BLUEPRINTING THE HYDROGEN MARKET – HYDROGEN SPOT MARKET SIMULATION (H2SMS)

PART 1: POLICY REPORT

FINAL REPORT – February 2024

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TNO innovation for life HyXchange Berenschot

In the course of this study, the approach and the intermediate results have been shared with many involved market parties and infrastructure operators during several digital meetings and working sessions. The researchers involved in this study extend their thanks to the involved private and public experts who participated, provided feedback and/or input and challenged us during the process.

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Part 2: Technical report

I. Background

Hydrogen has an important role in the future energy mix

Hydrogen is increasingly attracting interest as an important part of the energy transition. Hydrogen acts as a natural complement to the vast technical potential for intermittent renewable electricity production offered by the North Sea basin[1]. Hydrogen is therefore regarded by many as an important energy carrier for the future. The Climate Agreement, as well as recent statements by the Dutch Ministry of Economic Affairs and EU COM, therefore devote a great deal of attention to hydrogen.

Opportunities for development of a hydrogen market in the Netherlands

A recent exploratory study[2] focussing on the pros and cons of a hydrogen exchange in the Netherlands found that the Netherlands has a unique position with vast potential for green hydrogen production from offshore wind, the landing of seaborne hydrogen imports, a solid industrial base with large hydrogen subsystems, and, of course, the unique natural gas and industrial feedstock infrastructure as a gateway to industrial clusters in the north-western European hinterland.

A dependable and transparent trading platform, such as we have today for electricity and natual gas, greatly enhances market access, pools liquidity and reduces transaction costs and trading risks. Furthermore, the trading platform is expected to play a crucial role in the development phase of the market and in its day-to-day balancing. The trading platform is expected to catalyse an increasing demand for climate neutral hydrogen produced by an expanding asset base and to balance supply and demand through transparent pricing[3]. A hydrogen exchange has benefits for both major and minor players.

Need for better understanding of the hydrogen system and need for exchange services

As follow-up to the exploratory hydrogen exchange for the climate report[2], areas for further analysis were discussed with market parties. Areas selected for further development are:

1. development of a **certificate product** encompassing all types of hydrogen;
2. a **spot market** for hydrogen, taking into account supply, demand and available infrastructure as well as the obligations stemming from the Delegated Act[4]; investigated both by a physical and digital market simulation also involving hydrogen grid balancing and storage;
3. development of an **index product**, due to the need for price transparency.

Based on the needs mentioned by market parties, various projects have been initiated by HyXchange. All projects aim to increase the understanding of the future hydrogen market and provide insights in the requirements that a future hydrogen exchange would need to meet. This report is about the simulation study focussing on development of area 2. HyXchange is also working on a certificate product (area 1) and an index product (area 3) in other projects.

During the spot market study, multiple meetings and sessions with market parties were held. These included:
a) meetings with a simulation committee consisting of parties with high interest in the simulation process and experts working in this sector;
b) specific simulation sessions (online and on-site) open to all parties involved with HyXchange;
c) general meetings with all the parties involved with HyXchange where progress was presented and discussed. The involvement, input and contributions from market parties and infrastructure operators is highly appreciated. This has focused the study and has enriched the results.

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[1] Netbeheer Nederland, 2023. Integrale Infrastructuurverkenning: scenario's 2030-2050, 2e editie.
[2] B. den Ouden, 2020. A hydrogen exchange for the climate.
[3] Despite the significant use of hydrogen in Dutch industry, the need for a spot market resulting in more transparency in prices has not materialised. A reason why this could change is because of a decrease in local "grey" production/consumption and an increase in "green" production that is transported and distributed via a central infrastructure that serves an increasing number of consumers elsewhere.
[4] Commission sets out rules for renewable hydrogen (europa.eu).

II. Research objectives

This simulation study aims to increase understanding of the hydrogen system and associated dynamics and volatilty of the marginal cost of production as an indicator of hydrogen pricing on a future hydrogen exchange: the time-dependent variations in market volume and market price. A key question is whether this hydrogen market is volatile like the electricty market (with hourly or even quarter-hourly price differences), or more stable like the gas market (with a daily price). We need to know this in order to establish a robust blueprint for a hydrogen exchange.

Simulated is the hydrogen trade over the regional and national hydrogen backbone that is currently being developed by HyNetwork Services (HNS) and will connect the Dutch, NRW and Ghent-area industrial clusters and harbour regions going towards 2030. Three simulation models were applied, where each increases the overall understanding of the functioning of the future hydrogen system, its dynamics and the requirements that an exchange should meet:

1. First, the highly detailed optimization **I-ELGAS** model (dispatch simulation) is used to evaluate dynamics of optimal market allocation based on marginal cost of operation. The optimal dispatch assumes perfect foresight, i.e. certainty regarding future demand, intermittent power production, etc. across the full scheduling horizon.
2. Second, market dynamics accounting for bid behaviour in the face of uncertainty have been assessed with the more flexible **EYE** model (market simulation).
3. Third, in order to better understand the system coupling, the **CEHIM** model (imbalance simulation) provides insight in technical and financial effects of electricity and hydrogen market coupling. This was done on explicit request of the market parties.

Additionally, this study also aims to better understand the various "functions" of hydrogen in the future energy system, the "role" that participants in the hydrogen system are expected/required to play and the impact of recently introduced hydrogen regulation (such as the Delegated Act on green hydrogen production). More specifically, this study enhances the understanding of the market characteristics as a basis for development of the exchange:

1. Optimizing **the (renewable) feed of electrolysers**. A well-functioning hydrogen exchange will promote this, because it offers companies and traders opportunities to optimize on both markets simultaneously (hydrogen-electricity coupling).
2. Use of **hydrogen storage** (4 caverns in 2030 or later) to accommodate variations in green hydrogen, balance the network and create a continuous flow of renewable H2 for end users. As soon as the connection with the national storage facility is established, new opportunities will arise from which everyone can benefit optimally via the stock exchange.
3. **Balancing** varying "green" hydrogen with flexible "blue" hydrogen from national sources (SMR/ATR + CCS) and import of hydrogen (in this study green and blue ammonia have been selected as carriers). The hydrogen exchange will bring together supply and demand variations and provide optimal market value for both green and low-carbon hydrogen production.
4. Market role and market impact of **hydrogen imports**. Facilitated by the hydrogen exchange, such import flows can create additional market opportunities and contribute to the establishment of ports as regional or national hydrogen hubs.
5. **Interaction with demand** in different sectors. The interaction of this demand with the hydrogen supply can differ per region, depending on the specific situation. In addition, hydrogen offtakers can sometimes offer hydrogen on the exchange to manage their portfolio of forward purchases and actual demand realizations.
6. **Interaction between nodes/regions** in the hydrogen network. All the above market optimizations are present in diverse (port) regions, with different emphasis depending on the regional circumstances.

