with the fluctuations of storage in- and outflow. Reducing storage fluctuations can be of importance to realize an optimal operation time of the storage facility. A factor assisting in this on the seasonal scale is the planning of import, because of its monthly flexibility. An increased allowance of hydrogen import from ships in the energy system drastically decreases the fluctuation of storage levels. In Figure 9 the **North Sea Powerhouse** scenario – which is constraint by a maximum of 20% of the hydrogen demand being supplied by the import of hydrogen by ship - is compared to a scenario in which import by ship is constrained to some 7%. The impact on storage fluctuation is clearly visible. Where the 7% shipping case has a maximum storage necessity of 22.5 PJ_h during the year, the 20% shipping capacity only needs a 3 PJ_h maximum storage.

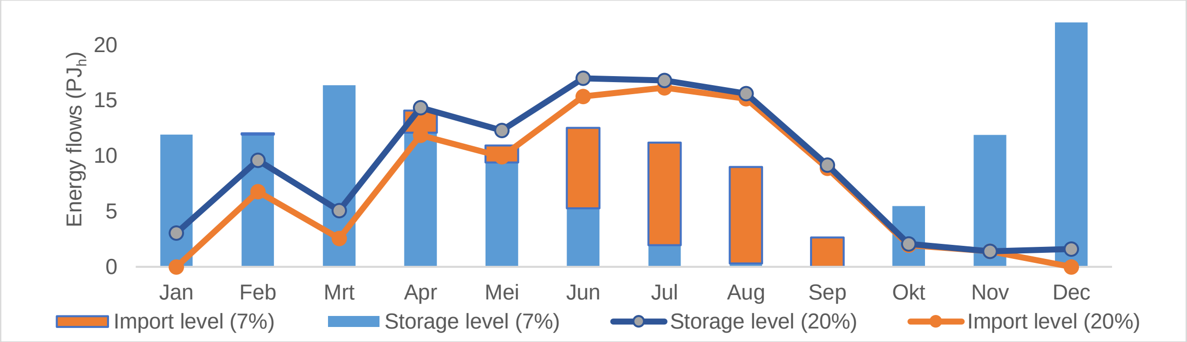

Figure 9: Seasonality provision by shipping and storage. Yearly combined pattern of storage levels and import volumes (both in PJ_h) for scenarios with 7% import capacity and 20% import capacity (with respect to the yearly hydrogen demand).

5.2 Synergies from cooperation

The value of cooperation can be highlighted by comparing the results in which the harbour regions are interconnected with the results in which the harbour regions are considered in isolation. The latter implies that the different harbour regions are not connected to the other harbours as far as energy flows is concerned. A connection between the individual harbours is a prerequisite for realizing synergies between harbours by utilizing unique harbour features and realizing economics of scale. To assess potential synergies three specific comparisons have been distinguished:

1. A case in which the harbours typically concentrate on satisfying their own regional demand for energy (for the three harbours together, $120PJ_h$), which is compared to a similar case but in which harbours mutually collaborate in dealing with energy system optimization.
2. A case in which the harbours additionally also individually focus on satisfying the energy demand from the hinterland (total energy demand, $450PJ_h$), which is compared with a set-up in which the three harbours work together to service energy needs both in the harbours regions and in the collective hinterland.
3. A comparison of the isolated condition in which the harbours typically concentrate on satisfying their own regional demand for energy (for the three harbours together, $120PJ_h$), and the set-up in which the three harbours work together to service energy needs both in the harbours regions and in the collective hinterland (for the three harbours and the backbone together, $450PJ_h$),

Note that – for the first two points - we have completely focussed on the **National Blues** scenario conditions as have been outlined above (see ‘Scenarios’).

5.2.1 Harbours focus on satisfying their own energy demand ($120PJ_h$)

The concept of not having specific energy exchange between the harbour regions, nor with the hinterland, limits each harbour region to focus on satisfying energy demand in their region themselves. This implies that each harbour region will make its own local investments in production, conversion and storage of energy. In the simulation, this has been worked out by assuming that the hydrogen demand from the hinterland is absent, as well as access to the hydrogen backbone[16]. The results of this scenario are shown in Figure 10. The scenario assumes the individual regions will invest in production, conversion and storage units in their own region. For instance, in this scenario the Amsterdam and Den Helder regions will not be able to use the salt caverns near Port of Groningen region as hydrogen storage facilities. These regions will therefore either have to invest in alternative storage options, e.g. via cryogenic storage facilities, or rely more on hydrogen imports shifting the storage burden to elsewhere.

In the alternative case in which again the hinterland is disregarded but harbours actively work together to optimize their energy system, the synergies of working together domestically will be achieved.

What does the domestic harbour offer in terms of synergies, even if the hinterland is not serviced jointly? Most important insights:

- The sensitivity analyses shows that annual energy system expenditures in the isolated case are some 5%-10%- higher than in the connected harbours case.
- Without collaboration, the Port of Amsterdam region with its relatively high local demand for hydrogen will typically have to organize supplying hydrogen to satisfy its own demand. A large share of this hydrogen will most likely be supplied by hydrogen produced from the regular seasonal surpluses of green power, which are typical for this region and result from seasonal supply overshooting demand. Because underground storage in salt caverns in the harbour region is no option, one has to rely on relatively expensive substantial local storage. If the harbour area instead could benefit from the cheaper storage options offered by the Groningen Seaports region, expenditure of the overall energy system would be lower.
- Because the Port of Den Helder is relatively small and in the absence of major industrial activity nearby the development of energy-related activities in the port region will be limited. This may hinder investment activity and raise energy handling expenditures of activities that have to be organized in the own region against higher rates (e.g. energy storage or transport). If the harbour is connected with the other harbours via the backbone infrastructure, the overall investment perspective of the Den Helder region may change, especially if some dedicated specialized energy activity can be set-up servicing a much wider region.
- The production of blue hydrogen in Groningen Seaports region will remain small without collaboration with the other harbour areas, because the local demand for hydrogen can typically be serviced with

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[16] In reality, there are already pipeline connections between the harbour areas, though the assumption is that these pipelines cannot be re-used for hydrogen transmission.

the help of green hydrogen. If instead the harbours are connected, blue hydrogen produced in the Groningen Seaports region may be transported to the Port of Amsterdam region, thanks to the lower land lease expenditures in the Groningen Seaports Region.

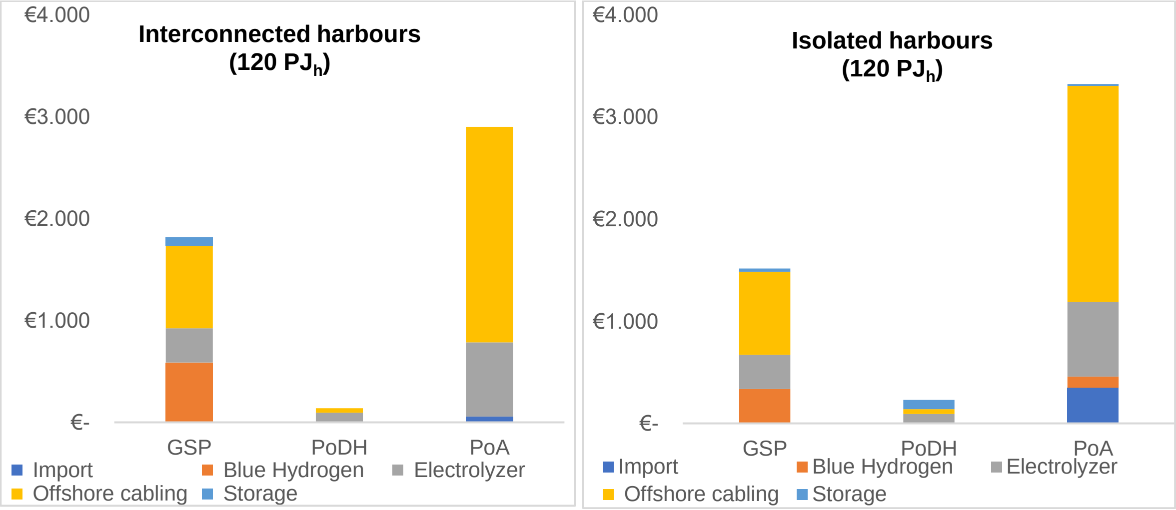

Figure 10: System expenditures (MEUR) for a 120 PJ_h energy system for (i) an interconnected harbour system and (ii) isolated harbour systems.

5.2.2 Harbours also supply the hinterland with hydrogen (450 PJ_h)

The results of the sensitivity analysis comparing an isolated with an interconnected system of harbours is shown in Figure 11. It shows that introducing an energy infrastructure connection with the hinterland is extremely important for the role of the Port of Den Helder. Without this, the role of this region as an energy harbour region will remain limited; a good connection with the hinterland may have dramatic impact on its growth potential. Secondly, the simulations show that collaboration will typically shift blue hydrogen production even more towards the region with the best conditions for it, namely the Den Helder region, due to the low UTC, becoming the blue hydrogen production hotspot (some blue hydrogen production will remain in Groningen region because of transport cost differentials). This obviously requires significant blue hydrogen production capacity to be installed in that region, as well as considerable CCS activity directed at offshore transport and storage of CO_2 potentially via the existing gas grid. Third, the annual system expenditures for isolated harbour regions (without a connection to the other harbours) are some 2%-5% higher: collaboration creates synergies.

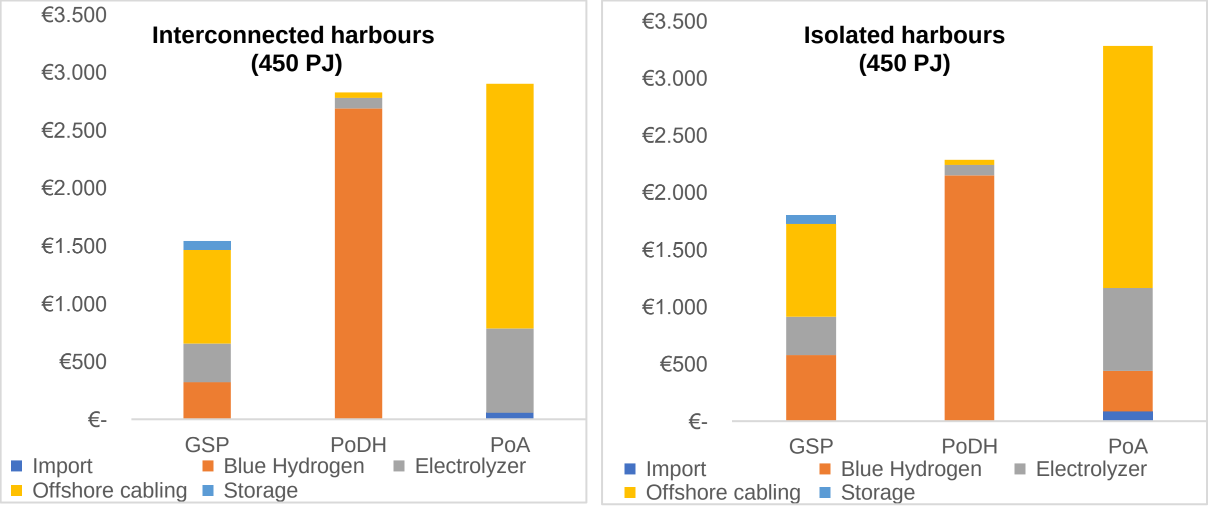

Figure 11: System expenditures (MEUR) for a 450 PJ_h energy system for (i) an interconnected harbour system and (ii) isolated harbour system.

5.2.3 Complete isolation or comparative advantage by collaboration

There is clear evidence that a close collaboration between the three harbours is likely to generate serious synergy benefits. The backbone connecting the harbour regions with each other and with the hinterland supports regional specialization and generates economies of scale because of the increase in demand. In the **National Blues** scenario, a 50% reduction in the system expenditure expressed in €/PJ$_h$ can be realized due to specialization in the harbor regions. A similar effect – though a bit smaller due to lower economics of scale – is present under the **Solar Shipping** scenario (40%) and the **North Sea Powerhouse** scenario (30%).