Disclaimer with respect to simulated outcomes of price levels

The purpose of this report is to study market dynamics, market volatility and time dependency. Simulated price levels were produced in the context of this purpose and cannot be used externally as a reference. More specifically, the following caveats apply:

- In the main dispatch simulation, market outcome was simulated based on variable operational cost. This is the standard and accepted methodology for energy dispatch simulations, also based on economic theories regarding competitive market equilibrium. In this methodology, investments in hydrogen assets are assumed to have materialized. Assumed investments are based on existing project initiatives and/or energy policy ambitions (assuming support schemes

required to achieve those). Investment cost, other fixed cost and commercial margin are not taken into account.
- Over the course of the project, important changes in the energy landscape have taken place. After the Russian invasion in Ukraine, many pathways of international energy supply have changed. Price levels of energy have temporarily taken alternate courses, with potentially more long-lasting effects. The research team has taken this into account as much as possible. Nevertheless, many uncertainties remain, including the effects of the recent inflation hikes.
- The objective of this study was NOT to predict future energy prices and/or market shares of production technologies, which are affected by many more factors. The main objective involves enhancement of joint understanding of the hydrogen system and associated dynamics and volatilty of marginal cost of production as an indicator of volatility of the hydrogen market.

III. Energy system outlook (2027 and 2030)

Scenario perspective

The energy supply will change significantly in the coming years, shifting from predominantly fossil fuels (natural gas, oil, and coal) to an almost entirely sustainable energy mix by 2050. Recent scenario studies (by Netbeheer Nederland) provide a broad outlook and among others, Netbeheer Nederland[1] assumes that the initial supply of hydrogen will be largely fulfilled through imports, steam crackers, and industrial waste gases. Green hydrogen production will start before 2030, with an ambition of 4 GW in 2030, and will grow significantly in the following years (16-45 GW in 2050). With the expected development of import facilities, the Netherlands will become a transit country for hydrogen, with an estimated transmission of 10 to 40 TWh by 2030 and between 50 and 150 TWh by 2050, mainly towards Germany. In the short term, the industry and electricity sector determines the demand for hydrogen. In the longer term (2040) it is assumed that hydrogen will play a role in more sectors and will, for instance, be the primary technology for peak demand in the built environment, for example as a (hybrid) heating solution for buildings. Towards 2050, the demand for hydrogen continues to grow to, among others, allow for decarbonisation of the international transport sector and electricty production.

Hydrogen scenarios and targets for 2027 and 2030

For the purposes of this study, the existing climate scenarios have been adjusted slightly. A scenario for 2027 was created. Recent developments, such as plans for the import of ammonia for the fertilizer industry and hydrogen used in steel manufacturing were added in the 2030 simulations. All relevant major conditions and renewable targets and ambitions for 2030 as set by Dutch government were included in the simulations, including 21 GW installed capacity offshore wind, and 4 GW installed capacity electrolysers in 2030.

Also included is the expected capacity of import terminals for hydrogen carriers (for the import of ammonia, including cracking capacity to produce hydrogen); this is assumed with two different green import price levels, to reflect possible international price fluctuations. We note that in case investment decisions to build the assumed production, transport and storage facilities are delayed, results will be different in practice.

Also included is the target set by the European Commission: 42% of hydrogen used in industry be renewable by 2030 (and 60 % by 2035). The consequence of this target for the volume of green hydrogen in the Netherlands has been calculated according to the insights at the end of 2022. In the points of departure for the market simulation, we included a mitigation of this green hydrogen volume: a lower hydrogen demand for the ammonia-based industry was assumed due to direct imports of ammonia (assumed is half of the ammonia volume). Recent developments indicate the possibility of further mitigation, also caused by moving implementation policies, which relaxes the base definition for applying the 42% target. These latest developments could logistically not be included in the exercises of this report.

Hydrogen infrastructure

For a hydrogen market to function, a transportation infrastructure is of key importance, obeying the priciples of full Third Party Acess (TPA), including hydrogen storage infrastructure in salt caverns. This is foreseen in the Netherlands by the rollout of the "national hydrogen backbone". The timing of this rollout was subject to change during the course of execution of this simulation

project. The figure below shows the most recent expectation of hydrogen infrastructure in both 2027 and 2030 in the Netherlands, as communicated by HyNetwork Services (HNS) in June 2023.

These plans are slight alterations from earlier plans existing at the time this study started, whereby there would already be a fully connected national system as early as 2026 (this perspective had to be postponed by HNS during the ongoing process of this study exercise, after the first simulation runs).

As a result, this simulation study has three main infrastructure cases, namely:

- a regional start-up in 2027, with disconnected regions and no storage capacity involved;
- a national start-up in 2027, simulated with the assumption of one salt cavern storage connected;
- a national system in 2030, simulated with the assumption of four salt cavern storages connected. (Latest practical planning: first cavern operational in 2028, 2nd and 3rd in 2031, 4th in 2034).