Table 7: benefit of cooperation identified in the various scenarios

Scenario	Isolated harbours (120PJ$_{h)}$	Interconnected harbours and hinterland (450PJ$_{h)}$	Reduction in the system expenditure
National Blues	38€/PJ$_h$	16€/PJ$_h$	Some 50%
North Sea Powerhouse	49€/PJ$_h$	33€/PJ$_h$	Some 30%
Solar Shipping	44€/PJ$_h$	23€/PJ$_h$	Some 40%

5.3 Sub-conclusion

It should be mentioned that the above analysis have been performed with the help of stylized cases and seriously simplifying assumptions. The results therefore have to be seen as broad indications of the kind of changes and impacts to be expected rather than the precise size of the effects. Keeping this in mind the results suggest that moving from isolated local harbours into collaborating (inter)national energy harbours will indeed have a serious impact towards 2050.

Three findings are important. First, the sensitivity analyses show that for a clear specialization pattern between the harbours, a backbone connecting the harbours and the collective hinterland is crucial. Generically speaking, Groningen Seaports is well-situated to develop into a major green hydrogen production and transmission location, e.g. because the presence of extensive chemical industry and its proximity to large-scale storage facilities (17); Port of Den Helder is well-positioned for blue and dedicated green hydrogen related activities e.g. due to its location next to feed-in points into major gas trunk lines and its proximity to offshore wind locations; whereas Port of Amsterdam has a promising profile to develop into a major hydrogen import location including related conversion and end-use (steel and aviation fuels), given that Port of Amsterdam is already a leading player in liquid bulk. In addition, the serious landfall of electricity is required in this region to service the regional demand for electricity.

Second, the sensitivity analyses have clearly indicated that a non-trivial benefit can be reaped by the harbour areas from working together: under all conditions, synergies result if the harbours collectively optimize their energy systems, are well connected, and are open for specializations to minimize overall system expenditures.

Finally the sensitivity analyses show that if towards 2050 the three northern harbours will increasingly serve as the energy hub(s) for the hinterland (in our simulations the Netherlands and Germany together), the total annualized expenditures on energy supply in the harbours will increase by about 50% if one moves from a continued locally oriented harbour perspective towards an internationally oriented energy hub perspective. In addition, though hard to quantify, the development of a well-established, secure and clean regional energy infrastructure may attract new industry and business to the harbour regions.

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[17] Significant parts of the North Sea are relatively shallow, which makes it easy to install wind turbines, and helps to produce power at relatively low costs (i.e. in the order of currently some 0.50€/MWh (51)).

6. Energy system activities, legal framework and stakeholder analysis

This chapter will firstly describe the envisioned future energy system activities in the harbour areas in 2050, hereby analysing how far away these envisioned futures are from today's reality and the stakeholders involved in those activities. Subsequently, the institutional and organisational structures and frameworks relevant to developing those activities are discussed on a high level. Lastly, the main results of the legal framework analysis are presented[18].

6.1 Future energy system activity and stakeholder analysis

This section gives an impression of (i) which preconditions apply to the presented future energy system changes, (ii) how these energy systems are linked with possible future roles of public and private parties, (iii) what the maturity is of the required technologies and activities, preconditions of these activities and (iv) how stakeholders have different power and interest levels when they collaborate together to realise these energy systems. Furthermore, this section gives an impression of how far away these envisioned futures are from today's reality. This study does not have the objective to summarize a complete overview of the maturity level of required technologies and/or activities and the current future energy system plans and ambitions from public and private parties in the Netherlands.

Firstly, the energy supply chains are visualised in section 5.1.1. Secondly, the stakeholders involved in that supply chain are identified (5.1.2). Subsequently, the maturity level and the minimum expected scale of each activity and their preconditions is discussed (5.1.3). Lastly, section 5.1.4 concludes with preconditions of green and blue hydrogen energy systems in the harbour regions of Amsterdam, Den Helder and Groningen.

6.1.1 Activities in the envisioned future energy systems

The research upon hand envisions a (more) renewable future energy system in the northern harbour areas in 2050. Multiple alternative system designs are presented, based on the earlier described four future scenarios. The previous chapters have covered the details of these scenarios. Figures 12-14 visualise the envisioned energy systems in a general energy supply chain and show the activities that are in place in each scenario, one figure for each harbour area. Note that this energy supply chain is limited to the activities and flows that were in scope of this research, for instance heat is excluded.

The coloured circles describe what activities take place in the harbour region under the various scenarios. For a more detailed overview, Table 8 presents the flow of energy in PJ for each relevant activity in the energy supply chain for the three harbour areas per scenario for 2050. Part of these activities are currently undertaken by a party in the Netherlands, other activities are not yet undertaken given the maturity of the required technologies and activities. The blue line describes the presence of transmission and/or distribution infrastructure facilitation the energy flow through the value chain. This infrastructure might be either public or privately owned.

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[18] The legal report is publicly available

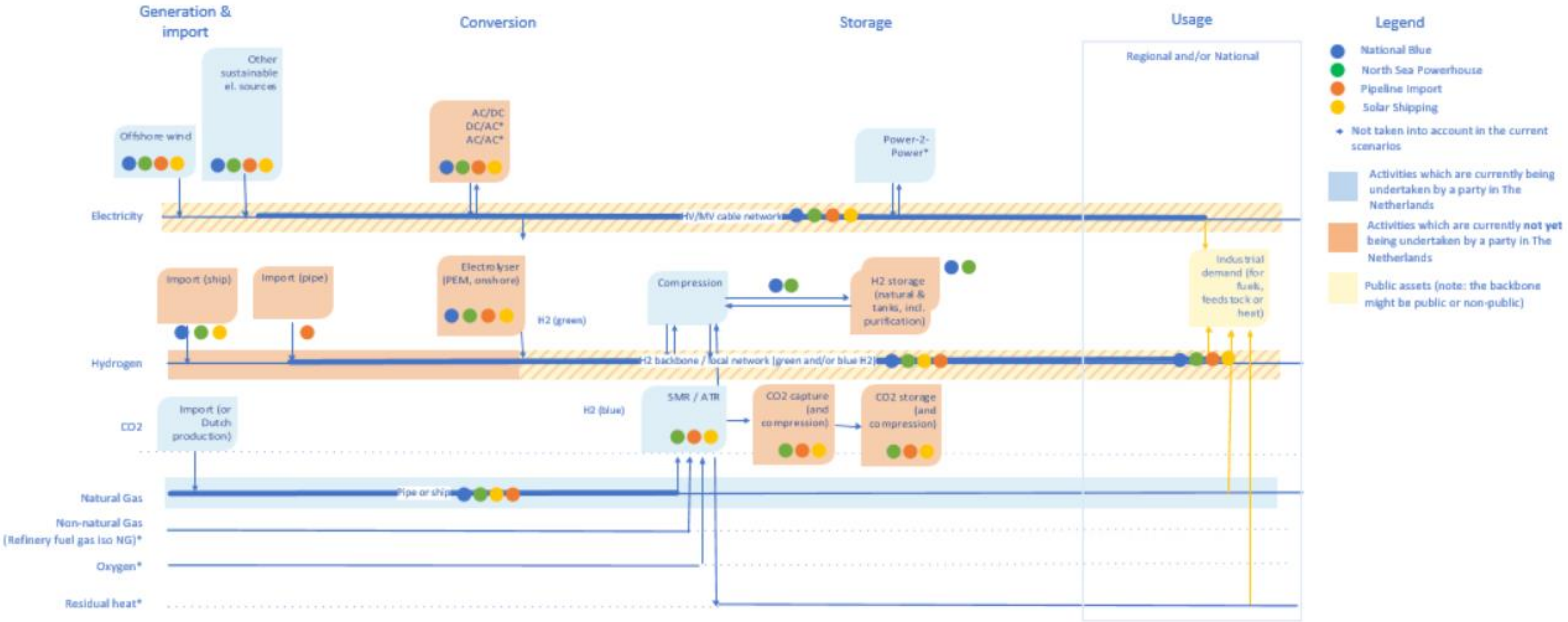


Figure 12: Energy supply chain diagram for the region of Port of Amsterdam

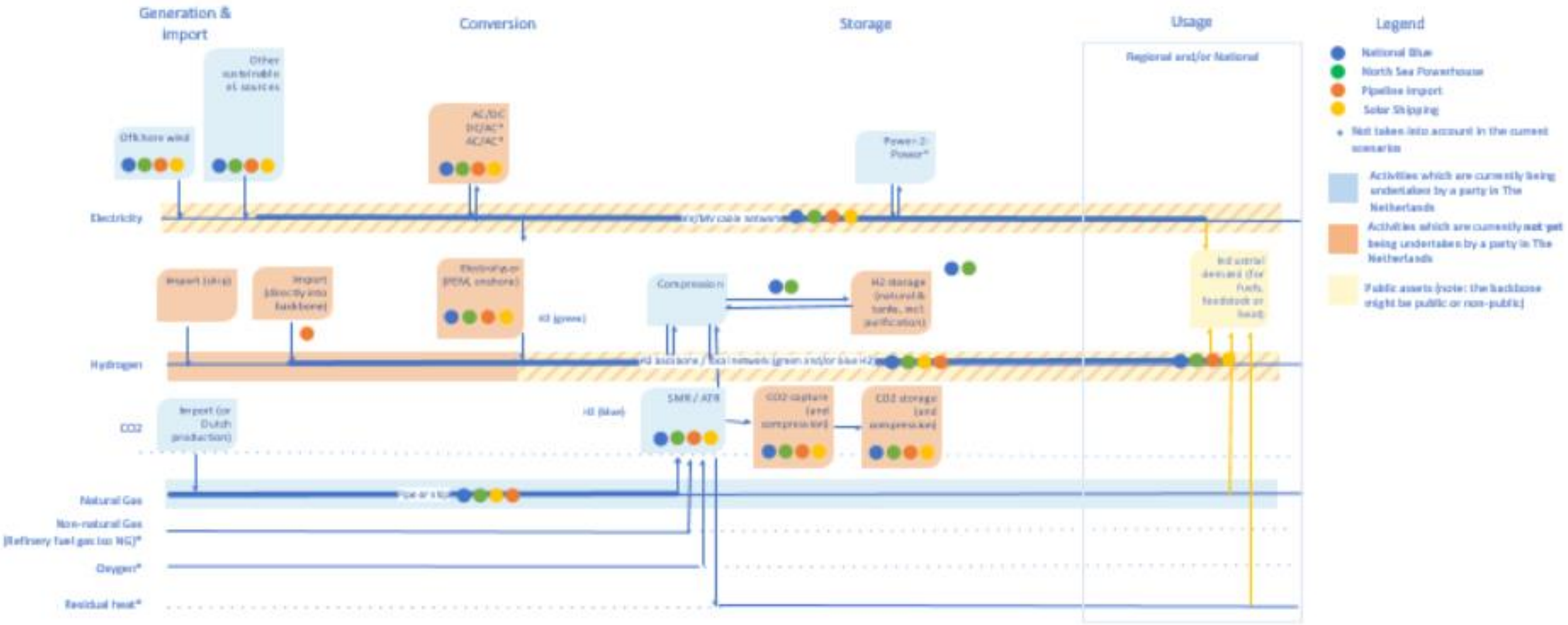


Figure 13: Energy supply chain diagram for the region of Port of Den Helder

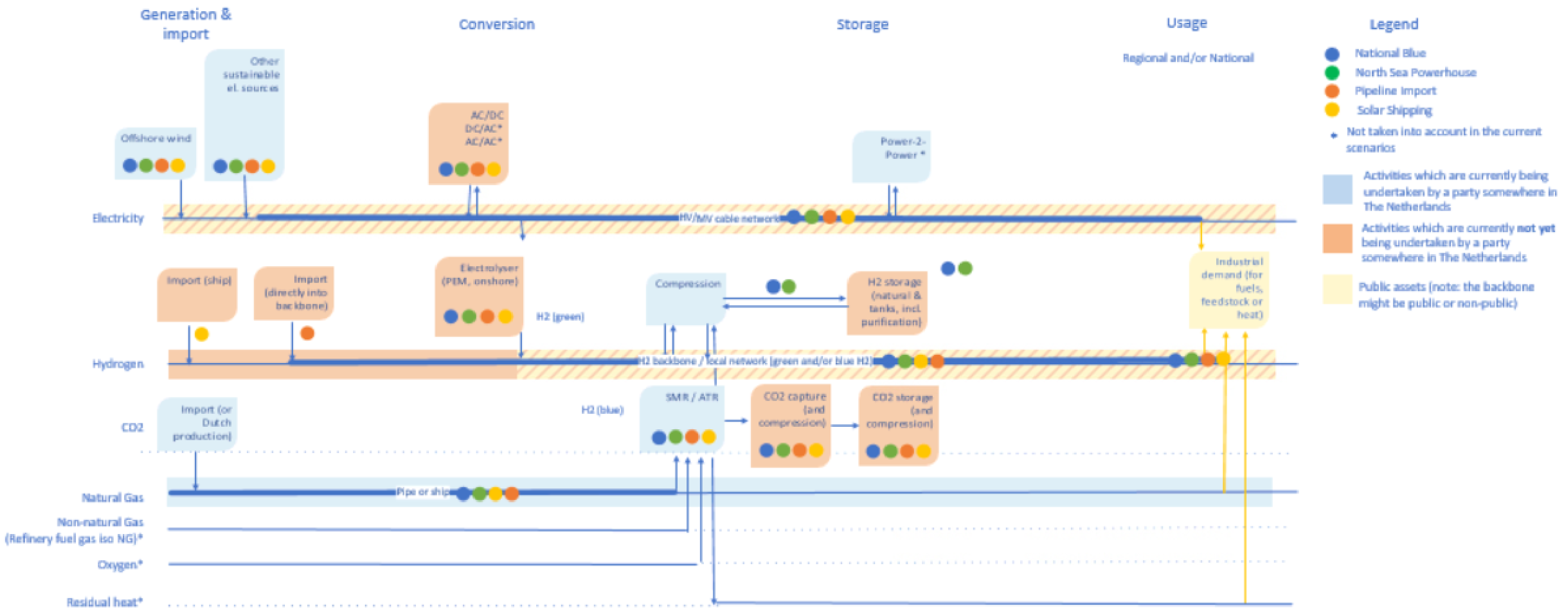


Figure 14: Energy supply chain diagram for the region of Groningen Seaports

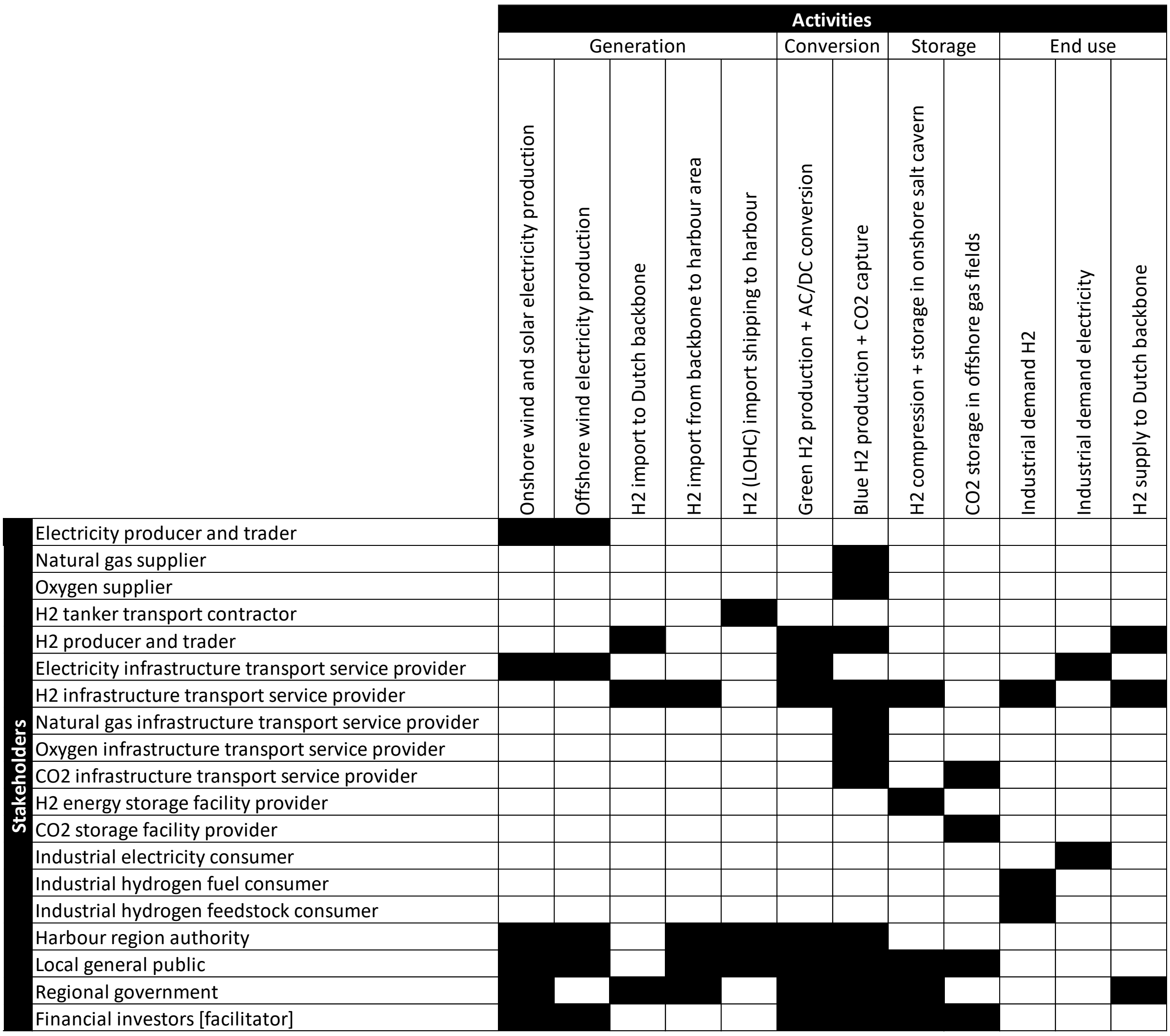
Table 8: Flow of energy for each harbour area in each scenario in PJ/year

			Scenarios											
			NSPH			Pipeline Import			NB			SS		
			POA	PODH	GS	POA	PODH	GS	POA	PODH	GS	POA	PODH	GS
Activities	Generation	Onshore wind (input)	20	15	2	20	15	2	20	15	2	20	15	2
		Rooftop PV (input)	12	1	1	12	1	1	12	1	1	12	1	1
		Solar fields (input)	10	3	1	10	3	1	10	3	1	10	3	1
		Offshore wind to harbour area	181	223	142	181	4	70	181	4	70	181	4	70
		H2 import from abroad via backbone to NL	0	0	0	102	102	102	0	0	0	0	0	0
		H2 import from backbone to harbour area	0	0	0	10	0	9	29	0	12	0	0	0
		H2 import from shipping	90	0	0	0	0	0	4	0	0	298	0	8
	Conversion	Green hydrogen production	33	169	70	33	4	16	33	4	16	33	4	16
		Blue hydrogen production	30	30	30	30	30	30	0	365	38	30	30	30
	Storage	CO_2 storage	2	2	2	2	2	2	0	23	3	2	2	2
		Hydrogen to salt cavern storage	3.1 inj. Max, 0.99 max withdrawal, 3.1 max volume			NA			4.6 inj. Max., 3.4 max withdrawal, 9.5 max volume			NA		
	End use	Industrial demand of hydrogen in harbour area	44	2	50	44	2	50	44	4	50	44	2	50
		Flow of hydrogen from harbour area to backbone	87	197	46	7	32	2	0	367	6	297	33	2

6.1.2 Stakeholders in the future energy supply chain

Developing future regional energy systems in the studied northern harbour areas requires collaboration of a wide variety of stakeholders. Involving multiple stakeholders subsequently leads to a broad variety of stakeholder objectives, perceptions and potential barriers. Moreover, these objectives, perceptions and barriers are likely to change over time. Each stakeholder, from large influential investment banks to regional policy makers, has a crucial role to play in the energy system supply chain development activities. Identifying the involved stakeholders, their (potential) role in the development of the energy system and their objectives is crucial to be able to collaborate effectively and develop the more renewable energy supply chain. The following paragraph identifies the stakeholders in the supply chain activities and the maturity level of the activities at this moment.

Diverse stakeholders carry out the activities in the energy supply chain as in scope of this research. The stakeholder-activity matrix in Figure 15 illustrates which stakeholders are directly involved in which energy supply chain activity.



		Activities											
		Generation					Conversion		Storage		End use		
		Onshore wind and solar electricity production	Offshore wind electricity production	H2 import to Dutch backbone	H2 import from backbone to harbour area	H2 (LOHC) import shipping to harbour	Green H2 production + AC/DC conversion	Blue H2 production + CO2 capture	H2 compression + storage in onshore salt cavern	CO2 storage in offshore gas fields	Industrial demand H2	Industrial demand electricity	H2 supply to Dutch backbone
Stakeholders	Electricity producer and trader	■	■										
	Natural gas supplier							■					
	Oxygen supplier							■					
	H2 tanker transport contractor					■							
	H2 producer and trader			■			■	■					■
	Electricity infrastructure transport service provider	■	■				■					■	
	H2 infrastructure transport service provider			■	■		■	■	■		■		■
	Natural gas infrastructure transport service provider							■					
	Oxygen infrastructure transport service provider							■					
	CO2 infrastructure transport service provider							■		■			
	H2 energy storage facility provider								■				
	CO2 storage facility provider									■			
	Industrial electricity consumer											■	
	Industrial hydrogen fuel consumer										■		
	Industrial hydrogen feedstock consumer										■		
	Harbour region authority	■	■		■	■	■	■					
	Local general public	■	■		■	■	■	■	■	■			
	Regional government	■		■	■		■	■	■				■
	Financial investors [facilitator]	■	■				■	■	■	■			

Figure 15: Stakeholders involved in supply chain activities in scope

Complementary to the stakeholders that are directly involved in the energy flow, multiple indirect stakeholders are influencing, or being influenced by the development of energy supply chain activities. Contributions of the indirectly involved stakeholders are a pre-requirement to the successful development of the renewable energy supply chains in the Port of Amsterdam, Den Helder and Groningen. The following stakeholders are indirectly involved in the activities in scope of this research:

- Technology innovators and manufacturers
- Domestic and industrial heat network operators (note: heat is not in scope of this research)
- National governmental policy makers & politicians[19]
- Regional governmental policy makers & politicians
- Trading organisations
- Media
- NGOs
- Policy, regulatory and legislation agencies (e.g. IRENA, Renewable energy directive, ACM, ETS)
- Education and research institutes
- Product substitute competitors (e.g. HVDC electricity system, energy carrier conversion, international interconnection or export offshore)

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[19] It is important that the national government recognizes the strategic position of the three northern harbours as a (green) energy hub for the national economy.

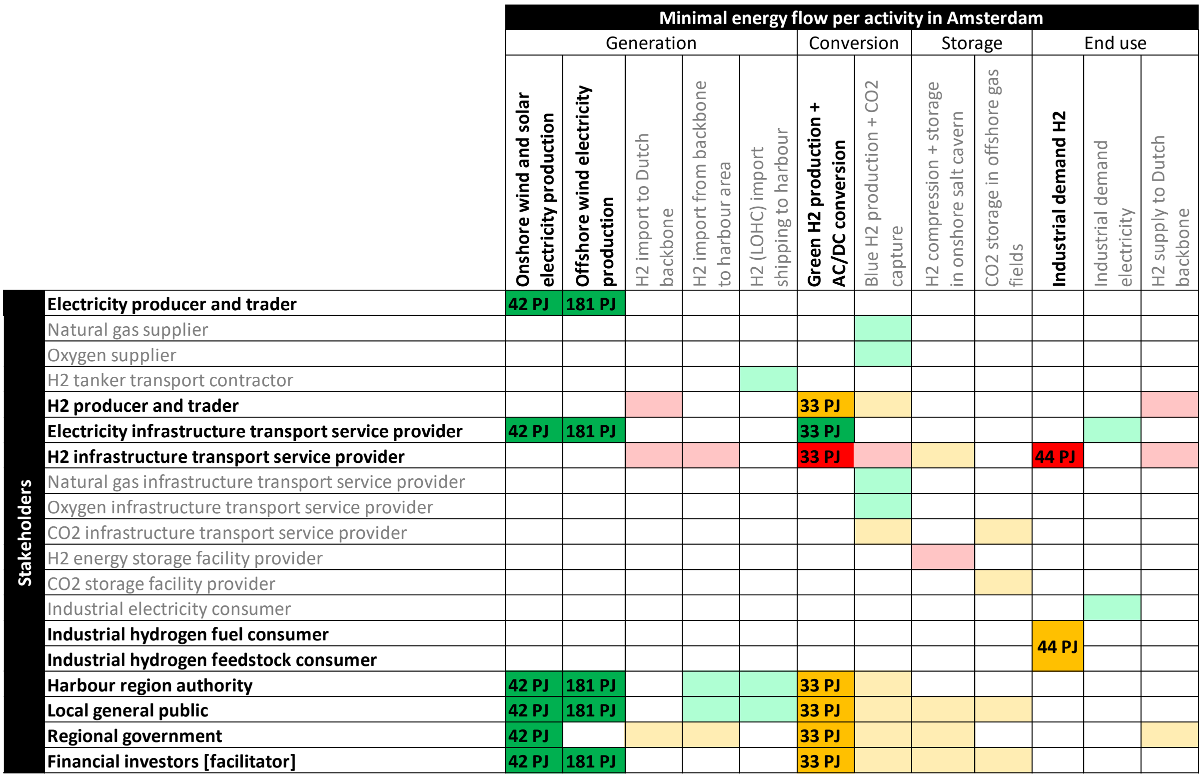
When transforming the current energy system into a more renewable energy system of the future, the question rises to what extend stakeholders can built on the current energy system experiences and matured technologies and which activities are new. For each stakeholder, and the supply chain as a whole, it is essential to have a clear understanding of the maturity level of the activities found in the future energy system and of the minimal scale those activities may be expected in each harbour. The next section provides more insight on both these topics.