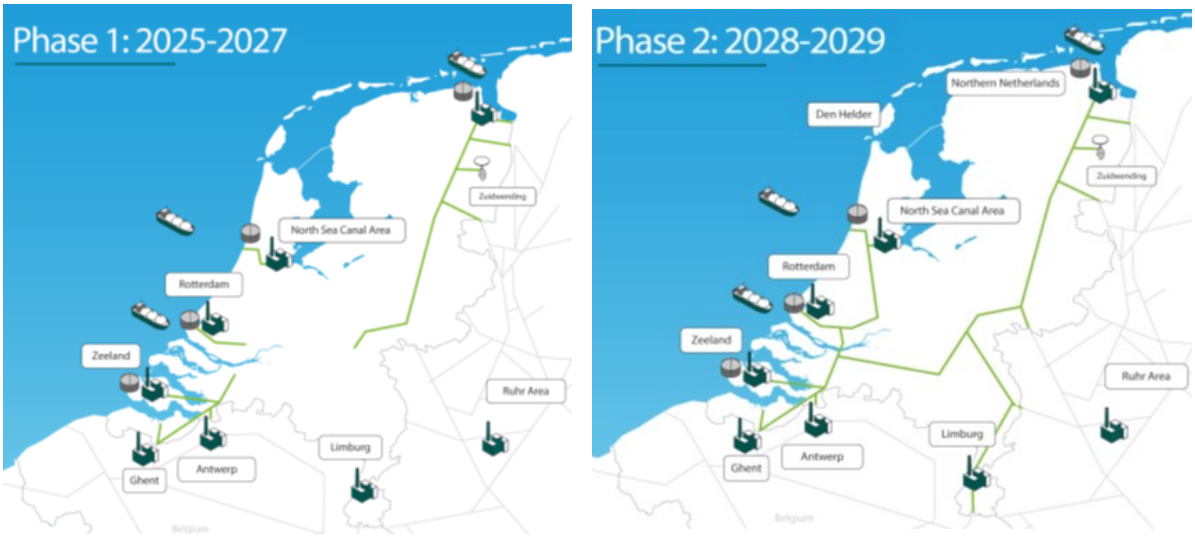

Figure 1 - Expected development of hydrogen network in the Netherlands 2025 – 2030[5]

Modelled hydrogen system not yet in place, need for investments in many areas.

The analysis in this report takes Dutch policy targets and ambitions as a point of departure: certain amount of installed capacity offshore wind generation, capacity of electrolysers, import- and cracking facilities and storage capacity in 2030. Currently many of the needed facilities are not in place yet and/or final investment decisions are yet to be made. In the coming years these plans would need to mature rapidly in order to meet hydrogen and climate ambitions.

IV. Main findings dispatch simulation

In this section main findings are presented, first for the dispatch simulation for 2027 and for 2030. The 2027 simulations cover the annual flow and the impact that a regional versus a national start-up (2027) as well as a number of scenarios (2030) have on system outcome. Second, we discuss the market dynamics, zooming in on the situation of a randomly selected week in autumn. Lastly, we discuss the dynamics of the hydrogen storage, and how it is expected to function under selected 2030 scenarios.

iv.1) Regional versus national start-up of the hydrogen system (2027)

For 2027 two infrastructure scenarios were analysed; a regional system with three disconnected areas that each had to manage their own supply, demand and balancing, and a national system

[5] Hynetwork Services, 2023. Market Update 29-6-2023.

where the national hydrogen backbone materialised as shown in Figure 1 (right side). This approach allows us to better understand the implications and importance of a national versus a regional system. The resulting load duration curves for both 2027 scenarios are shown in Figure 2.

We find that the 2027 regional infrastructure scenario is still very comparable to the current hydrogen system (apart from assumed higher demand based on the expected replacement of natural gas by hydrogen and hydrogen as fuel). The market is still dominated by SMR, with some additional production from electrolysis and ammonia imports. In the national infrastructure scenario the supply of green ammonia increases. It is expected to provide a role in balancing the (now larger) system.

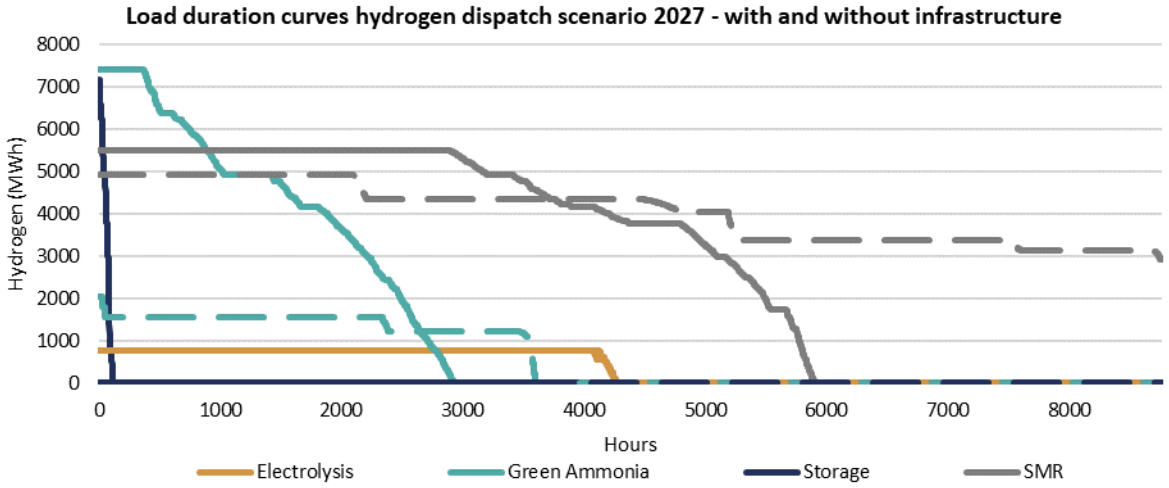

Figure 2 - Load duration curves of hydrogen supply for the 2027 scenario. The regional and national market, with and without infrastructure, are compared. The dashed lines represent the regional market.

Further detailed data-analysis shows that the marginal cost of hydrogen is found to be lower on average in a national than in a regional system, as the national infrastructure allows the most efficient conversion units to be maximally deployed. The cost reduction depends on the actual efficiency of SMRs and hence varies from region to region in practice.

iv.2) National hydrogen system with interconnection, storage and import (2030)

In order to determine the effect of a certain assumption or variable on market behaviour, a number of scenarios for 2030 were analysed. These scenarios and variants can be divided into two categories: physical variants and market variants. The physical variants show the effect of changes in supply or demand. The market variants show the effect of a higher ammonia price (both green and blue) and the effect of market versus subsidised electrolyser dispatch. The combined 8 variants provide understanding of the effect of an upward or downward shift in supply/demand and import prices; they do not provide a prediction of the future, as this is affected by many more factors.