6.1.3 Identification of maturity level and minimal scale per supply chain activity

In this section, each activity is rated on its maturity level. In addition, the minimal scale of each activity, based on the four scenarios, is included per harbour to illustrate so-called no-regret system developments. Stakeholders can use this information to better understand their role in the supply chain, and the effort that may be required to execute this role successfully. A more detailed analysis of activity and technology maturity levels is beyond the scope of this research.

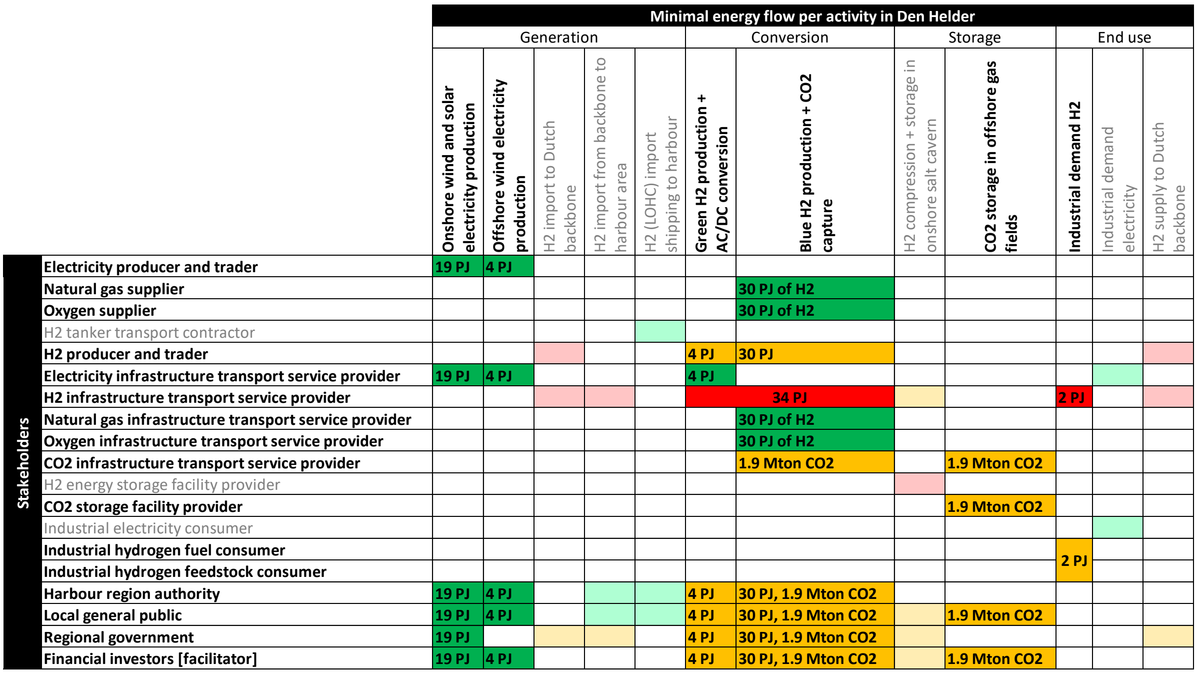
The maturity of an activity is estimated based on the Tracking Clean Energy Progress data of the IEA (42). An activity is green when the activity is mature globally, orange in case of an upscaling activity and red when the activity is still under development. It should be noted that mature activities elsewhere on the world might not imply that this activity can be introduced straight away in the Dutch harbour regions. Figures 16-18 illustrate the activities of the Port of Amsterdam, Port of Den Helder and Groningen Seaports respectively. For each activity, the maturity of the activity is given and the minimum flow in PJ. Please note that these flows do not add up as the flows given present the minimal values within the four scenarios to show the no-regret energy flow that may be accommodated based on the four scenarios.

Figure 16 shows the results for a no-regret system capacity in the Port of Amsterdam. Only green hydrogen is produced in the no-regret system. We see that there is no foreign import into the national backbone and or via shipping and no import into the harbour area from the backbone. No hydrogen storage is foreseen. Figure 17 shows the results for a no-regret system capacity in the Port of Den Helder. There is substantially more production of blue hydrogen than green hydrogen. We see that there also is no foreign import into the national backbone and or via shipping and no import into the harbour area from the backbone. Moreover, similar to the Port of Amsterdam, no hydrogen storage is foreseen. Figure 18 shows the results for a no-regret system capacity in Groningen Seaports. There is double the amount of blue hydrogen production compared to green hydrogen. We see that there is no foreign import into the national backbone and or via shipping, no import into the harbour area from the backbone and no hydrogen storage is foreseen.



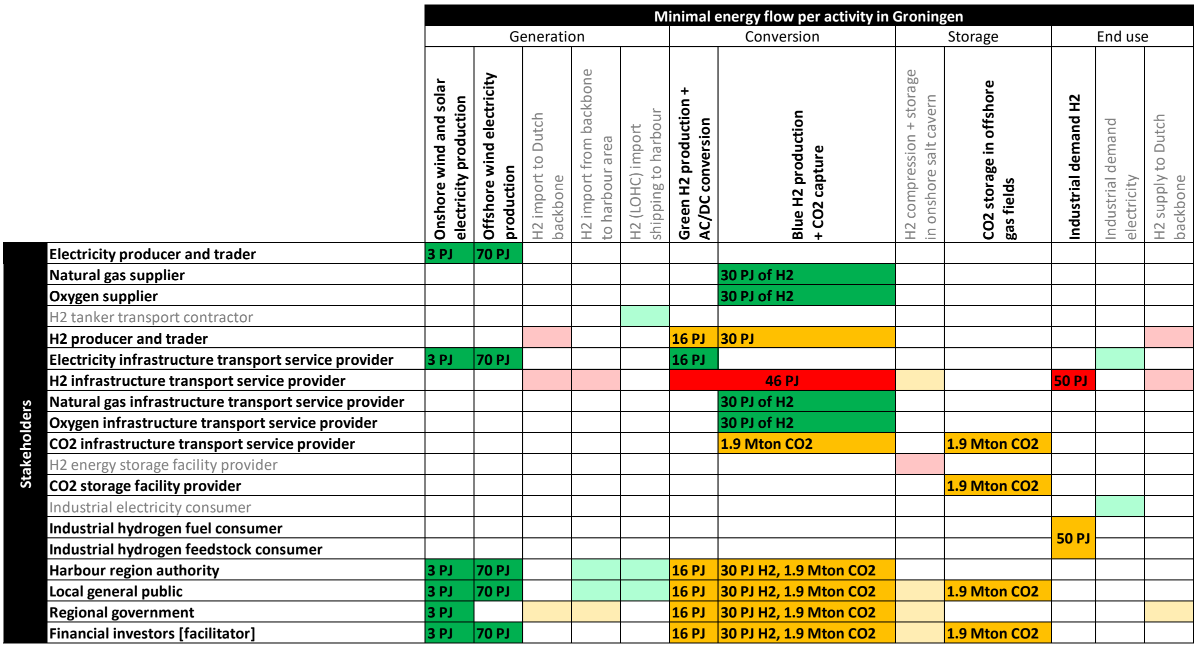
	Minimal energy flow per activity in Amsterdam											
	Generation					Conversion		Storage		End use		
Stakeholders	**Onshore wind and solar electricity production**	**Offshore wind electricity production**	H2 import to Dutch backbone	H2 import from backbone to harbour area	H2 (LOHC) import shipping to harbour	**Green H2 production + AC/DC conversion**	Blue H2 production + CO2 capture	H2 compression + storage in onshore salt cavern	CO2 storage in offshore gas fields	**Industrial demand H2**	Industrial demand electricity	H2 supply to Dutch backbone
Electricity producer and trader	42 PJ	181 PJ										
Natural gas supplier							🟩					
Oxygen supplier							🟩					
H2 tanker transport contractor					🟩							
H2 producer and trader			🟥			33 PJ	🟨					🟥
Electricity infrastructure transport service provider	42 PJ	181 PJ				33 PJ					🟩	
H2 infrastructure transport service provider			🟥	🟥		33 PJ	🟥	🟨		44 PJ		🟥
Natural gas infrastructure transport service provider							🟩					
Oxygen infrastructure transport service provider							🟩					
CO2 infrastructure transport service provider							🟨		🟨			
H2 energy storage facility provider								🟥				
CO2 storage facility provider									🟨			
Industrial electricity consumer											🟩	
Industrial hydrogen fuel consumer										44 PJ		
Industrial hydrogen feedstock consumer												
Harbour region authority	42 PJ	181 PJ		🟩	🟩	33 PJ	🟨					
Local general public	42 PJ	181 PJ		🟩	🟩	33 PJ	🟨	🟨	🟨			
Regional government	42 PJ		🟨	🟨		33 PJ	🟨	🟨				🟨
Financial investors [facilitator]	42 PJ	181 PJ				33 PJ	🟨	🟨	🟨			

Figure 16: Flows in no-regret system Port of Amsterdam



	Minimal energy flow per activity in Den Helder											
	Generation					Conversion		Storage		End use		
Stakeholders	**Onshore wind and solar electricity production**	**Offshore wind electricity production**	H2 import to Dutch backbone	H2 import from backbone to harbour area	H2 (LOHC) import shipping to harbour	**Green H2 production + AC/DC conversion**	**Blue H2 production + CO2 capture**	H2 compression + storage in onshore salt cavern	**CO2 storage in offshore gas fields**	**Industrial demand H2**	Industrial demand electricity	H2 supply to Dutch backbone
Electricity producer and trader	19 PJ	4 PJ										
Natural gas supplier							30 PJ of H2					
Oxygen supplier							30 PJ of H2					
H2 tanker transport contractor					🟩							
H2 producer and trader			🟥			4 PJ	30 PJ					🟥
Electricity infrastructure transport service provider	19 PJ	4 PJ				4 PJ					🟩	
H2 infrastructure transport service provider			🟥	🟥		34 PJ		🟨		2 PJ		🟥
Natural gas infrastructure transport service provider							30 PJ of H2					
Oxygen infrastructure transport service provider							30 PJ of H2					
CO2 infrastructure transport service provider							1.9 Mton CO2		1.9 Mton CO2			
H2 energy storage facility provider								🟥				
CO2 storage facility provider									1.9 Mton CO2			
Industrial electricity consumer											🟩	
Industrial hydrogen fuel consumer										2 PJ		
Industrial hydrogen feedstock consumer												
Harbour region authority	19 PJ	4 PJ		🟩	🟩	4 PJ	30 PJ, 1.9 Mton CO2					
Local general public	19 PJ	4 PJ		🟩	🟩	4 PJ	30 PJ, 1.9 Mton CO2	🟨	1.9 Mton CO2			
Regional government	19 PJ		🟨	🟨		4 PJ	30 PJ, 1.9 Mton CO2	🟨				🟨
Financial investors [facilitator]	19 PJ	4 PJ				4 PJ	30 PJ, 1.9 Mton CO2	🟨	1.9 Mton CO2			