The variants are shown in the table below. The resulting number of full-load hours and TWh operating capacity for each type of hydrogen supplied to the national system, is shown in the two graphs. In the main report the results for one of the variants, the low import prices case, is discussed in detail. Here we focus on meta findings.

Table 1 - Scenarios dispatch simulation 2030[6]

Physical variants	Market variants
A: Low import prices: reflected in cost assumptions for green and blue ammonia cracked into H2, marginal cost (HHV): - Green: 66 €/MWh H2 - Blue : 62 €/MWh H2	E.1 Import shipping marginal cost analysis – green ammonia cracked into H2, marginal cost (HHV): 88 €/MWh H2

[6] Variants A to E have an assumed 4.200 FLH subsidy for electrolysers, and as such stable production.

Physical variants	Market variants
B. Ammonia cracker analysis – like A, but reduction of capacity of ammonia cracker by 50%	E.2 Import shipping marginal cost analysis – LNG cost at Henry Hub price of 35 €/MWh and blue ammonia cracked into H2, marginal cost (HHV) €67 /MWh
C. Increased export analysis – increasing hydrogen demand in Germany	F.1 Market based electrolysis dispatch – low green import ammonia cracked into H2: marginal prices (HHV): 66 €/MWh
D. Worst case scenario – involving both alterations to the import case and halve storage capacity	F.2 Market based electrolysis dispatch – high green import ammonia cracked into H2: marginal cost (HHV): 88 €/MWh

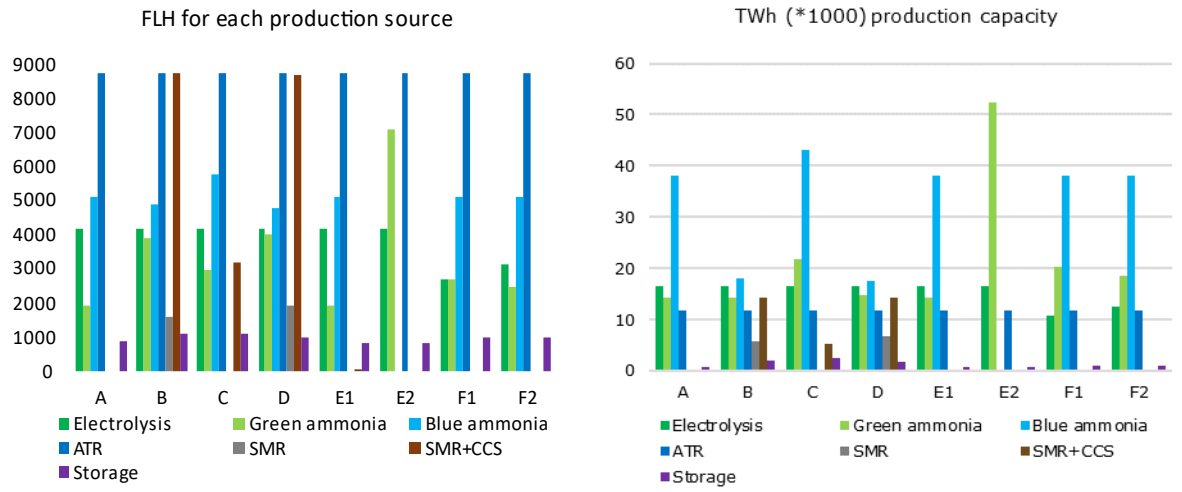

Figure 3 - Summary of results 2030 variants, full-load hours (left) and TWh production capacity (right). For ATR a CO_2 capture rate of 88% is assumed.

The main findings for the 2030 physical variants are as follows:

- Because of the assumed larger supply of green hydrogen, as well as a higher ETS price than in the 2030 variants compared to the 2027 scenario, we obtain a much more diverse market, with multiple supply options providing hydrogen to the market, depending on their cost.
- The role of hydrogen storage (HyStock) increases significantly when overall demand increases, this also holds true for the volume and production of imported blue and green ammonia.
- SMR+CCS production facilities provide an important back-up function to the system, in each physical scenario (apart from the low cost import case) it is needed to satisfy demand, although the number of full-load hours (hereafter: FLH) differs significantly.
- Final FLH/TWh for each technology will strongly depend on FIDs taken in the coming years.

The main findings for the 2030 market variants are as follows:

- Electrolysers run fewer FLH (scenarios F1 and F2) and hence produce less hydrogen when operating market-based (without a production subsidy). The number of operating hours is strongly affected by the assumed price of imported green ammonia, which acts as key competitor in the merit order.
- The cost difference between green and blue ammonia is small. Scenario E2 shows how an increase in price of blue ammonia can alter results. The ammonia cracker will swing to green ammonia if it can be obtained at lower prices than blue ammonia (which can be caused by change in price of renewable energy, etc).
- The use and importance of storage differs under changing market (price) conditions. An increase in national green hydrogen production leads to a more intensified use of hydrogen storage due to a higher number of injections/ejections of storage.

iv.3) Market dynamics hydrogen system (import case, 2027 and 2030)

Two types of variables affect the dispatch results, the first being the modelled infrastructure (being several regional networks or one national grid). Second, there is a difference in volume and legal criteria (in 2027 lower supply and demand, in 2030 higher supply and demand as partly driven by

the 42% industry target). Both of these variables have a significant impact on the dispatch, as can be concluded from the weekly snapshots of system dispatch of the three main scenarios in the four figures below (two scenarios for 2030).