Figure 17: Flows in no-regret system Port of Den Helder



	Minimal energy flow per activity in Groningen											
	Generation					Conversion		Storage		End use		
Stakeholders	Onshore wind and solar electricity production	Offshore wind electricity production	H2 import to Dutch backbone	H2 import from backbone to harbour area	H2 (LOHC) import shipping to harbour	Green H2 production + AC/DC conversion	Blue H2 production + CO2 capture	H2 compression + storage in onshore salt cavern	CO2 storage in offshore gas fields	Industrial demand H2	Industrial demand electricity	H2 supply to Dutch backbone
Electricity producer and trader	3 PJ	70 PJ										
Natural gas supplier							30 PJ of H2					
Oxygen supplier							30 PJ of H2					
H2 tanker transport contractor					🟩							
H2 producer and trader			🟥			16 PJ	30 PJ					🟥
Electricity infrastructure transport service provider	3 PJ	70 PJ				16 PJ					🟩	
H2 infrastructure transport service provider			🟥	🟥		46 PJ		🟨		50 PJ		🟥
Natural gas infrastructure transport service provider							30 PJ of H2					
Oxygen infrastructure transport service provider							30 PJ of H2					
CO2 infrastructure transport service provider							1.9 Mton CO2		1.9 Mton CO2			
H2 energy storage facility provider								🟥				
CO2 storage facility provider									1.9 Mton CO2			
Industrial electricity consumer											🟩	
Industrial hydrogen fuel consumer										50 PJ		
Industrial hydrogen feedstock consumer												
Harbour region authority	3 PJ	70 PJ		🟩	🟩	16 PJ	30 PJ H2, 1.9 Mton CO2					
Local general public	3 PJ	70 PJ		🟩	🟩	16 PJ	30 PJ H2, 1.9 Mton CO2	🟨	1.9 Mton CO2			
Regional government	3 PJ		🟨	🟨		16 PJ	30 PJ H2, 1.9 Mton CO2	🟨				🟨
Financial investors [facilitator]	3 PJ	70 PJ				16 PJ	30 PJ H2, 1.9 Mton CO2	🟨	1.9 Mton CO2			

Figure 18: Flows in no-regret system Groningen Seaports

It is observed that a number of activities are still in their development phase while those activities are essential to the successful functioning of the future renewable energy system. In the no-regret system, these activities are green hydrogen production & transport, blue hydrogen production and transport and local industrial hydrogen demand. For activities outside the no-regret system, maturing of additional activities is needed amongst which the national and regional hydrogen backbones, (pure) hydrogen storage in salt caverns and hydrogen market trade.

In addition to the conflict of activity maturity and estimated capacity required, additional activities can be considered preconditioned for the successful development of the regional energy system. The next paragraph will elaborate in more detail on the availability and prerequisites of four activities: large scale power-to-hydrogen technologies, hydrogen infrastructure, landfall of offshore windfarm electricity and hydrogen storage.

6.1.4 Future energy system preconditions and stakeholder power and interests

Realising the envisioned energy flows through the three harbours and developing the required renewable energy systems in 2050 requires multiple significant system developments. The largest developments required are discussed in this section. Preconditions regarding the following topics are discussed:

- Preconditions for green hydrogen
- Preconditions for blue hydrogen
- Preconditions for hydrogen transport
- Preconditions for hydrogen storage
- Preconditions for the hydrogen import

6.1.4.1 Preconditions for green hydrogen

All four extreme scenarios show green hydrogen production in the three harbour areas. There is a production foreseen for $33PJ_h$ in Port of Amsterdam, 4 to 163 PJ_h in Port of Den Helder and $16\text{-}70PJ_h$ in Groningen Seaports per year. To put these production forecasts in perspective: DNV-GL envisions a production of $16\text{-}88PJ_h$ in the region of Port of Amsterdam (Noordzeekanaalgebied) in 2050 and $42PJ_h$ in the area of Groningen Seaport (Noord Nederland) in 2030 (37). The ambitions in the northern investment agenda for the Groningen Seaports region are with some $100PJ_h$ of production even more ambitious (22).

For green hydrogen production, electrolyser assets have to be installed. There are multiple technologies in place for green hydrogen production. In the analysis the technology PEM is assumed but the technology is scaling up, and not ready large-scale application. The PEM technology has reached a technology readiness level of 7-8, which means that the system has been demonstrated in an operational environment (43) though cost reduction and upscaling of the PEM technology is necessary to enable large-scale capacity of green hydrogen production in the harbour regions. An alternative may be to combine alkaline with PEM technology. The alkaline technology is the most mature electrolyser technology (TRL 9) and available against a lower cost price (44). A main disadvantage of the alkaline technology is its longer response time to variances in the volume of power supplied. Lower overall system expenditures can be achieved by combining a baseload alkaline conversion system with a peak load PEM conversion system to deal with the intermittency of power supply from offshore wind. Further research is required for this.

The port authorities control all access to their area – though in certain instances they need an approval from the municipality before conducting a land lease agreement (long leasehold and/or superficies). The Port authorities have to consider that investors will request access to the harbour region. The spatial requirements of electrolyser systems are significant and based on the above number the port regions should consider this in their spatial plans. For the minimal envisioned flows, as are described above, estimated is that around 14ha. is required in the Port of Amsterdam region, almost 2ha. in Port of Den Helder Region, and some 7ha. in the Groningen Seaports region based on the reference of 8ha/GW (38).

Supply of electricity is preconditioned for green hydrogen production in the three harbours. This could be provided via nearby onshore green electricity production, supply via the electricity network or offshore electricity production transported to the harbours. The research upon hand assumes that the onshore green electricity production in the area will be used to meet the electricity demand, yet this will not be enough. To add up to this local production, supply via the electricity grid to the electrolysers is not possible on a large scale as the current electricity network in the three harbours is not capable of providing this transport. Therefore, it is assumed that the supply will be provided by offshore wind production transported to the harbour, for which no reinforcement of the grid is necessary as the electrolyser is placed right next to the sea.

The procedure for establishing a direct connection via cable between an offshore wind farm (generation asset) and an onshore electrolyser (end-user) is quite complex. The electricity cable establishing such a connection would most likely be classified as a ‘direct line’, i.e. it would not be part of either the onshore or the offshore transmission network. However, the classification of such a cable as a ‘direct line’ under Dutch law is problematic, as the provisions governing ‘direct lines’ in the Electricity Act are not applicable in the exclusive economic zone. There is thus no classification of such an electricity cable offshore in Dutch law. A definition, and possibly a separate legal regime governing such cables, must therefore be considered. Proposed amendments to the Dutch Wind Energy at Sea Act seem to promote the possibility of connecting offshore wind farms to onshore consumers (e.g. energy conversion installations) through the introduction of a new type of connection. There is, however, no clarification in this amendment as to how the cable establishing such a connection should be classified and who ought to be responsible for the development and operation of the cable.

There is supply of electricity generated by offshore wind that will have landfall in the harbour areas in all four extreme scenarios at least for $181PJ_e$ in Port of Amsterdam, $4PJ_e$ in Port of Den Helder and $70PJ_e$ in Groningen Seaports. To put these production forecasts in perspective: DNV-GL (45) envisions a supply of $66PJ_e$ to the region of Port of Amsterdam (Noordzeekanaalgebied) in 2050 and $21PJ_e$ to the area of Groningen Seaports (Noord Nederland) in 2030. For the minimal envisioned flows, as are described above, estimated is that around 13ha. is required in the Port of Amsterdam region, some 0.5ha. in Port of Den Helder Region, and 5ha. in the Groningen Seaports region based on the reference of a 2.4 GW HVDC-VSC station with a spatial footprint of 3ha/GW (46)[20].

Power and interests of green hydrogen supply chain stakeholders

It is crucial that the evolvement of (green) energy activities in harbour regions for the overall national and even European economic development is acknowledged and included in the organization of port-related activities. In accordance with the ESPO view, it will have to be organized that the harbours will explicitly be linked to the new energy corridors under the TEN-E and TEN-T network. That way harbour

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[20] As the use of VSC-HVDC eliminates the need for AC and DC filters and reactive power compensation there is a smaller footprint per station.

clusters can contribute to a swift introduction of alternative fuels by supplying hydrogen to inland industry clusters, bunkering infrastructure for inland navigation, and fuelling stations for road and rail. It is important that the national government recognizes the strategic position of the harbours such that these harbour regions can facilitate the development of energy-related activities initiated by various stakeholders.

To develop the green hydrogen activities in the harbour regions, stakeholders involved will have individual interests to contribute (or oppose) to collaborative developments. In addition, they have influence in the decisions for realising this activity in the specific harbour region, one more than the other. To have a better understanding at this, one can look at the power and interest of the required stakeholders contributing to the envisioned energy activities in the harbour regions in 2050. Figure 19 shows a suggested position in such a power-interest grid. The level of power tells us how much influence each stakeholder has on the decision making for and thus the realisation of this activity in the specific harbour area. The level of interest tells us how interested the stakeholder is in having this activity in the specific harbour area. Stakeholders with a high power and a low interest do not have an interest in having the activity in the specific harbour areas while they have a lot of power and could make or break having this activity in the specific harbour.

For realising green hydrogen activities in the three harbours, this could be wind electricity producer & trader companies and the electricity infrastructure transport service provider and financial investors, as they have less interest in where their electricity will come to land. As previously stated, each stakeholder may be vital to the energy system changes. Therefore, the power-interest analysis should merely be considered an indication whether a stakeholder may be part of a so-called coalition of the willing, and if so, what the expected level of influence is that this stakeholder can have.

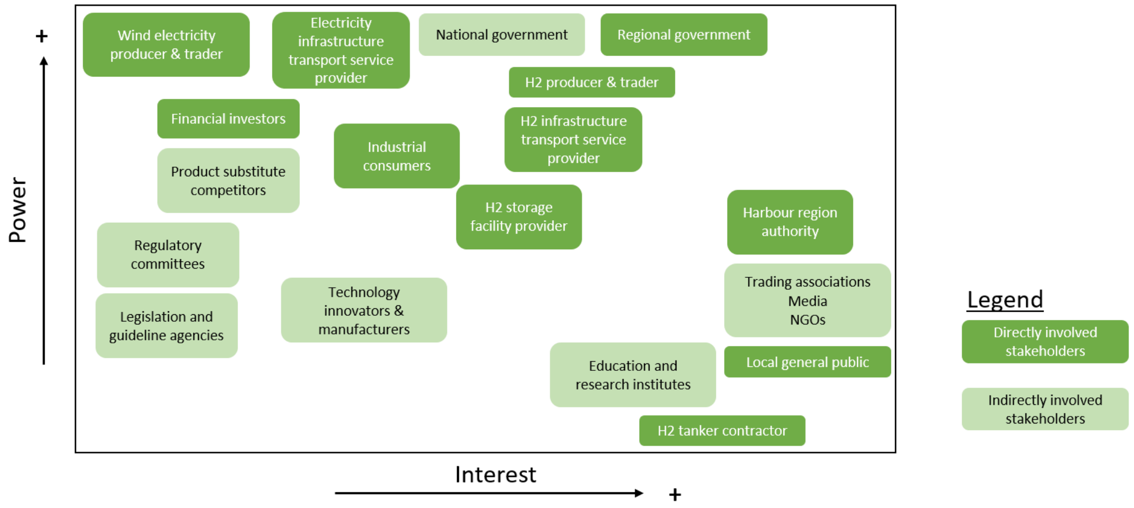

Figure 19: Power-interest grid of direct and indirect customers for green hydrogen

6.1.4.3 Preconditions for blue hydrogen

There is blue hydrogen production in all harbours in all four extreme scenarios in 2050. There is a production foreseen for 0-30PJ$_h$ in Port of Amsterdam, 30-365PJ$_h$ in Port of Den Helder and 30-38PJ$_h$ in Groningen Seaports per year. To put these production forecasts in perspective: DNV-GL (45) envisions a production for blue hydrogen of up to 28 PJ$_h$ in the region of Groningen Seaport (Noord Nederland) and 2-23PJ$_h$ of blue or green hydrogen in the region of the Port of Amsterdam (Noordzeekanaalgebied) in 2030.

For blue hydrogen production in the harbour areas, blue hydrogen production assets have to be installed. There are multiple technologies in place for blue hydrogen production. In this analysis, the technology autothermal reforming (ATR) is assumed capture technologies that are developed globally are currently in the pilot and demonstration phase (47). Because data on the actual space required for a large ATR plant is not or hardly available, simply because they do not exist yet, an estimation of the space needed is made based on much smaller-scale typologies and has been estimated to be about

17.5 Ha/GW_h (29). For the minimal envisioned flows, as are described above, estimated is that around 16.5ha. in Port of Den Helder Region and in the Groningen Seaports region.

CO_2 storage is preconditioned for the production of blue hydrogen in the harbour regions. The required volume is dependent on the volume of blue hydrogen production, which is 0-1,9Mton for the region of Port of Amsterdam, 1,9-23Mton for the region of Port of Den Helder and 1,9-2,5Mton for the region of Groningen Seaports. To put these numbers in perspective: DNV-GL (45) envisions a volume of 4,5Mton CO_2 storage in the region of Port of Amsterdam based on the Athos project up until 2030. They expect a supply of CO_2 to the region up until 6Mton in 2050. The supply of CO_2 for offshore storage from the Den Helder region is currently unknown, though the capacity of the existing infrastructure should suffice at least some 10Mton per year (41). Additional investment in CO_2 infrastructure is needed in the **National Blues** scenarios to facilitate the 23Mton of CO_2 stored per annum.

Storage facilities of course have to be in place and ready to accommodate these volumes. The research assumes that the CO_2 will be stored in depleted offshore natural gas fields. Infrastructure assets are necessary to transport the CO_2 to offshore fields, which could be in competition with hydrogen for pipeline capacity. These processes for CO_2 storage require heat. This could be facilitated by using residual heat from industry or domestic heat networks.

Power and interests of blue hydrogen supply chain stakeholders

To develop the blue hydrogen activities in the harbour regions by 2050, stakeholders involved will have individual interests to contribute (or oppose) to collaborative developments. Figure 20 shows assumed positions for the identified stakeholders in the power-interest grid. Stakeholders with a high power and a low interest do not have an interest in having the activity in the specific harbour areas while they have a lot of power and could make or break having this activity in the specific harbour. For realising blue hydrogen activities in the three harbours, this could be national government and financial investors, as they have less interest in where the blue hydrogen will be produced.

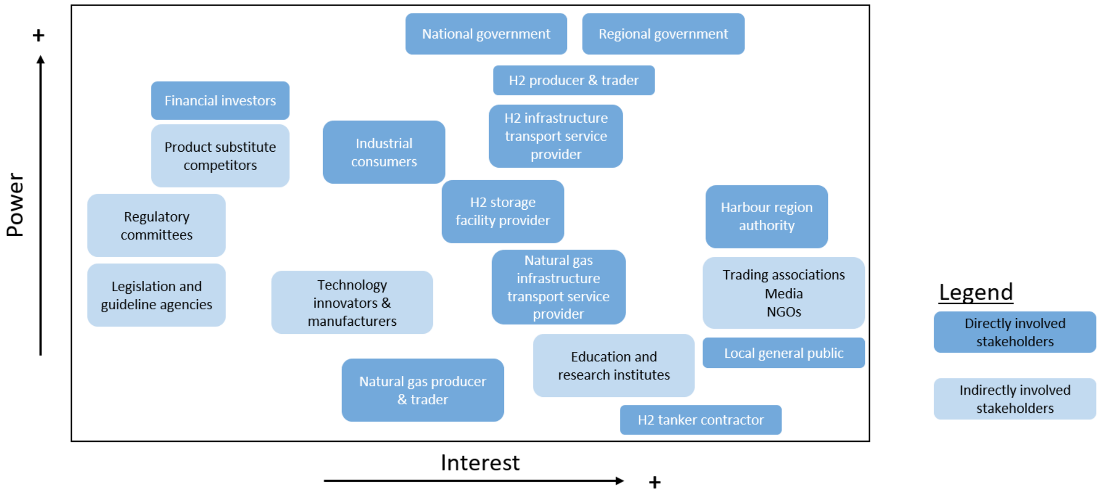

Figure 20 : Power-interest grid of direct and indirect customers for blue hydrogen

6.1.4.5 Hydrogen transport

The presence of hydrogen infrastructure is preconditioned for the envisioned volume of green and blue hydrogen production in the harbour areas. The hydrogen needs to be transported to the end consumers and the capacity of infrastructure present in each harbour area can limit the volume of production. The research upon hand assumes that the hydrogen backbone will be in place in 2050 and this seems to be a huge prerequisite to realise the envisioned volumes. Parts of the existing high-pressure natural gas grid need to be transformed and local hydrogen infrastructure needs to be built.

The modelling results in this study have shown that both an interconnection between the harbours as an interconnection between the harbours and the hinterland is conditional for the volume of hydrogen produced/transported via the harbour regions; i.e. “the backbone”. Having an interconnection with the hinterland is most important for the future activities in Port of Den Helder. Other infrastructure assets could also be used for transport, such as inland shipping or road transport, but these are limited in capacities.

There are a number of existing pipelines (both L-gas and H-gas) going to and from the harbour regions, which can potentially be reused for hydrogen transmission. Currently, two pressure regimes are studied more intensively for this backbone, which are 10 to 30 bar and 30 to 50 bar (48). The capacity could even rise, and probably this would be preferable by 2050, by increasing the pressure levels to 30-50 bar. The main pipelines going to and from the harbour regions are depicted in Table 9. At first sight, the injection/withdrawal capacity – either at individual pipelines or by combining multiple pipelines – is sufficient. However, further analysis should explore which pipeline sections should be used to transport the hydrogen produced in the harbour regions to the hinterland.

Table 9: High-level estimation of pipeline capacity going to and from the harbour regions.

50 barg		NPS	DN	Flow Rate	Monthly Capacity (PJ_h)
Den Helder region	A616	48	1200	251000	26
	A591	42	1050	191000	19.8
	A593	36	900	135000	14
Eemshaven region	A543	48	1200	251000	26
	A610	42	1050	191000	19,8
	A542	42	1050	191000	19,8
Amsterdam region	A803	48	1200	251000	26
	A553	42	1050	191000	19,8
	A551	36	900	135000	14

There is no general law regulating the construction and use of subsoil gas pipelines in the Netherlands. Hence, anyone who wishes to construct and operate such pipelines needs to comply with all other relevant laws such as planning, environmental and safety laws but also the Gas Act. Pursuant to the unbundling rules in the Gas Act, producers and supplies of hydrogen only have the right to construct and manage hydrogen pipelines that are in no way connected to the natural gas system. In the case of TSOs and DSOs, the main rule is that these parties cannot invest in and manage hydrogen infrastructure. A distinction must however be made between the activities of TSOs and DSOs active in the gas sector, and companies within the same corporate group as a TSO or DSO. ACM is of the opinion that companies within the same corporate group as a TSO or DSO are allowed to be involved in the transport of hydrogen and the construction and management of hydrogen infrastructure. Given that the transport of hydrogen through pipelines is expected to increase in the coming years, it is necessary to provide clear rules for hydrogen pipeline owners and operators.

The construction of a hydrogen pipeline is only permitted if the pipeline is laid in accordance with the local zoning plan, or if the pipeline is granted an environmental permit to deviate from the zoning plan in place. The same rules apply to the replacement or modification of an existing pipeline. If the intention is to repurpose a natural gas pipeline for hydrogen transport, various options are available for the relevant enabling municipalities. These options are discussed in the report on the legal framework (49).

6.1.4.6 Precondition for hydrogen storage

The volume of energy storage capacity varies between the four scenarios. Storage of hydrogen in salt caverns is the technology chosen in this research. EnergyStock foresees to run some tests on the application of hydrogen in a borehole and in storage equipment in 2020 and 2021. The expectation is to have the first hydrogen storage cavern with a working gas capacity of 6500 tons operational by 2026. There will no explicit role or activity for the harbour if supply will flow from the backbone to the salt caverns. Important to note here is that there are other technologies imaginable for short and/or longer term storage that could also entail activities in the three harbours. Further, please note that storage of electricity was not in scope of this research, but will be required next to storage of hydrogen.

6.1.4.7 Preconditions for the hydrogen import

Depending on the scenario there is import of hydrogen from other countries. This is supplied either through the backbone in the **Pipeline Import** scenario (10PJ_h in Amsterdam and 9PJ_h in Groningen Seaports) or through shipping in the **North Sea Powerhouse** scenario (in Amsterdam 90PJ_h) and in the **Solar Shipping** scenario (298PJ_h in Amsterdam, and 8PJ_h in Groningen Seaports). To put these forecasts in perspective: DNV-GL envisions import of hydrogen via shipping to the region of Zeeland, Rotterdam and Port of Amsterdam after 2030. These intentions are underlined with a MoU signed by the Portuguese and Dutch government in which they state to investigate the building of a hydrogen production facility in Sines to export and ship hydrogen to the Port of Rotterdam region. Import terminals, storage facilities and transport and/or distribution head stations are required to facilitate the import. In the **National Blues** scenario, in which the share of hydrogen import by ship in the total energy system is the lowest, the maximum import by ship during a month is 12.4 Mton of hydrogen, which comes down to 217.400 m3 of LOHC, which corresponds to roughly 9% of the current max. import levels of wet bulk per month[21].

6.1.5 Sub-conclusion

The activity and stakeholder analysis presented in this paragraph provides an overview of the variety of activities and stakeholders involved in developing a more sustainable energy system of the future. The three topics covered, (1) the minimal energy flows that may be expected in each of the three harbours, based on the four scenarios, (2) the current maturity level of each of the supply chain activities and their preconditions and (3) the differences in power and interest per stakeholder, lead to the final conclusion: The development of energy-centred port activities requires substantial interface management and inter-disciplinary stakeholder collaboration to make sure the supply, transportation, storage and demand all align. A number of envisioned activities are still in their development phase while those activities are essential to the successful functioning of the future renewable energy system. The next paragraph discusses this framework.

6.2 Legal framework analysis

The institutional and organisational structure must be considered to determine who is responsible for different types of developments and operations in port areas. As part of the wider trend towards privatisation, the Dutch national government and local governments retreated from performing active port related activities themselves. The privatisation of Dutch port authorities means that public tasks are now carried out by private law companies. Although these private law companies may be partially government-owned, government influence is limited.

Even though the legal title to the land in the ports still rests with the municipal government, the port authorities have leased this land from the municipal governments in perpetuity. The port authority is thus authorized by the municipality to perform all management and other activities in relation to the land located within the port area. The key activities of the port authority are now predominantly related to the operational side of the port. It manages the port affairs, provides port facilities and logistic services, and subleases land in the port area. Port authorities thus control all access to their area – though in certain instances they need an approval from the municipality before conducting a land lease agreement (long leasehold and/or superficies). Port authorities may invest in operations and facilitate the development of activities in the port area. Traditionally, port-related activities are associated with facilitating the arrival and departure of ships, the use of berths, sheds, and loading facilities and the discharge, storage and distribution of cargo. By contrast, the development and operation of energy activities within a port area are less perceived as typical port-related activities. **It is crucial that the emerging energy hub importance for the overall national and even European economic development is acknowledged and included in the organization of port-related activities.** As port authorities are only responsible for activities within their own port areas, it is important to act at national level to facilitate the development of an integrated energy infrastructure that transcends several port areas and as such different municipalities and provinces (e.g. in terms of spatial integration of hydrogen infrastructure to ensure access to land).

As ownership of the land remains with the government, the public sector remains responsible for port planning. Technically, there are no (or very few) obstacles to the development of hydrogen infrastructure in port areas. There is, however, a need to guarantee investment to fund new infrastructure and the repurposing of existing infrastructure in order to produce hydrogen and transport the hydrogen to the end users. Given that municipalities are the main shareholders in most Dutch ports, port authorities engaging with private companies do so through Private-Public Partnership (PPP) transactions, which may cover investment-intensive construction works. One should be aware that Dutch legislature has not enacted specific PPP law in the Netherlands, though, development of port areas may be subject to EU procurement rules (49).

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[21] Based on CBS statline data (40), 2.400.000 m3 of wet bulk in an import intensive month, derived from 6.200.000 tonne of wet bulk in the 2nd Quarter 2019 (Avg. crude oil density of 870 kg/m3).

7. Conclusion

Traditionally, port-related activities are typically associated with facilitating services such as: (i) the arrival and departure of ships; (ii) navigational aid and vessel traffic separation facilities; (iii) pilotage, tugging and mooring activities; (iv) the use of berths, sheds, and loading facilities; (v) the discharge, storage and distribution of cargo; and (vi) supply chain logistics and management. By contrast, the development and operation of energy activities (e.g. hydrogen production) within a port area are less perceived as typical port-related activities. In order for harbours to successfully progress into a major energy/hydrogen hub, a great number of organizational issues will have to be tackled timely and effectively. It is crucial that the emerging energy/hydrogen hub importance for the overall national and even European economic development is acknowledged and included in the organization of port-related activities. The inclusion of harbour regions in the European TEN-E network and linking them to the TEN-T corridors are strategic devices that should be initiated to avoid missing out of these key European energy supply lines. That way harbour clusters can contribute to a swift introduction of alternative fuels by supplying hydrogen to: inland industry clusters, bunkering infrastructure for inland navigation, and fuelling stations for road and rail. It is important that the national government recognizes the strategic position of the northern harbours as a (green) energy hub for the national economy.