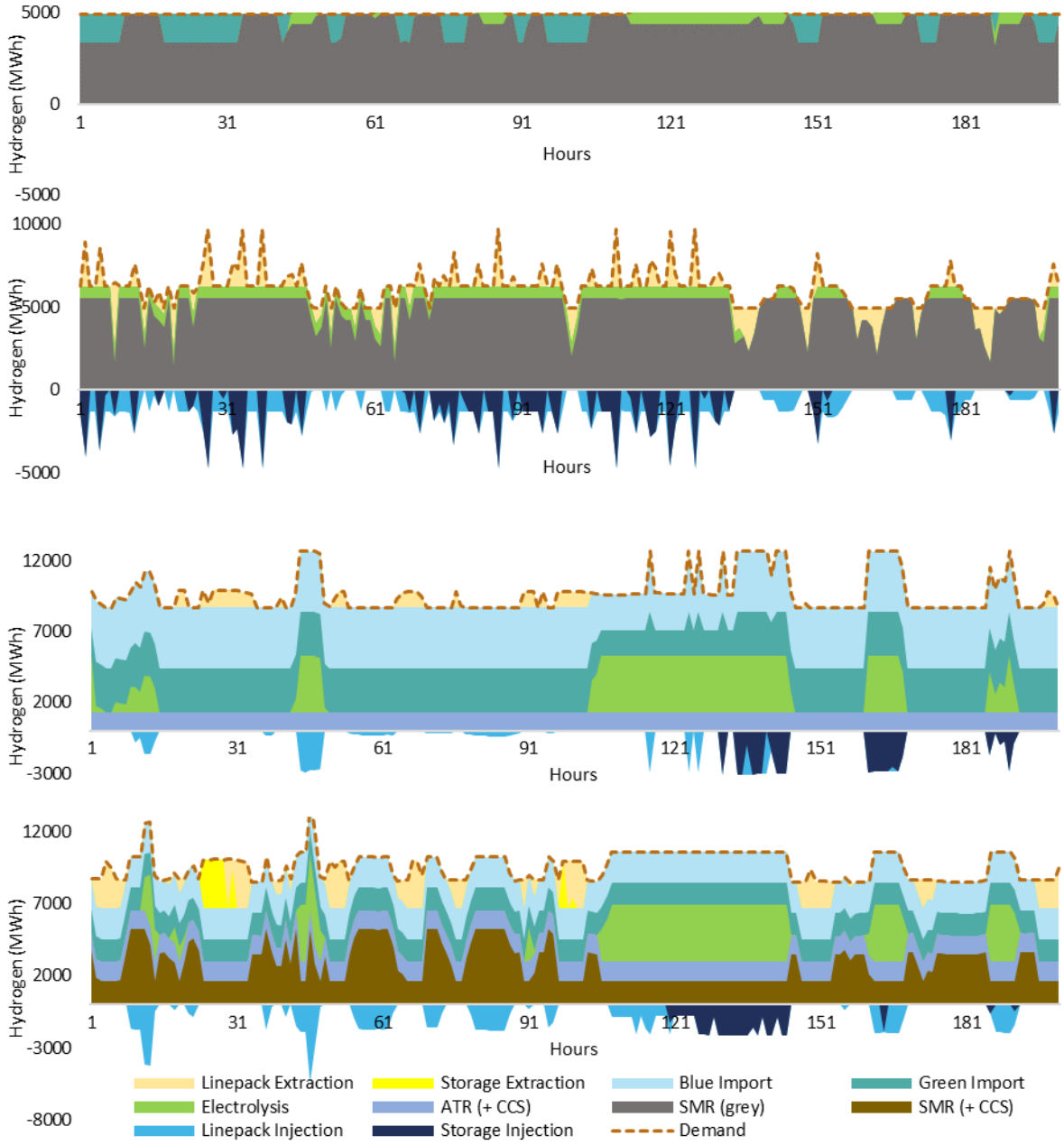

Figure 4 - Weekly hydrogen balance for a week in October (2027-reg, 2027-nat, 2030-A and 2030-D)

Key observations from the weekly dispatch scenarios for 2027 and 2030 are:

- In 2027, the system is still largely supplied through SMRs, due to the small electrolyser capacity and a lack of a (substantial) green H2 industry target assumed in this year.[7]
    - In a regional system, hydrogen is mostly supplied through a SMR; electrolysers provide hydrogen in limited quantities, requiring hours with low electricty prices in order to

[7] The Ministry of Economic Affairs and Climate Policy has stated that from 2026 onwards a green hydrogen target will be implemented, as precursor and to kickstart the market going to 2030. Setting an industry target will affect results.

compete. Depending on a region's access to ammonia import and cracking facilities, hydrogen produced from ammonia also plays a role.
    - The national system in 2027 would have added storage capacity to the mix. Both injection and extraction occur frequently (including linepack, as it spans a large area).
- A 2030 national system looks very different, with a 42% green hydrogen target in the industry, a fully developed national infrastructure, and import capacity in ammonia terminals through cracking. The green H2 supply from electrolysers has greatly increased to 4 GW, also supported by an assumed subsidy that increases the number of market-based FLH.
    - In the 2030 low import price scenario, import ammonia (green and blue) plays a large role in maintaining a steady system, resulting in a relatively limited use of storage capacity and no production by SMRs (with or without CCS) into the H2 system; a small role is played by new ATR with CCS.
    - In the 2030 worst case scenario (high import prices, lower cracking capacity), SMRs and H2 cavern storage plays a much bigger and dynamic role in maintaining a steady system. Imported ammonia (green and blue) has a smaller but still very significant role; green import is required to fulfill the 42% target.

iv.4) Hydrogen storage dynamics (2030)

Profiles of hydrogen storage level development over the year provide a seasonal perspective on storage behaviour and the role of storage in the aforementioned simulations. The resulting seasonal storage level is presented in Figure 5.

All variants show a seasonal storage pattern, with more extraction during wintertime when hydrogen demand is relatively high (this is caused by the higher gas prices, hydrogen users will hence rather use stored hydrogen). The increased winter demand calls upon storage as this offers the most cost-effective additional supply option at relatively limited cost of injection only. These results are only marginally affected by the assumed storage level set-point of about 650 GWh at the turn of the year.

There is a notable difference in the shape of the curve between the import case and the variants shown. While the storage remains largely undeployed in the import case during summer, the other two cases show significant injection volumes over summer. In case of low import costs and cracker deployment, the cracker is able to offer hydrogen cost-effectively for most of the year, at relatively flat hydrogen prices. The associated hydrogen pricing profile leaves relatively limited arbitrage opportunities for the exploitation of a storage asset. If the cracker operates under higher import cost assumptions, or if its capacity is decreased, the storage facility provides seasonal storage, exploiting hydrogen price differences.

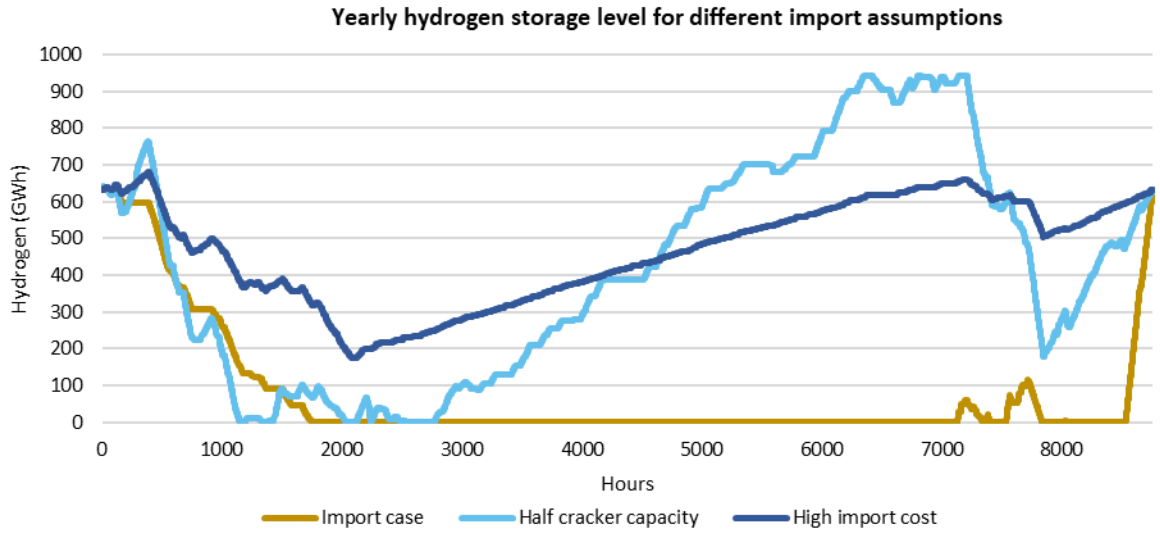

Figure 5 - Seasonal profile for storage level for differing import assumptions. Import case = scenario A, half cracker capacity = scenario B, high import cost = scenario E.

V. Main findings market simulation and imbalance analysis

v.1) Market simulation

TNO's market simulation model EYE represents a simplified merit order model for power and hydrogen in the Netherlands. It dynamically allocates the production and storage facilities in the system over the course of a year. Since it is a flexible model, it allows to take bid strategies other than marginal cost bidding as input (which is an underlying assumption of I-ELGAS), it allows for instance bidding using a (partial) PPA for electrolysis. Finally, since EYE does not optimize the system allocation across a pre-set horizon, it allows to evaluate the impact of uncertainty, rather than the typical perfect foresight assumption construed in optimization modelling.

For 2027, two uncertainties for hydrogen production were identified in collaboration with market parties: the presence of ammonia crackers and whether SMRs will bid on the hydrogen spot market or continue as dedicated hydrogen producers on-site. Four cases have been analysed: plain spot trading; bilateral contracting; high biletateral contracting; and low SMR market entry. In plain spot trading, the market dynamics closely resemble that of an optimal dispatch. By removing ammonia crackers and taking SMRs off the market, this changes. The share of hydrogen demand traded on the spot market decreases: 100% in the first case, 84% in the second, 68% in the third and only 3% in the final case. These lower volumes impact the added value of a hydrogen spot market. If existing dedicated hydrogen production remains to be dedicated to on-site hydrogen demand, private price and volume risk can remain limited at the expense of optimal system dispatch. To add, transparancy in hydrogen spot pricing will suffer, while pricing transparancy is one of the core benefits of an exchange. In 2027, we are only three years away from there being actual targets for green hydrogen in 2030. More transparency in prices in 2027 can be beneficial – maybe even crucial – to reach these targets.

For 2030, the focus of the simulations is on reaching the green hydrogen targets as proposed in the Delegated Act. We have simulated two cases: 1) the industry satisfies the targets via a dedicated spot market, and 2) the industry satisfies the targets via long-term contracts. We find that industry relience on a spot market to reach its targets (case 1) will result in an optimal dispatch. On the other hand, if the industry meets its targets via long-term contracts, this might give individual guarantees regarding price and volume risk, which may be needed to support final investment decisions on electrolysis projects in the initial phase of the market development.

For both 2027 and 2030, whether or not a hydrogen exchange will provide transparancy in prices is determined by the shares of hydrogen volume traded on the exchange. For 2027 these shares were determined by the hydrogen production: the presence of ammonia crackers and the use of SMRs. For 2030 these shares were determined by how industry wishes to satisfy its green hydrogen targets. A need for individual certainty can lead to decentralized production and/or long term contracts. However, this will decrease the volumes traded on the hydrogen market, which in turn leads to a lack of increased transparancy in prices.

V.2) Imbalance analysis

To better understand the system imbalance, a new simulation model has been developed upon specific request of participating market parties as part of this project. This model allows for technical and financial analysis of the coupling between the electricity imbalance market and the hydrogen imbalance market.

In total, four scenarios have been modelled. In each scenario the linepack capacity and imbalance volume have been altered. For each scenario we obtain information on the total revenue, which is calculated by multiplying the electricity imbalance volume cleared by the electrolyser and the imbalance prices of these periods and summing this for all periods. This revenue is compared with the revenue which the electrolyser has on the hydrogen spot market.