The aim of this study was to focus on the potential role of harbour regions in the energy transition in 2050. In doing so, we specifically zoomed in on the Northern Netherlands harbours: Groningen Seaports, Port of Den Helder and Port of Amsterdam. The potential of energy-related activities in these harbour areas were studied before for the individual regions of Noord-Holland (7) and Groningen (6) but these studies only focused on how the harbour activities could contribute to the regional energy system. The current study, instead, focussed on a much wider regional scale by analysing with the help of a scenario approach and energy flow modelling, what role these harbour regions can play as an energy hub not only for the harbour regions themselves, but also for a much wider hinterland covering part of the Netherlands and Germany combined. In doing so, a first-order estimation was provided of the energy/hydrogen hub perspectives of the three harbour regions individually, and collectively. The latter was done to assess how synergies between the harbour regions can be created if they closely work together on positioning themselves as a significant future energy/hydrogen hub.

Four scenarios were designed to gain a better understanding what energy-activities harbour regions can provide to the energy system via conversion, storage and imports, but also of the synergies that may be achieved if harbour areas collaborate in their roles as energy hubs. In developing the scenarios, a consistent reality check was carried out with the port authorities in order to get to an accepted overall picture of the harbours‘ future energy roles. As part of the scenarios energy flow modelling was carried out in order to assess the profiles of energy flows from a minimum cost perspective.

7.1 Activities and investment levels at the harbour regions

Assuming that the settlement location of energy-related activities will be based on economic reasons, the simulations performed suggest that, depending on the scenario and under the recognition that the harbour regions act as one energy hub, each region is likely to specialise in energy-related activities that fits best to their unique regional characteristics. How energy-related port activities will be divided over the three harbours is still hard to predict. The role of the individual harbours in channelling hydrogen will strongly depend on: the development of the hydrogen market as a whole; if the three harbours succeed in positioning themselves as a successful energy hub; the degree to which blue hydrogen will be part of hydrogen supply by 2050; and the share of imported hydrogen from other regions.

Broadly speaking and to provide a simplified picture, Groningen Seaports is well situated to develop into a major green hydrogen production and transmission location (chemical industry); Port of Den Helder is well-positioned for blue and dedicated green hydrogen related activities (if direct windfarm connections considered); whereas Port of Amsterdam has a promising profile to develop into a major hydrogen importing ecosystem including related conversion and end-use (steel and aviation fuels).

7.1.1 Port of Amsterdam Region

The decarbonisation of the Port of Amsterdam region – including the aviation sector at Schiphol airport – has a significant impact on the energy infrastructure prerequisites in the area. A large share of electricity produced via offshore wind may find a direct use in the Amsterdam-IJmuiden area for electrification. The energy infrastructure study for North-Holland (7) indicated that the expected electricity consumption in the region would grow from 60 PJ_e/year in 2020 towards 180 PJ_e/year in 2050. The investments for connecting the offshore wind capacities with the regional predefined market demands are estimated to be some 1.7 billion euro per annum.

The Port of Amsterdam region also host considerable demand for hydrogen – some 50PJ_h – even though hydrogen required for the production of bunker fuels (some 20PJ_h) for the shipping industry is not accounted for. A large share of this hydrogen will most likely be supplied by hydrogen produced from the regular seasonal surpluses of green power, which are typical for this region and result from seasonal supply overshooting demand. The development of green hydrogen facilities, with a minimal spatial footprint of 14ha. is needed to cover the summer-winter spread of the offshore wind coming to shore.

The opportunity for large ships to efficiently dock and unload hydrogen combined with the opportunities for sufficient local liquefied hydrogen storage gives the Port of Amsterdam region a competitive advantage. Amsterdam is currently the largest gasoline port in the world and specializes in blending products. The authorities in the port work together with their customers to develop and attract traditional liquid bulk, as well as green cargo such as biofuels and hydrogen. This requires a large import terminal to be developed in the current harbour, most likely behind the lock. The fact that Port of Amsterdam already has a 15 kilometres underground pipeline connecting the port (kerosene terminal of Oil Tanking Amsterdam) with Schiphol airport provides an additional competitive edge in the bunkering of synthetic fuels for North-Western Europe.

Although part of the current infrastructure might be reused, the spatial claim for HVDC-converter and hydrogen production facilities currently is quite substantial (minimum of some 27ha.) Currently, some 15 ha. is already available around IJmuiden and with the ambition to abandon coal by 2030, the resulting available harbour space of Port of Amsterdam (some 100 ha.) may create room for shifting to the production and/or import of low-carbon hydrogen (carriers). A low-pressure distribution network – some 10-17km – is required to connect the production locations in the IJmuiden area, production locations and bunker facilities behind the locks, as well as offtakes in the port region.

7.1.2 Port of Den Helder Region

The current projections of planned backbone investments suggest that Groningen Seaports and Port of Amsterdam will be connected to such a backbone (52). The scenario analysis unfold that connecting Den Helder to the backbone enables the benefit of full synergies between the three ports. To gain these significant benefits a minor extension of the backbone with a 35-40km pipeline section to Den Helder is required. This backbone connection is very important for the three harbour regions to generate comparative advantages for scaling up specific additional economic activity. The re-use of exiting offshore exploration pipelines (three in total) combined with the proximity to large CO_2 injection fields and to offshore wind location provides a competitive edge for hydrogen production in the Den Helder region, as a recent feasibility study has shown.

Based on general outcomes in the indicative study of EBN and Gasunie (17), promising results for Den Helder could be expected when a thorough analysis on the unit technical costs for storing the CO2 captured during the ATR/POX-production process is made. This analysis will be incorporated in phase 2 off the H2Gateway feasibility study.

Furthermore, a clarification in the Dutch Wind Energy at Sea Act as to how direct connections should be classified and who ought to be responsible for the development and operation of the cable. The Den Helder region is well located for dedicated green hydrogen production implying that all electricity from offshore wind farms is directly connected to onshore consumers (e.g. energy conversion installations) without any alterations to the regional electricity network.

Within the control region of the port authorities, there is currently some 30 ha. directly available (Kooypunt ca. 10 ha.; Kooyhaven ca. 15 ha.; Oostoever ca. 5 ha.). The spatial capacity in Kooyhaven can easily be developed further to support the evolvement of energy-related activities in the region. Although, the spatial claim for an ATR production facilities is quite substantial (minimum of some 16.5ha.) no harbour extensions are yet required to support the foreseen minimum ATR production capacities[22]. In addition, some 2-3 ha. is needed to facilitate the minimal envisioned flows for dedicated green hydrogen production.

7.1.3 Groningen Seaports Region

The Groningen Seaports region offers serious potential for the landfall of offshore wind. Until 2030, the landfall of electricity from the Gemini Wind Park is already planned in or near the Groningen province, either via Eemshaven, or via Vierverlaten, or via Bergum in Friesland (20)[23]. The region has the potential to host multiple GW offshore wind capacity, but this will require a strong build-up of electric infrastructure in the region as well of the integration of these capacities via a transport corridor through the international recognized Waddensea area. The Northern Netherlands holds a strong aspiration to become/remain a leading European hydrogen ecosystem with capacities of 100 PJ per annum by as early as 2030 (22). In addition, the region (in its broad definition) is very well located for nearby large-scale storage of hydrogen.

Currently, at least some 350 ha. is available in the port of Eemshaven and Delfzijl combined, so the availability of space, with a minimal spatial claim of some 28ha. for the HVDC-converters and hydrogen production facilities, in the harbour region should not be an issue. A low-pressure distribution network is required to connect the production locations in the Eemshaven area to offtakes in the Delfzijl port region. A first start has been made already. Groningen Seaports planned a hydrogen infrastructure route that initially runs from the newly built hydrogen plant Djewels 1 on the Nouryon site, parallel to the dike to BioMCN. A facility will be built near Teijin for a future connection, and the end of the pipeline will be built in such a way that it can easily be extended in the future. Concrete plans for this are already being made with the construction of a second electrolyser, the arrival of a sustainable aviation fuel plant (SkyNRG), the development of the Heveskes business park and the area south of the Oosterhornkanaal. The hydrogen distribution network will be expanded in phases so that all these areas can be connected to each other and all the players at Chemiepark Delfzijl can make optimum use of the available hydrogen.

7.2 Opportunities for synergies

There is clear evidence that a close collaboration between the three harbours is likely to generate serious synergy benefits. Our modelling suggests that, depending on the scenario, these benefits can amount to anywhere between €100 – €300 million per annum for the three harbours combined. These synergies seem to be strongly dependent on a hydrogen backbone grid connecting the three harbours, such that hydrogen flows can easily be exchanged and collectively transmitted further into the hinterland. By collaborating via the backbone, the harbours will be able to act as a flexibility provider to the energy system: because hydrogen can be easily transported back and forth, a stable energy supply can be guaranteed. This is crucial for the overall energy market' security of supply and some specific destinations such as dedicated industrial activities in particular.

Once isolated, the harbour regions of Port of Amsterdam and Port of Den Helder are unable to take advantage of the connection to the storage facilities in the Groningen salt caverns, which causes cost intensive local storage requirements in the range of 1.4 to 5 Mton for respectively the Port of Amsterdam and Port of Den Helder. The need for storage grows with the amount of produced green electricity from intermittent wind energy and the constant production levels of blue hydrogen, which both do not completely line up with expected monthly demand levels. The backbone will support the overall synergy effect because the strong points will complement each other rather than act as a source of mutual competition. For instance, import levels and storage levels, although inversely proportional, both fill the occurring shortages during low green hydrogen production months.

An important factor that affects the distribution of green hydrogen technology over the three harbour areas while attaining minimum system expenditures is the demand volume of green hydrogen. Once

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[22] Extension of the harbour region by a factor of four would be required to facilitate the maximum ATR production capacity (365PJ$_h$).The extension of the harbour area might not be the only issue. The offshore fields connected to Den Helder will with an annual CO_2 volume of 23Mton be full around 2050.

[23] There is a regional preference for the landing point Eemshaven Oost

the demand for domestic gree45n hydrogen rises, more wind energy is required to supply the increasing capacity of electrolyser systems in the harbours. Inherent in minimizing the total system expenditures is the connection of windfarms with the lowest connection costs. Under the **North Sea Powerhouse** scenario - the northern harbours provide some 50% (875PJ_h) of the total hydrogen demand the boundaries of offshore wind production on the North Sea become visible: there is insufficient offshore wind capacity envisioned on the Netherlands continental shelf (60GW (36)) at the moment to supply this amount of the total hydrogen demand. The maximum planned yearly capacity from the combined areas C until G is assumed to be 825PJ_e per year. Considering the losses of hydrogen conversion (25%) and subtracting the required supply to local electricity demand in the three harbour areas (some 185 PJ_e) the maximum supply of domestically green hydrogen from offshore energy comes down to 480PJ_h. A solution can be found by relieving the hydrogen import supply constraint (in the study set at 20% to 25%).

7.2.1 Future energy system activities and stakeholder analysis

The development of the envisioned future hydrogen-centred energy system requires substantial interface management and inter-disciplinary stakeholder collaboration to make sure the supply, transportation, storage and demand all align locally. A number of envisioned activities are still in their development phase while those activities are essential to the successful functioning of the future renewable energy system. Maturing of these and additional activities is needed amongst which the national and regional hydrogen backbones, (pure) hydrogen storage in salt caverns, production and import, and hydrogen market trade. To develop hydrogen activities in the harbour regions, stakeholders involved will have individual interests to contribute (or oppose) to collaborative developments. A proper insight in the interests and legal options of a wide group of stakeholders involved. This can be complex, because the stakeholders' objectives, perceptions and issues are likely to change over time. Therefore, identifying the stakeholders involved as well as their (potential) interest and power to develop these energy activities is crucial. Stakeholders with a high power and a low interest do not have an interest in having the activity in the specific harbour areas while they have a lot of power and could make or break having this activity in the specific harbour.