We find that both linepack capacity and imbalance volume have a positive influence on the revenue which the electrolyser can obtain on the electricity imbalance market. However, doubling the imbalance volume does not cause doubling in revenue. This is caused by the linepack capacity constraint: the electrolyser is not able to utilize all the imbalance volume when the linepack is either full or depleted. Increasing the linepack capacity available for the electrolysers will allow the electrolysers to utilise a higher imbalance volume, as can be seen from the table below.

Table 2 - Financial parameters from the imbalance model.

Scenario	Linepack capacity for electrolysers	Imbalance volume in 2030 w.r.t 2019	Total revenue	Revenue on E-imbalance market w.r.t H2 spot market
I	1400 MWh	Same	4.7 M€	0.5%
II	1400 MWh	Double	7.8 M€	0.8%
III	7000 MWh	Same	7.0 M€	0.7%
IV	7000 MWh	Double	13.0 M€	1.3%

The revenue on the imbalance market (for secondary reserves) with reference to the hydrogen spot market ranges from 0.5% to 1.3%.

Besides providing an additional revenue stream for the electrolysers, the electrolysers also provides a service to the electricity market. Because of the physical nature of hydrogen and electricity and the coupling of the hydrogen and electricity markets through the electrolysers, the hydrogen system can provide a service to the electricity system by solving its imbalance issues. These imbalance issues will increase due to the large-scale deployment of renewables, which increases the value of coupling the hydrogen and electricity systems.

In this simulation it is assumed that the electrolysers are able to clear all the volume on the electricity imbalance market. In practice there will be competition with other assets, such as E-storage.

VI. Main market dynamics and implications for hydrogen trading

Insights from this study and contributions offered by market parties during the simulation sessions help shape the next step in developing the Dutch hydrogen market and develop the rules and the trading system specification for the Dutch hydrogen exchange (HyXchange). Specifically, we have obtained the following insights that will be taken into account by HyXchange going forward:

The time unit of the market variations is hourly. The simulations show that variations of the simulated production volumes dispatch are hourly. In 2030, many of these hourly production variations are due to the variable hydrogen output of electrolysers, driven by underlying hourly variations of renewable power production and electricity spot prices. Simulated price variations are also hourly, albeit less volatile than electricity prices, due to: the stabilising effect of storage, line-pack, hydrogen production from gas-reforming units and assumed ammonia-cracking capacity as the dispatchable price-drivers. If those units are present and provide enough flexibility, the resulting price may be relatively stable while the underlying production components may show a high hourly variability in their volumes.

Hydrogen system dispatch is strongly affected by infrastructure (regional versus national), availability of ammonia (green/blue) imports and cracking, and storage capacity. Two time periods and two infrastructure situations have been modelled. From this we find that there are significant benefits from coupling of the regional hydrogen networks to a national grid, both with regards to costs for balancing of the system as for the average marginal cost of hydrogen. This is underpinned by the simulations for the start-up market in 2027 in two versions: with an interconnected national infrastructure (as foreseen initially), and without that national interconnection (due to delayed national infrastructure as now planned). In that latter case with isolated industrial clusters, it appears that the average marginal hydrogen cost is higher. The balancing role of storage and imported ammonia would be greatly diminished if main industrial regions cannot reach these facilities without the national infrastructure, creating a higher dependency on (non-renewable) balancing by local natural gas reformers. In 2030, this is even more apparent: meeting the national industry target of 42% renewable hydrogen simply requires a national infrastructure to be in place. According to current plans, this would involve the hydrogen link through the planned Delta Rhine Corridor, for the linking of vital flex from salt caverns and ammonia cracking to all industrial regions. Obviously possible changes to supply, demand, prices and final wording of relevant regulations will have a (significant) impact on outcomes.

Storage, imported ammonia cracking and SMR/CCS all offer grid balancing services and are all needed. Flexible supply is needed to balance the hydrogen grid. SMR/CCS, cracked import-ammonia and salt cavern storage could provide this service. We find that in case of low import costs and cracker deployment, the ammonia cracker is able to offer flexible hydrogen cost-effectively for most of the year, at relatively flat hydrogen prices. In such a "best import" case, the associated hydrogen pricing profile leaves relatively limited arbitrage opportunities for the exploitation of a storage asset. If the ammonia cracker operates under higher import cost assumptions, or if its capacity is decreased, the salt cavern storage facility would provide more seasonal storage, exploiting hydrogen price differences, also with a possibility of a bigger flexibility role (depending on gas price levels) for SMR/CCS and ATR/CCS. In all cases, all flexibility-providing facilities are needed, albeit with a different emphasis. With an increasing demand for hydrogen and an increasing supply of hydrogen from variable sources after 2030, the system would need ever-more flexibility, making the need for much bigger storage (e.g. in old gas fields) more urgent.

Day-ahead and intra-day variations are generated by the hourly varying renewable input (wind, solar) in electrolysers. This can be balanced by dispatchable sources: import ammonia cracking, hydrogen storage and/or gas reforming, depending on international price levels of LNG import and ammonia import. Green hydrogen supply from electrolysers is intermittent and this needs to be balanced, because the hydrogen demand is mostly a continuous baseload demand related to industrial processes. The flexible hydrogen sources for delivering this balancing are hydrogen storage in salt caverns and hydrogen production from cracking of imported ammonia (blue and green ammonia). Balancing by SMR and ATR gas reforming units is also possible. With the projected variable output of electrolysers in 2030, the balancing need would always be bigger than the size of the storage in salt caverns. Major balancing by ammonia cracking and/or SMR/ATR gas reforming will be needed in the mix depending on international prices of imported LNG and ammonia as well as availability of import ammonia cracking.

Electrolysers can balance part of the electricity market, with some additional revenue. Because of the physical nature of hydrogen and electricity and the coupling of the hydrogen and electricity markets through the electrolysers, the hydrogen system can provide a service to the electricity system by solving its imbalance issues. This coupling will function as an additional revenue stream for electrolysers, which will depend on the linepack capacity of electrolysers and the total volume of imbalance. These imbalance issues are going to increase due to the large scale deployment of renewables, which increases the market coupling.