7.3 Presence of legal uncertainties

Although no direct legal barriers were identified regarding the development of energy infrastructure in port areas, the legal analysis has identified several legal uncertainties to the development of energy infrastructure in general. Table 10 summarizes these main legal uncertainties. The pervasive problem is that legislatures are rarely proactive, with legislation often playing catch-up with technological developments. Although the use of hydrogen in the energy sector is not a completely new phenomenon, it has not gained a great deal of attention until recently. As a result, specific provisions on Power-to-Gas have not been incorporated into substantive EU and national law. Drafting a clear definition for Power-to-Gas, and more generally addressing the use of green hydrogen in the energy sector, should be prioritized by EU and national legislators: doing so would provide more clarification regarding which legal frameworks apply to the development of hydrogen infrastructure. For future research, it is thus important to further investigate whether it is sufficient to incorporate provisions pertaining to Power-to-Gas and the use of hydrogen in the energy sector into existing legislation (e.g. gas and electricity legislation), or whether it is necessary to adopt a more specialized hydrogen law.

Table 10: Overview of legal uncertainties and required actions

What uncertainty exists	What is required action
There is currently no direct reference to Power-to-Gas in Dutch planning, environmental and safety laws. Their applicability to hydrogen production sites, as well as the construction and operation of Power-to-Gas installations, are therefore partially open to interpretation. This is further complicated by the forthcoming amendments to Dutch environmental and planning laws, as it is unclear exactly how the proposed changes will apply to hydrogen production sites and Power-to-Gas installations.	In order to provide legal certainty to competent authorities and developers of Power-to-Gas installations, it is necessary to clarify what specific permit requirements that apply to the development of Power-to-Gas installations and the spatial integration of such installations in the forthcoming revision of Dutch environmental and planning laws. Consideration should be given to adopting provisions that explicitly regulate hydrogen production through electrolysis in environmental and safety laws.
There is currently no classification in the Dutch Electricity Act of direct electricity cables in the exclusive economic zone and no rules on who ought to be responsible for the development and operation of such cables. This creates legal uncertainty regarding the development of electricity cables that directly connect onshore Power-to-Gas installations and offshore wind farms.	A definition and possibly a separate legal regime governing such electricity cables must be considered by, for example, extending the rules on direct lines in the Electricity Act to the exclusive economic zone or considering such cables as part of offshore wind farm installations. Furthermore, consideration must be given to adopting provisions on the ownership and operation of such cables.
Although it may be technically feasible and safe to blend hydrogen in existing natural gas networks, strict blending concentrations have been imposed in the Dutch Decree on Gas Quality (the highest admixture level is 0.5mol%).	For the injection of hydrogen into the existing natural gas network to be commercially viable, it is crucial to adapt these admixing restrictions to bring them into line with the levels proven to be technically feasible and safe in practice.
Although it is technically feasible to reuse natural gas pipelines for hydrogen transport, it is uncertain which procedures must be followed in accordance with Dutch planning laws. In addition, there is a risk that natural gas pipelines reused for hydrogen transport will no longer meet the necessary safety distances prescribed in Dutch safety laws that govern pipelines transporting hazardous substances. Lastly, there are no rules on who ought to own and operate hydrogen pipelines, which is particularly problematic for natural gas pipelines that are to be repurposed for hydrogen transport.	Reuse of natural gas pipelines for hydrogen transport is only permitted if it complies with the applicable zoning plan(s). Various options are available for the enabling municipalities.24 Consideration must be given to providing guidelines that clarify which approach is appropriate. Furthermore, the risk contour is larger when transporting hydrogen than natural gas in pipelines. To enable large-scale hydrogen transport via pipelines, the calculation method must be adjusted. Lastly, consideration must be given to adopting provisions on the ownership and operation of hydrogen pipelines.
Various legal frameworks and guidelines pertaining to port development and operation generally focus on port-related activities, which do not encompass energy activities.[25] This is because energy activities are not one of the main functions of a port. Given the recent privatisation of port activities and the various public aspects of developing a hydrogen hub, the challenge is to design a framework that provides clarity on the development of energy activities in port areas.	A clarification of the extent to which ports can promote and participate in energy activities in their port area is necessary. As port authorities are only responsible for activities within their own port area, measures must be taken at national level to promote the development of a hydrogen hub involving several ports in different municipalities and provinces. This is especially the case for spatial integration of hydrogen infrastructure, such as a hydrogen backbone.

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[24] (i) a ‘stamp zoning plan’ can be drawn up for the route of the pipeline, (ii) an environmental permit can be granted, giving the pipeline operator permission to deviate from the applicable zoning plan(s), or (iii) the relevant municipality(-ies) can proceed to partially revise the applicable zoning plan(s) and amend the applicable regulation(s).

[25] It is usually understood that port-related activities encompass activities that facilitate: (i) the arrival and departure of ships; (ii) navigational aid and vessel traffic separation facilities; (iii) pilotage, tugging and mooring activities; (iv) the use of berths, sheds, and loading facilities; (v) the discharge, storage and distribution of cargo; and (vi) supply chain logistics and management.

8.1 Results in context of other studies

The report conclusion are reflected upon in light of: (i) the landfall of offshore wind after 2030, (ii) the market consultation on the hydrogen backbone, (iii) the taskforce industry documentation on energy demand in industrial clusters, (iv) the potential to produce hydrogen offshore, and (v) the Regional Energy Strategies for Noord-Holland and Groningen.

8.1.1 Reflection on the effect of future offshore wind locations

The current available data on offshore wind locations is based on the projections of PBL, but will differ over the course of the near future. The recently (Dec. 2020) North Sea Energy Outlook considers two pathways for offshore wind development in the Netherlands: a 72GW scenario for energy independence and 38GW scenario in which large share of the energy will be imported (1). The 'Verkenning Aanlanding Windenergie op zee 2030-2040' (forthcoming) considers the designation of new wind farm zones (27GW) beyond 2030 (1). The choice of which and how many of these possible search areas will actually be used, as well as the final size and shape of the areas is still uncertain[26]. However, there are most likely deviations from the projections by PBL with more designated search areas above the Wadden. Because the length of a cable is an important factor in its total expenditures, the landing locations of offshore electricity can change due to different cabling lengths to the considered ports. This will affect the cabling distribution as is calculated by the simulation. In addition to the Dutch North Sea Energy Outlook, the European Commission released a strategy in which 300GW of offshore wind should be operational in 2050, an immense increase compared to the current 12GW of installed capacity (2). Increasing wind capacities require additional investments in grid reinforcements, or in direct conversion as has been assumed in this study.

8.1.2 Reflection on the market consultation for a hydrogen backbone

This year, a future outlook on the potential of an international, dedicated hydrogen backbone is presented by some of the largest European gas infrastructure companies. In this report, it is stated that the realization of this backbone is of key importance to meet the climate goals as set by the European Union, namely a net-zero energy system in 2050. In practice, mainly converted natural-gas pipelines are considered to transport hydrogen on the European level within the European-borders and with neighbouring non-European countries. Both 36' and 48' diameter pipelines are commonly present in the existing gas infrastructure, which represents resp. a 7 and 13GW hydrogen transport capacity, and are expected to be able to transport the hydrogen demanded in 2040 and onwards[27].The market consultation performed by Gasunie New Energy will provide more insight in the pressure regime and the quality of hydrogen that is transported via the backbone. These technical details of the backbone may prompt additional investments in the region, for instance additional compression or PSA-facilities.

8.1.3 Reflection on the Taskforce Infrastructuur Klimaatakkoord Industrie

Industry in the Netherlands has the potential to make the largest contribution to achieving national climate targets. The Taskforce Infrastructuur Klimaatakkoord Industrie indicates a prominent increase in hydrogen demand from the Dutch Industrial sectors (45). To put our production forecasts in perspective: the taskforce envisions a production of 16-88PJ$_h$ in the region of Port of Amsterdam (Noordzeekanaalgebied) in 2050 and 30-70PJ$_h$ in the area of Groningen Seaports already in 2030 (37). These production capacities due though not comprise of the demand for hydrogen from bunker fuels and demand in the mobility sector. The 2050 hydrogen demand volumes considered in this report (43PJ$_h$ in the Port of Amsterdam region and 53PJ$_h$ in the Groningen Seaport Region) are in the middle range and might be perceived as conservative. The development of the port regions as sustainable energy regions will attract new industries (e.g. synthetic fuel production unit) which will create extra demand for sustainable energy.

8.1.4 Reflection on offshore hydrogen production

Guidehouse investigated the possibilities of combining wind energy with hydrogen production at sea. The research shows that this combination can play a role after 2030 and that additional landing options can become favourable. The potential benefits of offshore hydrogen production do not go unnoticed.

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[26] There are 8 designated areas among which 1: Between IJmuiden-Ver and the border with UK 2: North of IJmuiden Ver; military area must rotate 3: North-west of IJmuiden Ver 4: In military area; need for alternative exercise area 5: North-east of the Frisian Front at the border with Germany 6: Area north of the Frisian Front 7: East of Cleaver Bank 8: North-west of Texel; not possible if area 2 is designated.

[27] These numbers are based on a discharge pressure of 67-80 bar en suction pressure of 30-40 bar (all LHV based)

The North2 initiative has the ambition to produce by 2040 about 10GW of green hydrogen production, initially in the Eemshaven and later possibly also offshore. The model initially considered offshore production of hydrogen. However, the cost factor for offshore production is subject to many sensitivities and production location specific factors. Therefore, the cost factor for offshore production could not be generalised for each of the wind areas. Further optimisation of our model should include the potential of producing offshore hydrogen, as offshore hydrogen production is perceived as potential scenario to accommodate investment reduction in transmission infrastructure. However, further research should reveal whether this is cost advantage outweighs the higher investment and maintenance costs for offshore electrolysis. Market parties expect that electrolysis at sea can be significantly more expensive than on land, but accurate calculations or checkpoints are currently not available. The NSE 4 programme tries to reduce the uncertainty by researching how much electrolysis capacity can be realised on offshore platform structures.

8.1.5 Reflection on Regional Energy Strategies

The reported was initiated under the notion that the harbour regions would not only provide their own region with carbon free and affordable energy, but also the other energy regions in the Netherlands and Germany. The more surprising fact was that the Regional Energy Strategy for the Province of North-Holland only encompassed a total of 4.1GW of offshore wind capacity landing in the region. Although, this might have been enough to serve the energy demand in the region, the outcome of this report shows that, the North-Holland region has an important role in channelling (offshore) energy to the other energy regions. The same observation does however not hold for the Regional Energy Strategy for the Province of Groningen en Drenthe, in which almost 20GW was foreseen. Nevertheless, the RES for North-Holland shows that some caution should be considered when optimising the regional energy system only within the designated RES-regions.

8.2 Critical notes and future improvements and outlook

A first note is the geographical scope of this study. The study only considers the three northern harbours. The other Dutch harbours (Port of Rotterdam and North Sea Port), but also the ports in Germany, will have an important role in transiting clean energy to the studied hinterland. The potential of the other harbours is embedded under the assumption that the other harbours would eventually deliver 65%-85% of the total hydrogen demand of the Netherlands and Germany by 2050 (set at 1800 PJ/y). However, these harbours may have unique features that favour specific investment in their regions. For instance, the investments related to low-carbon hydrogen production facilities in the Rotterdam area might be lower than in other areas. The current hydrogen production facilities could be decarbonised by installing carbon capture facilities and store the carbon in nearby offshore fields. The realisation of low-carbon hydrogen production facilities may for this region be limited to new capture and storage investments, which will lead to a lower cost factor.

As second note is the limited amount of technologies considered in the model. Investment in electrical storage technologies, such as batteries, may be required in the regions investigated. Batteries, and other flexibility technologies, are expected to play an important role in stabilising the electricity grid and in the balancing of demand and supply of electricity on the short term (50). The focus of the report is on seasonal stability, among which hydrogen storage, is key. The importance of other flexibility technologies will come visible when one increased the dynamics of the model (e.g. daily or hourly data).

In the optimization process the demand for heat, as well as the infrastructure requirements for heat networks, is not included because it is expected to be delivered otherwise. To illustrate, the potential annual demand for heat in the various regions is: some 14PJ (typically utility and built environment) for the Port of Amsterdam Region, and some 3PJ for the Groningen Seaports region (typically industry). Detailed information about the quality (temperatures) for heat demand were missing in the Regional Energy Studies. To improve the validity of the model the demand for heat as well as the infrastructure requirements for heat networks should be specified.

At last, it is assumed in the model that green hydrogen production in the harbours does not require electricity infrastructure as the electrolysers will be placed right next to the sea. It means that no potential reinforcement in electric infrastructure in the harbours is required for landfall of wind energy to these harbours. This is a very important assumption and could lead to different results than other studies on this topic.

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