There is a clear premium of green hydrogen certificates. Also, imported green ammonia may be needed to reach the 42% renewable hydrogen industry target. We expect the value of the green certificate to be set at the difference between the marginal production cost of blue and green ammonia (assuming both are in sufficient supply and based on current wording of relevant regulatory documents). This difference will become more apparent going towards 2030 and will increasingly depend on green hydrogen targets (for industry and other sectors) set by other countries. Further, we find an important role for green ammonia in many simulations (partly based on our initial assumptions regarding the 42% target). In most of the simulations for 2030, imported green ammonia is needed to satisfy the assumed industry target. In practice, this may depend on many factors: the amount of direct ammonia feedstock import, the practical (national) implementation of the 42% target and the final outcome of recent discussions regarding the base for the 42% calculation, that could lead to mitigation of the required green hydrogen volume in 2030.

Care for the early market conditions with limited sources for balancing and liquidity. From this study, it appears that the (green) hydrogen market can be well stable, if there are sufficient providers of dispatchable hydrogen (flexibility and storage). It also illustrates that at the start-up onset of the market (2025 onward), this dispatchable hydrogen may not be there yet, or it may not be connected to all regions or end users, also due to the gradual buildup of the infrastructure which takes time to become fully deployed. This may also lead to a temporary inequality between regions regarding fair market access to green hydrogen as well as the hydrogen balancing. According to current insights, this may also be worsened by the strict rules of mass balancing in green H2 EU certificates (which work best in a fully developed market and infrastructure). Temporary measures may be required to provide a secure and "fair for all" environment for the market in the early years. Transparent exchange-based access to green hydrogen certificates and capacity flexibility could be part of the solution.

VII. Further recommended research

The analysis and conclusions in this report give rise to a number of new ideas and recommendations regarding further research, which are briefly discussed below. Performing this additional research/these additional simulations will shed more light on the market consequences, synergies and advantages. This in turn could provide more arguments for developing new technologies and combinations thereof.

- **Firstly, we recommend a hydrogen market simulation projected in the years 2035 and 2040.** In the current report, we could only simulate the starting years of the market; 2027 and 2030.[8] We still have the wish to look further ahead, as this would still involve more important changes with even more market players, also due to the move from gas power plants to hydrogen power plants, expected from 2030 to 2035. This is of importance for the Dutch power supply. It will create completely new interactions, well-simulated in the multi-commodity nodal I-ELGAS model. This could also involve the optimal location of electrolysers with respect to minimising transportation and congestions (and costs thereof) in the Dutch electricity grid.
- **Secondly, this would also facilitate the inclusion of new technologies with added value.** The results of this project spark ideas about hew synergies and market benefits from technologies such as i) a combination of battery storage and hydrogen production (by batteries and electrolysers, but also integrated concepts like the battolyser), and/or ii) reversible electrolysers/power plants (e.g. the solid oxide fuel cell SOFC, and flow battery).
- **Thirdly, inclusion of more hydrogen storage concepts.** Other large- and small-scale storage concepts are currently being developed. With respect to large-scale storage, we refer to hydrogen in (offshore) old gas fields. Time of delivery upon these projects will likely have a large impact on the future hydrogen system (with a significant expected increase in supply-demand). Small-scale concepts, such as storage in (pressurised or iron oxide absorption) containers, could have an impact on balancing and on broader distribution of hydrogen to other sectors. Such new concepts are not yet included in the simulation for 2030, but are to be included in the simulation 2035 and 2040.
- **Finally, inclusion of a wider range of international hydrogen carriers.** Next to the currently modelled main ammonia import for 2030, for 2035/2040 this would also imply LOHC's, liquid hydrogen, methanol and DME (Dimethyl Ether).

Seperately, it would be conceivable to apply this simulation model more internationally, e.g. to other countries with hydrogen grid ambitions, or to hydrogen regions (e.g. Central Western Europe).

VIII. Final remarks

The study has provided insight into many aspects of the future hydrogen system and market requirements. Insights from the performed simulations (intermediate results) have been shared during a number of digital events and were presented at various conferences. The learnings from this project will support the next steps in the further development and blueprinting of the hydrogen exchange based in the Netherlands. The models (further) developed in this project will be used by TNO in other research projects, e.g. focussing on the 2035-2040 hydrogen market and related challenges.

The researchers involved in this study extend their thanks to the involved private and public experts who participated, provided feedback and/or input and challenged us during the process during various digital meetings and working sessions.

[8] It was the original intention to include 2035 in the simulation years, but this simulation year had to be sacrificed in favour of inclusion of balancing analysis and the priority for the start-up years 2027 and 2030 (on request of the market parties), and additional complexity due to changes in the start-up environment during the course of this project (publication of the EU Delegated Act on Renewable Hydrogen, announcement of delays in the development of the national hydrogen network and the like).

ABOUT THE HYXCHANGE INITATIVE: HYXCHANGE AIMS TO REALIZE A TRADING PLATFORM FOR HYDROGEN ON THE MAIN DUTCH HYDROGEN INFRASTRUCTURE.

Introduction: Hydrogen is increasingly attracting interest as an important part of the energy transition. Due to the position that hydrogen will occupy in the future and the many ways in which it can be produced and used, with a variety of producers and users, the development of the trade in hydrogen will become important. As a result, parties from the sector have started the "HyXchange" initiative. HyXchange is supported by Gasunie, Port of Rotterdam, Port of Amsterdam, Groningen Seaports, North Sea Ports and a large, growing number of interested market parties.

Key objectives: For the functioning of a hydrogen exchange it is important that the underlying conditions for market forces in hydrogen are met. Firstly, an openly accessible transport infrastructure for hydrogen is important condition; this will be facilitated with the establishment of the backbone that allows storage and independent management. Secondly a diverse supply of hydrogen is important, in which, in addition to the electrolysis of Dutch sustainable electricity, other sources also play a role, in particular the import of (green) hydrogen from other countries and continents, and low-carbon hydrogen from industrial processes. This also contributes to the security of supply. Thirdly, a dependable and transparent trading platform greatly enhances market access, pools liquidity and reduces transaction costs and trading risks.